EFFECT OF SELECTED SOIL WATER CONSERVATION PRACTICES ON WATER BUDGETING IN ROBUSTA COFFEE (*COFFEA CANEPHORA)* IN UGANDA

BY

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19/U/GDSB/18977/PD

A THESIS SUBMITTED TO KYAMBOGO UNIVERSITY DIRECTORATE OF RESEARCH AND GRADUATE TRAINING IN FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN BIOLOGICAL SCIENCES OF KYAMBOGO UNIVERSITY

SEPTEMBER 2025

DECLARATION

I, KOBUSINGE JUDITH, hereby do declare that this thesis being submitted for the degree of Doctor of Philosophy in Biological Sciences at Kyambogo University is my original work and has never been presented for a degree in any other university.

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APPROVAL

We as supervisors confirm that the thesis was developed by the candidate under our supervision.

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DEDICATION

I dedicate this thesis to my grandmother, Cecilia Kahwe, whose prayers made it possible for me to complete this work.

ACKNOWLEDGEMENTS

I am profoundly grateful to God for the gift of good health, wisdom, strength, and the provision of resources that made it possible for me to complete this PhD. This has truly been a remarkable journey of learning and growth.

I sincerely appreciate the United States Agency for International Development (USAID), through the Scaling Project, and the International Foundation for Science (IFS) for providing financial support for my study. I am equally thankful to ICRAF Uganda for generously lending me the four sap flow meters used in this research. My heartfelt gratitude also goes to the National Coffee Research Institute and Kaweri Coffee Plantation Limited for hosting my experiments.

I extend special appreciation to my supervisor, Assoc. Prof. Charles K. Twesigye, for his unwavering support, insightful guidance, and encouragement throughout this journey. I am also deeply grateful to Dr. Godfrey H. Kagezi, who entrusted me with the opportunity to develop this study under his project, and for his constructive criticism and mentorship.

My sincere thanks go to my support system Dr. Joel Buyinza, Dr. Godfrey Gabiri, and Dr. Godfrey Sseremba for your invaluable guidance, encouragement, and genuine care. I am also indebted to the field assistants and research technicians whose dedication and assistance at every stage of data collection made this work possible.

Finally, I wish to express my deepest gratitude to my family and friends for their unconditional love, patience, and constant encouragement during this demanding period. Your support has been my anchor, and I could not have achieved this milestone without you

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ACRONYMS

ACS	Coffee *Albizia coriaria* system
BBCH	Biologische Bundesantalt Bundessortenamt and CHemische Industries
CD	Canopy diameter
CH	Canopy height.
cm	Centimeter
CMS	Coffee mulch system
CMS	Coffee cover crop system
COSS	Open sun coffee system
ETa	Actual Evapotranspiration
Ha	Hectare
KCPL	Kaweri Coffee Plantation Limited
LAI	Leaf Area Index
LLP	Length of longest primary
m	Meter
mm	Millimeters
NaCORI	National Coffee Research Institute
NP	Number of primaries
NPI	Number of primary internodes
NSI	Number of stem internodes
PAR	Photosynthetic Active Radiation
RCP	Representative Concentration Pathway

SG	Stem girth
SL	Stem length
SMC	Soil moisture content
SMCP	Soil moisture conservation practices
SSP	Shared Socioeconomic Pathway
WUE	Water Use Efficiency

ABSTRACT

Coffee is a vital crop globally, employing over 125 million people. In Uganda, more than 12 million depend on coffee-related activities, yet yields remain below the potential of 2.2 tons/ha due to pests, diseases, poor management, and climate change. Climate change, marked by erratic rainfall and rising temperatures, increases evapotranspiration and crop water stress. While studies on Arabica dominate, there is limited information on how soil moisture and conservation practices affect Robusta coffee production in Uganda. This study addressed three objectives. First, the effect of climate change on soil moisture was assessed using historical data (1990-2022) and projections (2025-2050) from eight Global Climate Models under SSP245 and SSP585 scenarios. Soil moisture suitability maps were generated using MATLAB climatology tools, Mann-Kendall trend analysis, and a Mamdani Fuzzy Inference System. Findings revealed that historically, soil moisture was highest around Lake Victoria (115-143 mm) and lowest in Northern and Southwestern Uganda (<30 mm). SSP245 projections indicate a slight moisture decrease near Lake Victoria but an increase in other regions, with Rwenzori and Kitgum seeing the highest rise (0.08 mm). Under SSP585, soil moisture remains high in Kigezi and Rwenzori with varying yearly patterns. Historically, 71% of Uganda was highly suitable for coffee, but future predictions suggest suitability will rise to 74% under SSP245 and 81% under SSP585, potentially boosting coffee suitability by 10%. Second, water use efficiency (WUE) of Robusta coffee under *Albizia coriaria* shade (ACS) and open sun (COSS) systems was evaluated at the National Coffee Research Institute (NaCORI) using a randomized block design. Sap flow meters measured water use, while growth, yield, and phenological data were collected. Coffee in the open sun significantly ($p<0.001$) used more water per day (1.43 l/day) compared to coffee under shade (0.62 l/day). There was a significant difference ($p<0.001$) in water use per unit leaf area per system. ACS used more water (0.12 mm/day) compared to COSS (0.10 mm/day). WUE varied by system and phenological stage, with ACS being more efficient during fruit development stages. Third, the effect of soil moisture conservation practices (SMCPs) on soil-water relations was assessed at NaCORI and Kaweri Coffee Plantation Limited (KCPL). Four systems were tested: COSS, coffee cover crop (CCS), coffee mulch (CMS), and ACS. CMS significantly ($p<0.05$) increased soil moisture by 45.32% at NaCORI, followed by CCS at 13.68%, while ACS decreased soil moisture by 29.32% within the coffee root zone. At KCPL, there was no significant difference in the efficiency of SMCPs in conserving soil moisture, though, CCS increased soil moisture by 21.29%, followed by ACS (20.17%), with the least increase observed under CMS (16.17%). In conclusion, Climate change will result in higher soil moisture, which will increase the suitability of coffee by 10%. Some areas that are currently suitable like, Northern Uganda will not be suitable in the future. CMS, CCS and ACS improved the soil water relations better compared to COSS. Therefore, near future unstable areas should adopt soil moisture conservation practices to reduce on water stress likely to come due to climate change. *Albizia coriaria* should be optimally used as a way of improving water use efficiency for better fruit development without compromising on bean weight and yield.

CHAPTER ONE: INTRODUCTION

1.0 Introduction

This chapter presents the background of the study, statement of the problem, conceptual framework, research objectives and questions, scope, significance of the study, definition of terms and an outline of the thesis

1.1 Background to the study

Coffee is a major cash crop and a leading source of foreign exchange for Uganda. In the 2023/24 financial year, the country exported 6.13 million 60-kg bags, generating USD 1.14 billion (UCDA, 2024). Over 1.8 million households are employed in the coffee-related business at the production level, while over 12 million individuals employed in activities related to coffee production of which 11.9 million are farmers (Kaufman, 2023). Over 80% of these are smallholder farmers who contribute 90% of Uganda's coffee (NCP, 2013). They own coffee fields ranging from 0.5 to 2.5 hectares (UCDA, 2012; NCP, 2013; Mugoya, 2018). Arabica (*Coffea arabica*) and Robusta (*C. canephora*) are the two main types of coffee grown and estimated to comprise 20% and 80% of the total production, respectively (UCDA, 2019a Handbook). The average clean (green) Robusta coffee yield is about 0.6 t ha^{-1}, which is nearly four times lower than the potential yield of 2.2 t ha^{-1} (Kobusinge *et al.,* 2023). This yield gap is linked to several challenges, including socio-economic factors, poor farm management, declining soil fertility, pests and diseases (Liebig *et al.,* 2016), and more recently, the impacts of climate change (Kagezi *et al.,* 2018). However, Uganda is one of the most unprepared

(145th) and vulnerable countries (15th) in the world in respect to the impacts of climate change disasters (Twecan *et al.,* 2022). Uganda's average temperatures are projected to rise by about 2 °C, accompanied by increasingly unpredictable rainfall patterns (MWE, 2015). Water availability is also predicted to reduce in the global climate change context and scenario (Abudulla *et al.,* 2018). Climate change has been reported to increase on crop water requirements so as to meet the increased evapotranspiration demands (Shafeeque & Bibi, 2023). This will present a great challenge as water is already a scare resource (Chakkaravarthy & Balakrishnan, 2019). Reduced water availability will also make it difficult for irrigation (Rao *et al.,* 2007; Abudulla *et al.,* 2018). Furthermore, water stress restricts photosynthesis by causing stomatal closure and reducing other physiological functions within the plant (Haggar & Schepp, 2012; Silva *et al.,* 2022). Consequently, the land area suitable for coffee cultivation is projected to decline (Bilen *et al.,* 2023). At the same time, the occurrence and severity of key pests and diseases including the coffee berry borer (*Hypothenemus hampei*), coffee stem borer (*Monochamus leuconotus*), and coffee leaf rust (*Hemileia vastatrix*) are expected to rise, leading to lower yields, reduced quality, and higher production costs (Kagezi *et al.,* 2018). Feng (2015) noted that climate variations can make changes in soil moisture more unpredictable. Rising temperatures increase evapotranspiration, while shifts in rainfall patterns can lead to both drought and excessive moisture, each of which negatively impacts soil health and water availability. These changes can affect coffee during its growing, blossoming, and backing stages, influencing flower bud development (Kath *et al.,* 2023). Such climate-related risks pose a serious threat to the future supply of coffee, especially in the face of growing demand driven by population growth and rising incomes (Torga & Spers, 2020). Climate change will make it difficult for farmers to predict when to plant (Wangui, 2012; Mubiru *et al.,* 2018). Projected climate conditions could pose a significant threat to coffee production, particularly in less favorable environments (Jaramillo *et al.,* 2011).

All in all, this climate change will add to the challenges smallholder farmers are already facing, putting the livelihood of farming families at risk (Jassogne *et al.,* 2013). Smallholder farmers face high vulnerability to climate change because they rely on rain-fed farming, often cultivate marginal lands, and have limited access to technical and financial resources needed to adopt climate-resilient practices (Morton, 2007). Nonetheless, smallholder farmers can lessen potential impacts by adopting adaptive strategies, particularly through the use of various conservation practices (Mano *et al.,* 2003; Maddison, 2006; Gokavi & Kishor, 2020). However, these conservation methods are laborious to establish and maintain (Narayanan *et al.,* 2009).

Research has shown that it will be impossible for farmers to achieve their production targets without application of best soil and water conservation practices (Kumar & Bhople, 2017; Mwanake *et al.,* 2023). Soil conservation practices such as shade trees, cover crop and mulch, among others have therefore been recommended as effective means to mitigate temperature and water stress induced by climate change (Kumar & Bhople, 2017; Brempong *et al.,* 2023). The benefits of soil conservation practices include control of weeds, provision of additional nutrients to the soil, minimizing soil temperature and protecting the soil surface from the impacts of heavy rain and wind (Baumhardt & Blanco-Canqui, 2014). By reducing evapotranspiration through reduced temperatures, they reduce on the amount of water required for irrigation, increase crop productivity and improve soil quality (Kumar & Bhople, 2017; Brempong *et al.,* 2023). However, shade tree and cover crops may reduce the water that is intended to reach the soil by rainfall interception and utilizing the water that would otherwise be for coffee (Righi *et al.,* 2008).

Literature shows that studies on water use and effect of climate change on coffee have concentrated mostly on Arabica as opposed to Robusta coffee elsewhere (e.g. Tausend *et al*., 2000; Carr, 2001; Jaramillo-Botero *et al.,* 2010) and recently, in Uganda Buyinza *et al.* (2019) and Sarmiento-soler *et al.* (2019). The climate risks associated with Robusta coffee systems at plot and landscape levels are yet to be fully studied in Uganda (Nakyagaba, unpublished data), though Mulinde *et al*. (2019) analyzed the perceived climate risks at household level in Robusta coffee systems. This is despite the importance of Robusta coffee in Uganda (UCDA, 2019a Hand book). Secondly, these Robusta coffee farmers are being encouraged to adapt to adverse effects of climate change by planting shade trees (Kiyingi & Gwali, 2011; Jassogne *et al*., 2013), mulching and planting cover crops (SUSTAINET EA, 2010), but without taking into account water use in these systems (Sarmiento-Soler *et al*., 2019). Therefore, this study aimed at i) Predicting the effect of climate change on soil moisture in Uganda, ii) Estimating the water use efficiency (WUE) of Robusta coffee at various phenological stages under coffee *Albizia coriaria* and Open sun Robusta coffee systems and iii) determining the effect of selected soil moisture conservation practices on soil-water relations in Robusta coffee agro-systems. This information will be utilized in mapping out the suitability of Robusta coffee growing in relation to soil moisture and therefore develops and recommend adaptation interventions in the threatened areas (González-Orozco *et al*., 2024). Secondly, determine best-bet soil moisture conservation practice for optimum soil moisture stress management for maximum productivity of coffee (Kobusinge *et al*., 2023). This generated information will advise research, policy, farmers and other stakeholders on the best-bet adaptation strategies against soil moisture stress of coffee systems (Ajani *et al*., 2013; Disingizimana, 2018). These outputs will lead to increased yields, thus, incomes of the farmers. This will thus lead to improved livelihoods.

1.2 Statement of the problem

Robusta coffee accounts for 80% of Ugandan coffee (Masiga & Ruhweza, 2007) and 83.97% of the total exports in financial year 2023/24 (UCDA, 2024). However, the productivity is still below attainable yields. The actual yield of 0.6t /ha is far below the attainable yield of 2.2t/ha or the potential yield of some of the newly-released improved Coffee Wilt Disease (CWD) resistant (CWD-r) Robusta coffee varieties such as KR10 (Kyalo *et al*., 2024). Various factors, including socioeconomic, inadequate plant management, biotic (such as pests, diseases, nematodes, and weeds) and abiotic (such as environmental conditions) factors have been suggested as the causes of this low production (Liebig *et al.,* 2016).

Climate change has emerged as a major abiotic constraint, affecting coffee production in Uganda (Mulinde *et al.,* 2019) and globally (Haile, 2018). Rising temperatures and unpredictable rainfall threaten soil water balance and increase the risk of water stress in rainfed coffee systems. It is projected that global coffee yields could decline by 25% by the end of the 21st century (Tavares *et al.,* 2018). In Uganda, mean temperatures are expected to rise by about 2°C in the coming decades (Nsubuga & Rautenbach, 2018), with yield losses estimated at 116 kg/ha for every 1°C increase (Jawo *et al.,* 2023). In addition, availability of water for production has been predicted to reduce under climate change scenarios (Orkodjo *et al.,* 2022). Soil moisture is introduced into the soil through precipitation and removed through evapotranspiration. As the temperatures increase, evapotranspiration is anticipated to increase due to climate change, which will lead to a water deficiency (Ajjur & Al-Ghamdi, 2021). Water stress limits photosynthesis of the coffee plant, affects expansion and ripening of the coffee berries, affects nutrient uptake and may cause the coffee plants to wilt. All these could lead to reduced coffee yields and quality (Bracken *et al.,* 2023).

Several studies have examined the projected impacts of climate change on rainfall and temperature (King'uyu *et al.,* 2000). However, limited attention has been given to how climate change directly influences soil moisture, a key determinant of coffee growth (Nsubuga & Rautenbach, 2018). In Uganda, most climate impact studies have concentrated on Arabica coffee (Markandya *et al.,* 2015), with the earliest projections for Robusta coffee dating back to Simonett (1989). His maps suggested that a 2% rise in temperature would substantially reduce suitable Robusta-growing areas in the country. These findings are now outdated. Later modeling indicated that Robusta could shift to higher elevations in southwestern Uganda, bordering Rwanda and, to some extent, Tanzania (Haggar & Schepp, 2012), though these results were speculative due to a lack of empirical validation. More recently, Mulinde *et al.* (2022) assessed Robusta suitability in central Uganda. Nonetheless, these studies primarily relied on rainfall and temperature, overlooking actual soil moisture conditions within the root zone. Since predictive tools are critical for anticipating and adapting to climate change impacts, this study aimed to address this gap by evaluating how climate change affects soil moisture in Uganda.

In addition to climate projections, adaptation through use of soil moisture conservation practices remains vital. Agroforestry, for example, has been highlighted as a promising climate adaptation option (Sarmiento-Soler *et al.,* 2019). Most research on water use in coffee–shade systems in Uganda has concentrated on Arabica coffee (Buyinza *et al.,* 2019; Sarmiento-Soler *et al.,* 2019), providing little information on Robusta systems. This study therefore assessed the water use efficiency of Robusta coffee across different phenological stages under Albizia coriaria shade and in open-sun conditions. In addition, although extension services recommend soil moisture conservation practices (SMCPs) such as mulching and cover cropping (UCDA, 2019a Handbook), their adoption by farmers remains limited, largely due to the absence of quantitative evidence demonstrating their effectiveness. Yet, these practices directly influence soil water budgets and water use efficiency (Dagnachew *et al.,* 2020), which are critical for sustaining yields under climate change. Moreover, with agriculture in Uganda being rainfed, production systems are highly vulnerable to unpredictable shifts in rainfall patterns, which have negatively impacted critical crop growth stages through water stress. This study also therefore also determined the effect of soil moisture conservation practices on soil water relations in Robusta coffee, identified the best-bet soil moisture conservation practices for mitigating soil moisture content deficiencies and hence enhancing Robusta coffee yields in Uganda.

1.3 Conceptual frame work

Temperatures above 30 °C negatively affect coffee production (DaMatta & Ramalho, 2006; Yamane et al., 2022). Similarly, coffee requires well-distributed rainfall between 1,200 and 1,800 mm over nine months, with both the amount and distribution being crucial for growth and productivity (UCDA, 2019a Handbook). In Uganda, climate change, manifested through rising temperatures and erratic rainfall has been identified as a key driver of reduced coffee yields. However, its adverse effects can be moderated through soil moisture conservation practices (SMCPs) such as mulching, cover cropping, and agroforestry. Climate change and SMCPs both directly influence the soil water balance, which regulates soil moisture content and water use. Soil moisture availability subsequently affects coffee physiological processes and phenology, including flowering, fruit set, and berry development, which in turn determine yield and quality.

In this framework, climate change variables and soil moisture conservation practices represent the independent variables. Soil moisture content, coffee phenology and yield form the dependent variables while soil type and coffee clones act as extraneous variables (Figure 1)

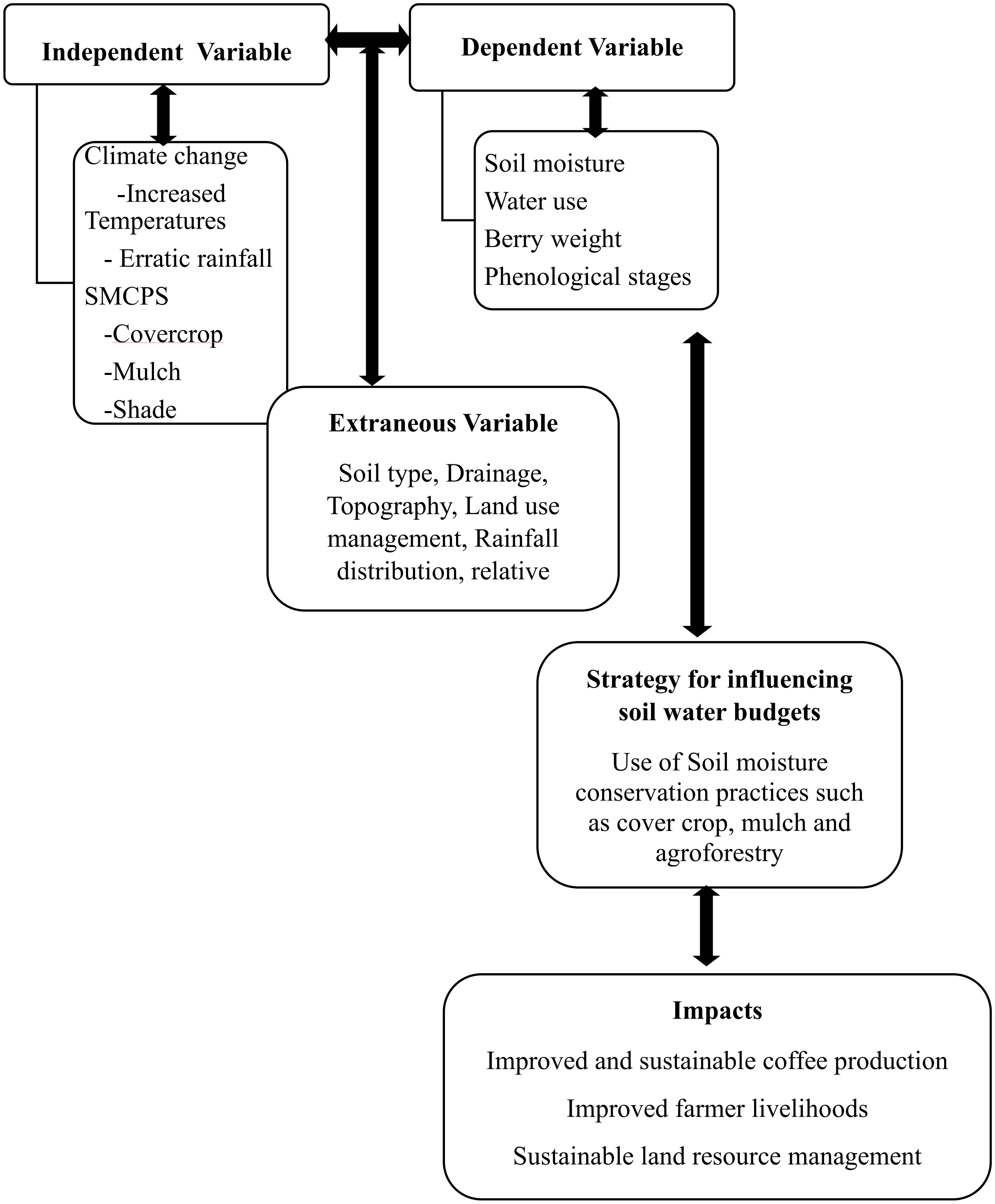


Figure 1: Conceptual frame work of the effect of climate change and soil moisture conservation practices on soil moisture content

1.4 Objectives of this study

1.4.1 General Objective

To assess the effects of selected soil moisture conservation practices on water budgeting in Robusta coffee systems in Uganda, with the aim of identifying best-bet adaptation strategies to mitigate soil moisture stress

1.4.2 Specific objectives

The specific objectives of this study were:

1) To determine the current status of soil moisture content and model its projected changes under future climate scenarios in Uganda.
2) To estimate the water use efficiency (WUE) of Robusta coffee at various phenological stages under coffee *Albizia coriaria* and Open sun Robusta coffee systems
3) To determine the effect of selected soil moisture conservation practices on soil-water relations in Robusta coffee agro-systems.

1.5 Research Hypothesis

1) Climate change will lead to an increase in soil moisture content in Uganda
2) Coffee *Albizia coriaria* systems have better water use efficiency compared to open sun coffee systems
3) Coffee *Albizia coriaria* systems influences soil water relations more as compared to other soil moisture conservation practices.

1.6 Scope of the study

The prediction of climate change effects on soil moisture content was conducted across Uganda. Historical suitability was analyzed for the period 1990-2022, while future suitability was projected for 2025-2050. Data for the second objective were collected at the National Coffee Research Institute (NaCORI) in Mukono district, central Uganda, from June 2022 to January 2024. For the third objective, data collection occurred at two sites: NaCORI and Kaweri Coffee Plantation Limited (KCPL) in Mubende district, with study periods spanning February 2022 to April 2023 at NaCORI and June 2023 to June 2024 at KCPL. The NaCORI experiment took place in a coffee field with a breeding population segregating for Coffee Wilt Disease, while the KCPL experiment was conducted on six mature commercial lines of Robusta coffee. For the second objective, two systems were compared: Robusta intercropped with *Albizia coriaria* and open sun coffee. For the third objective, three soil moisture conservation practices were tested alongside open sun coffee: coffee with a cover crop (*Desmodium intortum*), coffee with mulch (*Miscanthidium violaceum*), and coffee intercropped with *Albizia coriaria*."

1.7 Significance of the study

Numerous studies have demonstrated the high sensitivity of Arabica coffee to climate change and highlighted its projected impacts on coffee suitability, yields, pest and disease pressures, as well as farmers' livelihoods (Bilen *et al.,* 2023). However, only few research studies has been conducted on Robusta coffee. This study specifically generated suitability maps of coffee growing in relation to soil moisture content under changing climate conditions. Secondly, best-bet soil moisture conservation practices for optimum soil moisture stress management for maximum productivity of coffee were identified. The generated information will advise research, policy, farmers and other stakeholders on the best-bet adaptation strategies against soil moisture stress in coffee systems. These outputs will lead to increased yields, thus, incomes of the farmers. This will thus lead to improved livelihoods.

1.8 Definition of terms

Climate change: refers to a long-term alteration in climatic conditions, typically spanning decades or more, which can be identified often through statistical analysis by shifts in the average values and/or variability of climate characteristics (IPCC, 2007).

Adaptation: Refers to adjustments in natural or human systems made in response to actual or expected climatic stimuli and their impacts, aimed at reducing negative effects or taking advantage of potential benefits (MWE, 2015).

Water Use Efficiency: Refers to the amount of dry matter produced by a plant per unit of water consumed (Kramer and Boyer, 1995).

Soil moisture conservation practices: refers to methods used to reduce soil water loss through evaporation and transpiration (https://www.agrifarming.in/soil-moisture-conservation-methods-for-beginners).

Water budget: is an accounting of all the water that flows into and out of the system (Healy *et al.,* 2007)

1.9 Outline of the thesis

Chapter one discusses the background of the study. It also presents the statement of the problem, conceptual framework, objectives of the study, research questions, scope of the study, significance of the study and definition of the key words. Then it shows the outline of the thesis.

Chapter Two reviews literature on topics relative to the research such as effects of climate change on coffee production, effects of climate change of water relations, coffee phenology, water use under agroforestry systems and the different soil moisture conservation practices.

Chapter Three discusses the effect of climate change on soil moisture content in Uganda. It also presents soil moisture suitability maps across the whole country (Paper 2).

Chapter Four examines water use by coffee, taking particularly a phenological viewpoint, examining the underlying relationships between different coffee phenological stages, water use and water use efficiency.

Chapter Five discusses the effect of coffee selected soil water conservation practices on soil water relations in Robusta coffee systems and also shows the potential of soil moisture conservation practices in improving soil properties and plant nutrition in Robusta coffee (Paper 1).

Chapter Six provides general conclusions, recommendations and suggestions for further research

CHAPTER TWO: LITERATURE REVIEW

2.0 Introduction

Coffee is a globally popular beverage and one of the most traded commodities, supporting the livelihoods of nearly 125 million people (Voora *et al.,* 2019). For many low-income countries, it serves as a critical source of foreign exchange, enabling access to global markets for goods and services. Brazil and Vietnam are the world's top producers, together accounting for nearly half of global output (ICO, 2019). In 2023, global coffee production was valued at approximately USD 23 billion, with international trade exceeding USD 26 billion, and the overall coffee industry contributing more than USD 200 billion annually (ITC, 2024).

In Africa, coffee remains a cornerstone of national economies, particularly in Ethiopia, Burundi, and Uganda, where it contributed 33.8%, 22.6%, and 15.4% of total merchandise exports in 2023, respectively. In the same year, coffee earnings covered more than 80% of Uganda's food import bill and over half of those of Burundi and Ethiopia. Within East Africa, Ethiopia is the largest producer, followed by Uganda, with Tanzania and Kenya also playing key roles. Beyond producing countries, the sector contributes significantly to employment, value addition, and tax revenues in importing nations, underscoring its global economic importance. Globally, coffee is the most commonly consumed source of caffeine and is linked to numerous health benefits, including lower risks of stroke in women, colorectal cancer, type 2 diabetes, hypertension, cardiovascular complications, obesity, and depression. It is also known to enhance alertness and mood, while offering protective effects against certain neurological and metabolic disorders.

Nevertheless, when consumed in excess, coffee may have negative health impacts, such as reduced appetite and unfavorable changes in lipid profiles, which can vary with preparation methods (Wachamo, 2017)

In Uganda, the economy is mostly based on agriculture and this sector employs 70% of the labor force and generates 54% of export revenue (Fowler & Rauschendorfer, 2019). For several decades, coffee has been one of Uganda's most important cash crops, for example, in the Financial Year 2023/24, the crop contributed a record high US$ 1.14 billion from export volumes totaling 6.13 million bags (UCDA, 2024). Over 1.8 million households are employed in the coffee-related business at the production level, while over 12 million individuals employed in activities related to coffee production of which 11.9 million are farmers (Kaufman, 2023). Coffee is very essential to smallholder farmers because it is the primary source of income that gives them a cash boom once or twice a year (Van Asten *et al.,* 2011). In Uganda, two most widely grown varieties of coffee are Arabica (*C. arabica*) and Robusta (*C. canephora*), which account for 20% and 80% of production, respectively (Masiga & Ruhweza, 2007; UCDA, 2019a Handbook). Arabica coffee is farmed in highland regions at elevations between 1,200m and 2,500m above sea level, including the Okoro highlands in the West Nile, Mount Elgon in the East, Mount Rwenzori in the West, and Mount Muhabura in the South Western Region (Mugagga *et al.,* 2017; UCDA, 2019b Handbook). On the other hand, Robusta coffee is grown in low-altitude regions of Uganda that are between 900 and 1,500 meters above sea level, including Central, Eastern, Mid North, West Nile, Western, and South Western Uganda, (Kiyingi & Gwali *et al.,* 2012; UCDA, 2019a Handbook).

Despite the significance of Robusta coffee in Uganda, the yields are 0.6 t ha^{-1} and four times below the achievable yields of 2.2 t ha^{-1} (Kobusinge *et al.,* 2023). This low productivity has been linked to a number of factors including: socioeconomic factors, inadequate management, deteriorating soil fertility, pests and diseases (Liebig *et al.,* 2016) and recently, climate change (Jassogne *et al.,* 2013; Läderach *et al.,* 2017; Kagezi *et al.,* 2018). Climate in Uganda is changing, with temperatures rising and the rains becoming less predictable (Obubu *et al.,* 2021). This therefore implies that the regions ideal for coffee production will significantly decline in important coffee-producing nations including Brazil, Honduras, Uganda, and Vietnam, while coffee demand will continue to climb globally (Panhuysen & Pierrot, 2014; Bilen *et al.,* 2023). Decreased production regions will have an impact on the global coffee industry, particularly for premium or gourmet coffees or brands with denomination of origin designation, and will put more pressure on prices (Haggar & Schepp, 2012). Adaptation by cultivating on fresh land risks encroachment on protected land and delicate ecosystems (Ahmed *et al.* 2021). Transitioning to types more resilient to climate extremes and their concomitant effects, such as increased pest and disease prevalence, is a commonly suggested adaptation strategy (Pham *et al.* 2019). Nonetheless, the adoption of new varieties is hindered by cultural and economic barriers, since coffee is a perennial crop that requires substantial long-term investment (Abigaba *et al.,* 2024). Farmers' incomes, food production, and the well-being of agricultural families are all at jeopardy because of the climate change, which is compounding difficulties they already face (Wangui, 2012). Nevertheless, some smallholder farmers are already adapting their systems to climate change locally through planting of shade trees (Jassogne *et al.,* 2013). Generally, Robusta coffee is cultivated beneath newly planted and kept native trees, which diversifies the system's output (Isabirye *et al.,* 2008). The development and promotion of adaptation techniques for climate change, such as tree planting, mulching, and the use of cover crops in coffee, are crucial. However, these soil moisture conservation practices could offer competition to the coffee plant for soil moisture.

2.1 Climate Change predications for Uganda

Climate change continues to be a worldwide concern and it is linked to severe phenomena such as floods and droughts, impeding development, especially in emerging and developing economies (UNDP, 2018). Existing studies, including that by New *et al.* (2006) and Domroes and El-Tantawi (2005), have predominantly focused on temperatures and precipitation, revealing a global trend marked by increasing temperatures and diminishing rainfall. This trend closely aligns with observations in Uganda (Mubiru *et al.,* 2018). Projections from global climate models (GCMs) anticipate temperature rises of 1 to 1.3 ^{o}C by 2060s and 1.4 to 4.9 ^{o}C by 2090s, consistent with reports for eastern Africa by the IPCC (Niang *et al.,* 2014) and a review by Adhikari *et al.* (2016). Rainfall variability is expected to intensify between wet and dry seasons, resulting in an overall decrease in rainfall for most of Uganda (-5 to -30 mm per month) (Collins *et al*., 2013; Markandya *et* *al*., 2015). According to Nsubuga and Rautenbach (2018), the December-January-February (DJF) season is predicted to become significantly wetter, while the rest of the year will experience drier conditions due to a prolonged wet season from September-October-November (SON) towards DJF. These changes, coupled with considerable temperature increases, especially during the March-April-May (MAM) and June-July-August (JJA) seasons, necessitate various adaptation strategies.

On a seasonal scale, a projected increase in seasonal rainfall for the DJF season (up to 100% from present) indicates an extended wet season from SON towards DJF. Lake Victoria might experience a substantial decrease in rainfall (-20% from present), coupled with a 1°C temperature increase, impacting the lake water level (Kisakye & Bruggen, 2018). Notably, water resources serve as a proxy for climate change (Nsubuga *et al.,* 2015). Community perceptions of precipitation variability in eastern Uganda, as revealed by Bomuhangi *et al.* (2016), underscore the realization among farmers that rains arrive late, with short, intensive, and erratic seasons. The frequency and duration of droughts are on the rise, particularly in the western, northern, and north-eastern regions, with an average annual damage of US$237m in the past decade (MWE, 2015).

Simulated future runoff for East Africa is contingent on precipitation changes, projecting an overall increase despite uncertainties in spatial and temporal distribution (Adhikari *et al.,* 2016). Anticipated floods in some regions raise cost-related concerns that necessitate quantification (Markandya *et al.,* 2015). River discharge is expected to undergo alterations, becoming more variable both temporally and spatially. Despite increased rainfall, lake water levels may decrease due to higher evapotranspiration (Mubialiwo *et al.,* 2020)**.** Projections for evapotranspiration indicate an increase for eastern Africa e.g. up to 0.6 mm/day (Onyutha *et al.,* 2021). However, in Uganda, the implementation of adaptation strategies has been notably limited (Alinda *et al.,* 2020). Smallholder farmers in southwestern Uganda are especially vulnerable, with more than 70% likely to be negatively impacted by climate change because of shrinking farm sizes and limited livelihood options (Call *et al.,* 2019). These transformative changes possess the potential to disrupt or reverse the country's development trajectory (Hepworth & Goulden, 2008).

2.2 Effects of climate change on coffee production and productivity

In Uganda, Robusta coffee is grown in low altitudes ranging from 900 m to 1,500 m above sea level (UCDA, 2019a Handbook). It necessitates warmer temperatures within the range of 22-28 ºC (Camargo, 2010; UCDA, 2019a Handbook), showcasing higher tolerance to elevated temperatures. However, temperatures exceeding 30 ºC can induce various physiological issues (DaMatta & Ramalho, 2006; Yamane *et al.,* 2022). A well-distributed rainfall of 1,200 mm to 1,800 over 9 months is essential for Robusta, with both the total amount and distribution pattern playing crucial roles (UCDA, 2019a Handbook). The average annual water requirement for coffee is reported as 951 mm (Wintgens, 2004). Robusta coffee is more tolerant of high air humidity, approaching saturation, while Arabica prefers drier conditions (DaMatta *et al.,* 2007); however, very high vapor pressure deficits can negatively affect coffee growth (Carr, 2001). The optimal relative humidity is around 60% for Arabica and about 75% for Robusta (Adhikari *et al.,* 2020). Variations in humidity can either favor or suppress the development of insect pests and pathogens, as well as their natural enemies, depending on the local environment and the specific species involved (Gagliardi *et al.,* 2020). Adverse effects on coffee yields can also result from strong winds, leading to reduced leaf area and internode length (Caramori *et al.,* 1986). Strong winds also increase evaporations increasing the need for irrigation (UCDA, 2019a Handbook). Supra-optimal temperatures and drought stress emerge as significant constraints to both current and future coffee production (Bunn *et al.,* 2015). Deviations from optimal environmental ranges induce stress in plants, disrupting their physiological functions (DaMatta & Ramalho, 2006). These stress factors interfere with crop phenology, subsequently influencing productivity and quality (Haggar & Schepp, 2012).

2.2.1 Coffee phenology

Coffee plants are affected by climatic variables in a variety of ways during their growth phases (Camargo, 2010). Water stress limits photosynthesis because the stomata close (Haggar & Schepp, 2012), which also decreases other physiological functions in the plant like metabolism (Camargo, 2010). Water availability influences the ability to sustain maximum photosynthetic rates, achieve high fruit set, and attain optimal fruit size. Consequently, coffee phenology is sensitive not only to the amount of rainfall but also to its seasonal timing (Magrach & Ghazoul, 2015). Moreover, sudden temperature changes result in leaf burn whereas, temperatures below 10 ºC cause chlorosis (leaf yellowing), which destroys the chloroplasts and leads to diminishing of photosynthesis (Wintgens, 2004). This will affect flowering and thus, fruit-filling phases of coffee (DaMatta *et al.,* 2008). Coffee will flower at various periods throughout the year because of erratic precipitation, forcing growers to repeatedly pick small amounts (Wangui, 2012). This leads to increased harvesting costs (Wangui, 2012). Prolonged rains are likely to cause reduced flowering, affect fruit set, lower photosynthesis due to continued coldness (Fischersworring *et al.,* 2015). Robusta coffee takes 9 to 11 months to ripen from flowering under optimal climatic conditions (Wintgens, 2004; UCDA, 2019a Handbook). Understanding how climate change affects coffee phenology will help us better understand how these effects ultimately affect the yield and quality of coffee berries (Wangui, 2012). According to Bertrand *et al.* (2016), not all agroecological systems will experience the same consequences of climate change. Factors like shading, sunshine intensity, and altitude may either lessen or increase the effects of climate change on the coffee, depending on the system (Jassogne *et al.,* 2013).

2.2.2 Coffee pests and diseases

It has been noted that a rise in temperature can expand the spectrum of some pests and diseases in an area (Bongase, 2017). For instance, the white coffee stem borer, which has historically been more prevalent on Arabica coffee at low elevations, is anticipated to become a significant pest at higher altitudes under the scenarios of climate change (Kagezi *et al.,* 2018). Similarly, the coffee berry borer (CBB), which had been largely inactive at altitudes of 1500-1600 m.a.s.l. in several countries (Kyamanywa *et al.,* 2012), has now been spotted at elevations of more than 1800 m.a.s.l (Agegnehu *et al.,* 2015). On the other hand, due to increased temperatures and rainfall, the coffee leaf rust (CLR) disease has reportedly become more common recently at higher altitudes (Bebber *et al.,* 2016). This will impact coffee quality and yield while also raising production costs (Filho *et al*., 2012) and thus, will deter Uganda's productions targets of increasing coffee exports from the current 6.13 to 20 million 60 kg bags by 2030 unrealistic (UCDA, 2024).

2.2.3 Coffee quality and yields

Coffee yields and quality are all determined by the climate (Killeen & Harper, 2016). A direct detrimental effect on the quantity and quality of coffee will result from accelerated ripening caused by higher temperatures (Ahmed *et al.,* 2021). Unlike separate wet and dry seasons that result in the desired harvest of huge quantities during a short harvest season (Jassogne *et al*., 2013), prolonged droughts are predicted to cause coffee plants to become weak and wilt, mortality in young plants will increase as well as flower abortion (Fischersworring *et al.,* 2015). Research studies show a loss of 116 $kgha^{-1}$ of green coffee for every increase in temperature of one degree (Craparo *et al.,* 2012). In addition, coffee branch internode length and leaf area are reduced by wind stress (Caramori *et al.,* 1986). Also, warm winds enhance water loss through evapotranspiration and therefore increase coffee water requirements (Amin, 2017).

Experts predict a sharp decline in global coffee supply by mid-century, with production in South America projected to fall more steeply than in Africa, 7.6% compared to 0.3%, respectively (ICO, 2023). Extreme weather events have already demonstrated this vulnerability. For instance, severe frost across Brazil's coffee belt in July 2021 triggered a 13% spike in global coffee prices (Figueiredo & Teixeira, 2021). Similarly, prolonged droughts accompanied by abnormally high temperatures have devastated Brazil's coffee-growing regions, leading to shriveled berries and empty husks. These reductions in production directly affect world market prices. In Viet Nam, extended dry spells caused a 20% decline in production during the 2023/24 season, with exports dropping by 10% for a second consecutive year. Indonesia also experienced a 16.5% fall in coffee output in 2023/24 due to excessive rains that damaged coffee cherries, resulting in a 23% decline in exports. Uganda has not been spared from climate-related challenges. In the last thirty years, coffee-producing regions have experienced hotter and drier conditions, characterized by increasing annual temperatures, higher potential evapotranspiration, and more irregular rainfall patterns (Bunn et al., 2019). In 2017, drought in the Greater Luwero area led to a 60% drop in coffee yields (McDonnel, 2017). More recently, recurrent droughts in Isingiro District have been reported to significantly reduce coffee production (Matyanga, 2023).

Research in Nicaragua suggests that rising altitude may negatively affect the quality of coffee beans, with projections indicating a decline in the potential to produce acidic and flavorful beans by 2050 (Läderach *et al.,* 2017). Joët *et al.* (2009) showed that altitude positively influences glucose content, and that sorbitol levels after wet processing are directly related to the glucose concentration in fresh seeds. Coffee quality is also strongly affected by climatic factors such as rainfall and temperature. Inadequate rainfall during the growing season places stress on the plants, leading to branch dieback and leaf loss, which limits resources for fruiting and produces smaller, defective beans (DaMatta *et al.,* 2018). Higher temperatures speed up berry development and ripening (Craparo *et al.,* 2015), which can restrict bean filling and result in smaller bean sizes (DaMatta *et al.,* 2018). In addition, unfavorable climatic conditions can reduce sugars and acids while increasing bitterness, thereby diminishing cup quality. Excess rainfall also poses significant risks. Intense downpours can cause flowers and fruits to fall, and if they occur during harvest, elevated moisture levels promote mold development, disease incidence, and over-fermentation, ultimately leading to higher bean defect rates (Taniwaki *et al.,* 2014). Ultimately, such shifts in the physiology of the coffee plant and the chemical composition of the beans translate into significant alterations in beverage quality (Bilen *et al.,* 2023).

2.2.4 Coffee growing area

Regional assessments of climate change impacts on Arabica coffee indicate that suitable growing areas are expected to shrink and shift toward higher elevations (Schroth *et al.,* 2000, Haggar & Schepp, 2012). It is therefore anticipated that fewer area would be suited for growing Arabica coffee (Jaramillo *et al.,* 2011). In Uganda, it is projected that there will be changes in areas suitable for growing coffee by 2050

(UCDA, 2019a Handbook). Projections also show that Robusta coffee will move to higher elevations (Haggar & Schepp, 2012) forcing Arabica coffee to even higher elevations (Bracken *et al.*, 2023). This shift will likely adversely affect the coffee ecosystem (Bilen *et al.,* 2023). A temperature increase of one degree centigrade is equated to 500 feet of elevation (Baker & Haggar, 2007). Shifts in the suitability of coffee species have been linked to the relocation of production areas (Bilen *et al.,* 2023). Projections suggest that while some regions in South and Central America, Africa, and Asia may become less favorable for Arabica, they could become more suitable for Robusta cultivation (Bunn *et al.,* 2015). Nonetheless, most forecasting studies on Robusta suitability have focused primarily on temperature and rainfall, with limited attention to other critical variables such as soil moisture (Nsubuga & Rautenbach, 2018). In Uganda, suitability research has largely concentrated on Arabica coffee (Markandya *et al.,* 2015), highlighting the urgent need to assess the future suitability of Robusta coffee in the country.

2.2.5 Coffee markets

Climate change is anticipated to have a considerable impact on global coffee trade patterns, affecting prices and volumes, with certain African nations facing greater vulnerability in international trade due to their unfavorable positioning (Panhuysen & Pierrot, 2014). The reduction in global coffee production is expected to lead to an escalation in coffee prices (Aduteye *et al.,* 2023). While this could be advantageous for some market participants, it poses a threat to many individuals, particularly smallholder farmers whose primary source of livelihood revolves around coffee sales (ICO, 2009). The rise in the risk associated with coffee cultivation due to climate change is likely to result in increased financial and planning costs, attributed to the substantial uncertainty in climate scenarios (Bilen *et al.,* 2023).

2.3 Water availability in Uganda

Uganda possesses substantial renewable water resources, estimated at 2,085 m^3 per year, well above the global water scarcity threshold of 1,000 m^3 per year (Rüttinger *et al.,* 2011). Nevertheless, the country's water sector is still underutilized, with only 0.5% of these resources accessed annually, distributed across agriculture (40%), municipal use (43%), and industry (17%) (Rüttinger *et al.,* 2011). Rainfall, contributing significantly to ground and surface water recharge, plays a crucial role in Uganda's water dynamics (MWE, 2013; Osaliya, 2021). The country receives an average precipitation of 1180 mm/yr, equivalent to 280 km^3/yr nationwide. Only about 10% of Uganda mainly around Lake Victoria and the highland areas receives rainfall that exceeds potential evaporation. In contrast, the remaining 90% of the country experiences an annual water deficit, which in some regions, such as the Rift Valley and the northeast, exceeds 600 mm per year (MWE, 2013). Agriculture, especially in the bimodal rainfall zone, faces heightened challenges with unpredictable rainfall patterns, risking harvest losses. In 2012, only 0.1217% of the total cultivated area was equipped for irrigation, totaling 11,140 hectares (FAO, 2015).

Historical data, including findings by Mubiru *et al.* (2012), show that the onset of rainfall has shifted by approximately one month in certain regions of Uganda, which could impact cropping schedules. In addition, potential evaporation can reach up to 75% of the annual rainfall (Katusiime & Schutt, 2020). The country's rapid population growth, urbanization, and industrialization further strain these resources (UNESCO, 2006). The escalating water scarcity globally intensifies pressure on irrigation systems, necessitating the release of water for other uses and improved performance (Malano *et al.,* 2004). Projections therefore indicate a looming increase in water demand in Uganda due to population growth and economic and agricultural development, posing a threat to food security and the economy (MWE, 2013). The projected rise in water consumption is estimated to range from 2.8% to 14.1% by 2030, with groundwater withdrawals expected to increase by up to 15% over the same period (Katusiime & Schutt, 2020). Experimental results reveal a 600% decrease in yield when crops receive only enough water to survive but lack additional water for flowering and seeding (Mwaura & Katunze, 2014). Moreover, farmers lack incentives to enhance water use efficiency and conservation in agriculture (Hsiao *et al.,* 2007). The nation's weak capacity to adapt to these changes is compounded by the high climate sensitivity of key sectors like coffee and fishing, which contribute significantly to export revenues but are vulnerable to climate change (Rüttinger *et al.,* 2011). The availability of water in Uganda is further compromised by a lack of reliability, as much of the rainfall is evaporated and doesn't contribute to surface water or deep groundwater. Uganda’s internal surface water resources are estimated at 39 km^3 per year, while groundwater availability is around 29 km^3 per year (Taylor *et al.,* 2015). About 61% of the country’s water comes from groundwater, primarily accessed through springs and boreholes near

Lake Victoria and in southwestern Uganda (Nsubuga *et al.,* 2014). Capillary movement of groundwater plays a crucial role in supplying moisture to the crop root zones and the upper soil layers. Over 95% of the cultivated crops in Uganda rely on rain-fed agriculture, heightening the risk to crop production and national food security (Sridharan *et al.,* 2019). Uganda has a massive resource potential for irrigation of 3,000,000 ha. In 2015, only 0.1% of total agricultural production came from irrigated land (Dale *et al.,* 2015). Historical data also highlights a shift in rainfall onset, potentially altering cropping patterns (Mubiru *et al.,* 2012), making Ugandan crop production more vulnerable to climatic change than its Eastern African neighbors (Sridharan *et al.,* 2019). Moisture stress has emerged as a significant challenge in Uganda's agricultural industry, with supplemental irrigation identified as a potential solution, albeit with high capital investment requirements (Kimera *et al.,* 2008). The Government of Uganda is implementing various initiatives to develop and strengthen the irrigation sector. However, there is limited modeling studies have been conducted to manage water resources effectively in Uganda's future (Mehdi *et al.,* 2021). Application of the AquaCrop model showed that soil mulching is an effective adaptation measure for minimizing evapotranspiration losses, thereby enhancing maize yields (Kikoyo & Norbert, 2016). Therefore, the promotion of soil moisture conservation practices remains one of the most viable solutions in enhancing production and productivity agriculture (Abiye, 2022).

2.4 Influence of climate change on soil moisture

In the interplay between ground and atmosphere, soil moisture is crucial (Berg *et al.,* 2014). In Uganda, rainfall is becoming erratic; some places see torrential downpours that cause property damage, while other areas experience little to no rain (Jassogne *et al.,* 2013). The rains fall early and stop while it is still projected to continue in other seasons (Mubiru *et al.,* 2012). Feng (2015) stated that variations in the climate could make alterations in soil moisture more unclear. The primary source of soil moisture is precipitation, whereas temperature has an impact on soil moisture via regulating evapotranspiration (Wang *et al.,* 2018). Studies to determine whether rainfall patterns have changed have been sparked by this pattern of volatility (Ayugi *et al.,* 2016; Nsubuga & Rautenbach, 2018). Understanding how climate change affects soil moisture is crucial for managing water resources and adapting to climate change (Wang *et al.,* 2019). This is because climate, especially precipitation and temperature, are the main determinants of soil moisture. In addition to altering regional precipitation amounts and temporal variability, climate change also has an impact on flow of soil water and moisture (Holsten *et al.,* 2009). Variability in land use and climate always causes variation in soil moisture (Wang *et al.,* 2019).

According to King'uyu *et al.* (2000), numerous studies have projected how climate change will affect temperature and rainfall, but there is currently little knowledge on how it will affect other variables like soil moisture (Nsubuga & Rautenbach, 2018). It is therefore crucial to understand soil moisture variability and to quantify the distinct impacts of climate change and land use change on soil moisture for effective water resource management and land-use planning (Wang *et al.,* 2019). Farmers will be able to manage water more effectively if water flows around the farm are well understood, measured, and analyzed because not all the rain received is converted into soil moisture (Kumar & Bhople, 2017).

2.5 Coffee phenology

Coffee, as an evergreen plant, consistently produces leaves year-round (Marias *et al.,* 2017), influenced by temperature and water availability. However, during drought periods, the leaves are shed (Carr, 2001). In addition, Robusta coffee has a shallow root system and absorbs most of its water within the 0.4 m depth (Fries *et al.,* 2020). The productive stage of coffee plants is attained after approximately three years, allowing for one or two harvests annually depending on environmental conditions (Wintgens, 2004). Robusta coffee exhibits irregular flowering, with cherries taking 9–11 months to ripen depending on rainfall patterns (UCDA, 2019a Handbook; Rahman *et al.,* 2024). Flower initiation occurs during the cool, dry season, and once flowers reach an average length of 4±6 mm, they enter a dormant phase. Water stress lasting 1±4 months breaks flower bud dormancy, leading to blossoming after the initial showers preceding the primary rains (Amend, 2002). Meiosis occurs over the next three to four days following the stimulus, accompanied by a significant increase in gibberellic acid content, believed to counter the inhibiting effect of abscisic acid (Browning, 1975; Damatta *et al.,* 2008). Subsequently, over the next 6±12 days, the water content of the flower buds rapidly increases, growing three to four times in length, progressing to blossoming and anthesis-a rate influenced by temperature (Carr, 2001).

During the first six to eight weeks after fertilization, Robusta coffee ovaries undergo cell division, producing small fruits, known as pinheads, which show minimal growth (Sureshkumar *et al.,* 2013). These dormant pinhead fruits begin to expand following the onset of rains, coinciding with the emergence of new leaves stimulated by the same “blossom” showers (Damatta *et al.,* 2008). Continuous, heavy rainfall throughout the year, without a distinct dry season, can result in scattered harvesting and reduced yields (Wintgens, 2004). From approximately 6-16 weeks after flowering, the fruits grow rapidly in volume and weight, mainly due to pericarp development (Ramaiah & Vasudeva, 1969; Sureshkumar *et al.,* 2013). During this stage, the two fruit locules reach full size, and the endocarps lining the locules lignify. The maximum seed (bean) volume is established during this swelling phase and is strongly influenced by the tree’s water status, with wet conditions producing larger beans than hot, dry periods (Cannell, 1974; Carr, 2001). Between 12 and 18 weeks after flowering, the beans develop and fill the locules, increasing rapidly in dry weight with little change in fruit size. Full fruit ripening occurs around 30-35 weeks after flowering, marked by chlorophyll loss, ethylene production, and red coloration (Agwanda, 1997). Cannell (1974) and Damatta *et al.* (2008) also noted that approximately 50% of year-to-year variation in large bean production could be attributed to the number of rainy days.

2.6 Concepts of Water Use Efficiency (WUE)

The depletion of water resources has driven advances in Water Use Efficiency (WUE), which encompass both improved irrigation methods and better management practices (Kumar *et al.,* 2024). WUE reflects the balance between gains such as biomass production or CO_2 assimilation and costs, including water used or transpired, and can be assessed across multiple spatial scales (Medrano *et al.,* 2010) (Figure 2), from leaves (net photosynthesis per unit leaf transpiration) to entire plants or crops. WUE can also be examined over varying time scales, from minutes (instantaneous gas exchange) to months (biomass accumulation or yield) (Mir, 2012). Leaf-level WUE is often the starting point for evaluating climate change impacts on crop water use. Two primary measures exist: instantaneous WUE (WUEinst), calculated as net photosynthetic rate (A_n) divided by transpiration rate (E), and intrinsic WUE, calculated as A_n divided by stomatal conductance (g_s) (Hatfield & Dold, 2019). WUEinst is sensitive to environmental conditions, as transpiration depends on stomatal opening and atmospheric vapor pressure deficit (Driesen *et al.,* 2020). It reflects short-term changes (minutes to days) in carbon gain relative to water loss (Rizza *et al.,* 2012). Intrinsic WUE, by contrast, removes the influence of changing evaporative demand, focusing solely on stomatal behavior, and is commonly used in varietal screening (Rizza *et al.,* 2012). WUEinst can also be integrated over a day to estimate daily leaf WUE by summing A_n and E for the day (Medrano *et al.,* 2003; Mir, 2012). Scaling up from leaf to whole-plant WUE (WUEWP) is possible by incorporating leaf area (Medrano *et al.,* 2012; Mir, 2012). Studying both WUEinst and intrinsic WUE under different environmental conditions, such as water-limited versus non-limited situations, helps disentangle genetic and environmental influences on crop water use. Although many crop varieties have been screened for WUE using leaf gas exchange or $\delta^{13}C$ measurements, defining crop-level WUE based solely on leaf data is challenging (Blum, 2009, 2011). Differences in light interception across a canopy cause substantial variation in leaf photosynthetic rates (Medrano *et al.,* 2012), meaning higher leaf WUE does not necessarily equate to higher crop WUE (WUEc).

Whole-plant WUE (WUEWP), also known as transpiration efficiency, represents the ratio of total plant dry matter production to total water consumed (Iland *et al.,* 2011). WUEWP is influenced by water losses during non-photosynthetic periods (e.g., cuticular and nighttime transpiration) (Caird *et al.,* 2007) and by plant respiration, which are not captured by leaf gas exchange measurements, potentially lowering WUEWP without affecting WUEleaf.

For practical agronomy, WUE is often assessed at the yield level (WUEy), as the main goal of crop production is harvestable yield. Yield WUE is the ratio of harvested yield to total water used over the growing season (Mir, 2012), considering either evapotranspiration (ET) or transpiration as the denominator (Blum, 2009). WUEy can be expressed as yield per unit of water applied (irrigation and rainfall) or per unit of evapotranspiration, with units such as kg/m^3 or mm (Jones, 2004;

Bacon, 2004; Iland *et al.,* 2011). Chaves *et al.* (2004) referred to yield per irrigation as irrigation water use efficiency, while Steduto (1996) defined WUEy as the product of above-ground biomass WUE and the harvest index.

At the crop level, WUEc is defined as the yield produced per unit of water used during the growing season (Howell, 2001; Wallace, 2002; Zhang *et al.,* 2019). It accounts for water lost through runoff, percolation, soil evaporation, and transpiration, typically expressed as dry or fresh mass per unit water (Jones, 2004a). WUEc is also referred to as agronomic or production WUE (Iland *et al.,* 2011). In this thesis, chapter five focuses on yield WUE (WUEy), while chapter four uses a modified form, defining WUE as the change in berry volume per unit of water used during specific fruit phenological stages.

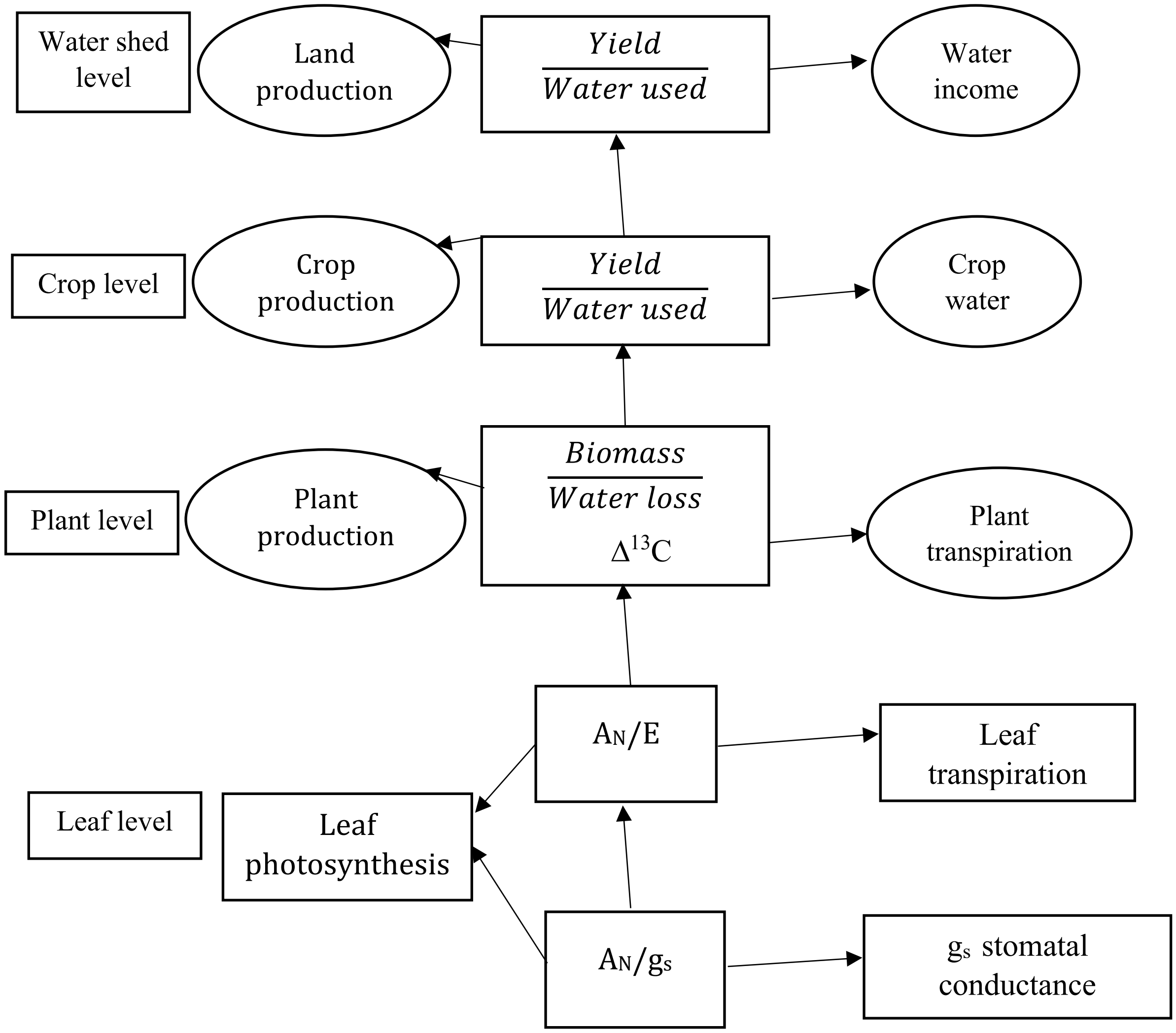


Figure 2: Different measurement levels of water use efficiency (Medrano *et al.,* 2010)

Some researchers argue that the term Water Use Efficiency (WUE) may not accurately reflect true efficiency, as only a small fraction of water absorbed by plants contributes to growth and biomass accumulation, while the remainder is lost to the environment (Heydari, 2014). For this reason, some suggest that the ratio of carbon gained to water lost should be referred to as water productivity rather than WUE (Heydari, 2014). Other studies, however, use WUE and water productivity interchangeably (Boutraa, 2010), while some advocate for a clear distinction between the two terms, emphasizing that they represent different concepts (Heydari, 2014). Despite these criticisms, WUE remains widely used across agriculture and plant physiology (Vadez *et al.,* 2014), forest ecology (Lévesque *et al.,* 2014), and studies addressing global climate change (Cernusak *et al.,* 2019).

2.7 Water use in coffee agroforestry systems

Coffee agroforestry systems are viewed as a climate-smart farming practice (Vaast *et al.,* 2016). This is because shade trees cushion extreme temperature variations at the plot level, reduce soil evaporation rates and incoming radiation, all of which help to maintain the microclimate (Assefa & Gobena, 2019). Shade trees shield coffee from the rays of the sun, keep temperatures moderate, and may even lessen the effect of drought on the crop (Partelli *et al.,* 2014). In addition to their ecological functions, shade trees give farmers access to timber, fuel, and poles, boosting their revenue diversification and enhancing food security (Mbow *et al.,* 2014), all the while absorbing carbon dioxide through biomass production. Despite the above benefits, shade trees compete with the crop understory (Abdulai *et al.,* 2018). This might restrict adoption of agroforestry as a method of coping with climate change (Abdulai *et al.,* 2018). By raising system level transpiration and increasing rainfall interception, shade trees alter soil water content, potentially limiting the amount of water available for the understory crop (Cannavo *et al.,* 2011). Rising temperature and water scarcity brought on by climate change are becoming severe challenge for coffee production (DaMatta & Ramalho, 2006). Therefore, this calls for species-specific knowledge on water use to guide in climate smart recommendations.

Previous studies have concentrated on the water use of Arabica coffee compared to Robusta coffee (Tausend *et al.,* 2000; Carr, 2001; Jaramillo-Botero *et al.,* 2010). This could be due to the sensitivity of Arabica coffee to high temperatures (Tavares *et al.,* 2018). In Uganda, research done by Sarmiento-soler *et al.* (2019) where they compared water use of Arabica coffee under open sun, Arabica coffee-banana systems and Arabica coffee-*Cordia africana* system, showed that the mean sap flux density did not differ significantly across treatments. However, daily water use differed significantly between bananas and *C. africana*. *C. africana* used more water than bananas. In this same study, Arabica coffee-banana systems transpired more per ground area followed by Arabica coffee *C. africana* systems than Arabica coffee open sun. Arabica coffee used similar water across the above cultivation systems. This study also showed no system influence on water consumption of Arabica coffee and hence no water competition between coffee and associated shade tree species. Another study conducted by Buyinza *et al.* (2019) comparing water use of two shade trees reported that *C. africana* uses more water as compared to *Albizia coriaria*. They also noted that *A. coriaria* has a reverse flow during the dry season meaning it releases water back to the soil during the dry season which is a good characteristic for an adaptation shade tree species. However, no document studies are available on Robusta coffee in Uganda despite the fact that it contributes 80% of the export volume (Masiga & Ruhweza, 2007; UCDA, 2019a Handbook). Hence it is important to have a solid scientific understanding of how the existing Robusta coffee systems work in terms of water use. There is therefore a need to generate information on amount of water used by coffee so as to inform on the water requirements in order to give it the amount it needs for a productive harvest.

2.8 Soil water balances

The water balance approach represents the most straightforward technique for investigating plant water consumption (Saraswati *et al.,* 2022). It involves applying the principle of mass conservation, often known as the continuity equation, which asserts that, for any arbitrary volume and over any given timeframe, the discrepancy between total input and output will be counterbalanced by alterations in water storage within the volume (Healy *et al.,* 2007). Water budget models, rooted in this principle, offer versatility and applicability across various spatial scales (e.g., entire basin, individual field) and temporal scales (e.g., hourly, daily, multi-year). The moisture balance component encompasses input sources such as precipitation, irrigation, and capillary rise, while moisture storage outputs comprise runoff, deep percolation, evaporation, and transpiration-factors influenced by land use type, soil characteristics, and climatic conditions (Saraswati *et al.,* 2022). Examining each Water Budget Component in isolation proves valuable for discerning patterns and distinctions between systems, providing insights into the foundational assumptions of the water budget (Joyce *et al.,* 2002; Safeeq *et al.,* 2021).

2.8.1 Precipitation

Precipitation is the main component of weather, supplying water to the soil surface (Sun et al., 2018). Water can also enter the soil through snowmelt, infiltrating vertically into the ground (Waring & Running, 2007). Once in the soil, it may be retained in the root zone for crop use or contribute to groundwater reserves (Bronstert et al., 2023). While some of this water is available to plants, part of it is lost as surface runoff, which can lead to soil erosion and nutrient loss into streams and water bodies (Winter et al., 1998). Despite its critical role in the water balance, precipitation is one of the most difficult variables to measure due to its high temporal and spatial variability (Zhang & Srinivasan, 2010). Moreover, climate change is expected to alter soil moisture patterns through increasingly erratic rainfall (Holsten et al., 2009), highlighting the need to assess how future climate variability will impact soil moisture.

2.8.2 Evapotranspiration

Transpiration refers to the process by which water vapor is released from plant tissues into the atmosphere, occurring alongside evaporation, which involves water loss from bare soil surfaces or water bodies when heat energy is available (Allen *et al.,* 1998). Evapotranspiration combines these two processes, as they typically occur simultaneously and are difficult to separate (Jovanovic & Israel, 2012). It plays a crucial role in maintaining soil water balance and is closely associated with ecosystem productivity, species distribution, and overall ecosystem health (Christensen *et al.,* 2008). On average, approximately 65% of annual precipitation is lost through evapotranspiration, highlighting its significance within the water cycle (Bennie & Hensley, 2001; Jovanovic *et al.,* 2015). Beyond water loss, evapotranspiration also represents a significant energy transfer, consuming approximately 25% of the total energy reaching the earth's surface, or about 1.26×10^{24} joules (Babkin, 2009). Thus, it plays a crucial role in regulating water and energy exchanges between the earth's surface and the atmosphere (Xiong *et al.,* 2023).

Accurately estimating evapotranspiration is particularly important in arid and semi-arid regions to enable precise irrigation scheduling and sustainable water use (Yamaç, 2021). For evapotranspiration to occur, three conditions must be met: a continuous supply of heat to satisfy the latent heat of vaporization, a vapor pressure gradient between the evaporating surface and the atmosphere, and a continuous water supply at the site of evaporation (Hillel, 2004). Evapotranspiration rates are influenced by the complex interaction of topography, soil properties, vegetation, and climatic factors, which together determine water availability, energy balance, and vegetation type in a given area (Western *et al.,* 2004; Zhao & Ji, 2016). Despite its importance in the soil water balance, evapotranspiration remains one of the most challenging parameters to quantify within the soil-plant-atmosphere continuum due to the complexity of the process (Jovanovic & Israel, 2012; Banimahd *et al.,* 2015). Accurately understanding and quantifying evapotranspiration is essential for designing effective and sustainable water management strategies, particularly in regions with limited water availability (Watanabe *et al.,* 2004).

Furthermore, this quantification is essential for validating hydrological models (Miralles *et al.,* 2011) to ensure precise simulation of water fluxes and crop productivity. In agricultural systems, estimating actual crop evapotranspiration (ETa) through in-situ measurements can be challenging and costly, making water budget and soil monitoring techniques valuable alternatives (Wan *et al.,* 2015). Studies have demonstrated that field-scale water budget estimates of ETa provide reasonable quantification of actual ETa when compared to established methods using crop coefficients (Gochis *et al.,* 2000; Zeleke *et al.,* 2012).

2.8.3 Runoff

Surface runoff occurs when rainfall or water application exceeds the soil's infiltration capacity (Schwab *et al.,* 1993; Le Bissonnais *et al.,* 2005). The extent and behavior of runoff are influenced by several factors. Important land surface factors influencing runoff include topography, land use and cover, and surface sealing (Rejani *et al.,* 2015). Additionally, soil characteristics such as initial moisture content, soil type, lithology, and hydraulic properties also play a significant role (Rejani *et al.,* 2015). Climatic factors, especially rainfall characteristics intensity, duration, and frequency play a critical role as well (Rejani *et al.,* 2015). Additionally, catchment slope influences runoff generation, with steeper slopes generally producing more runoff; mountainous areas with steep slopes also tend to receive higher precipitation (Dodds, 1997). Despite this, many hydrologic models do not treat soil or field slope as a highly sensitive parameter for runoff prediction, though it becomes important when evaluating nutrient loss risks at the field scale (Haggard *et al.,* 2005).

2.8.4 Drainage

Deep drainage, or percolation, refers to the downward movement of water through the soil below the rooting zone (Healy & Cook, 2002; Healy, 2010). A portion of this water moves along subsurface pathways into streams, a process known as interflow or subsurface stormflow (Kumar, 2003). The occurrence of deep drainage varies both spatially and temporally. Surface drainage occurs when water inputs, such as precipitation or irrigation, exceed the combined sinks of soil storage, evapotranspiration, and runoff, while deep drainage happens when water in the root zone surpasses its holding capacity (Gates *et al.,* 2014). Drainage is affected by multiple factors, including the intensity and duration of rainfall or irrigation, soil properties like hydraulic conductivity and capillary pressure, and land surface characteristics such as topography, land use, land cover, and management practices (Brom *et al.,* 2021). Quantifying deep drainage or groundwater recharge is challenging because only a small fraction of water contributes to recharge relative to other components of the water balance. Studies suggest that less than 5% of precipitation becomes groundwater recharge, a component that is often overlooked in water balance assessments (Gieske, 1992; Dang *et al.,* 2017).

2.8.5 Soil water content.

Estimating soil water content has become increasingly important under changing climate conditions (Seneviratne *et al.,* 2010). Soil water content, which refers to the quantity of water per unit of soil volume or mass, is a fundamental element of the soil water balance (Porporato *et al.,* 2002). Numerous studies (Hébrard *et al.,* 2006;

Mahanama *et al.,* 2008) highlight its critical role in influencing various elements of the water balance. As a result, considerable research has focused on understanding the spatial and temporal variability of soil water content across landscapes (Mahanama *et al*., 2008). Soil water distribution within an area is shaped by the interaction of local topography, climate, soil properties, land use, and vegetation cover (Zhao *et al.,* 2011). Williams *et al.* (2009) noted that these factors have the greatest impact during wet periods, with rainfall and land use strongly influencing topsoil water content (Mello *et al.,* 2011), although their effects decrease as soils dry. While it is generally assumed that gentle slopes retain more water than steep slopes, this is not always the case, as differences in soil texture, hydraulic conductivity, and water retention can lead to variations in soil water content across slope classes (Western *et al.,* 2004).

2.8.6 Infiltration

Water infiltration is the movement of water from the soil surface into the ground, playing a vital role in the water cycle by replenishing groundwater and supplying moisture to plant roots (USDA, NRCS, 2014). It controls essential processes including leaching, runoff, and the availability of water to crops (Franzluebbers, 2002). The infiltration rate is influenced by factors including soil texture, moisture content, structure, rainfall intensity, and management practices. As soil moisture rises, infiltration rates generally decline. Soil moisture itself is shaped by evaporation, plant water uptake, surface residues, vegetation cover, irrigation, and drainage. Storm depth and intensity are considered major factors controlling infiltration (Yu *et al.,* 2018), and some studies suggest that topography also contributes to variations in infiltration patterns (Wang & Chen, 2021). When rainfall intensity surpasses the soil's infiltration capacity, the excess water leads to increased runoff. A decrease in rainfall, deceases infiltration and soil water storage and thus plants water supply (Várallyay, 2010)

2.8.7 Lateral flow

Lateral water flow in soil refers to the horizontal movement of water within the soil profile, primarily driven by gravity and capillary forces. This process is important for redistributing soil moisture, affecting vegetation distribution, contaminant transport, and slope stability (Gao *et al.,* 2024). Climate change is expected to alter temperature, the water cycle, atmospheric conditions, and the Earth's energy balance (Collins *et al.,* 2013). These changes can modify precipitation patterns and evaporative demand, making the understanding of soil moisture critical for evaluating plant responses to shifting climate conditions (VanDerWal *et al.,* 2013). In response, communities have implemented adaptation measures such as soil and water conservation practices to improve water use efficiency in rainfed agricultural systems under increasing droughts and changing rainfall patterns (Aturihaihi *et al.,* 2022). Consequently, assessing how these conservation practices influence soil water budgets is essential.

2.9 Soil water relations

Water scarcity is now widely acknowledged as a global problem. (Vörösmarty *et al.,* 2000). The hydrological cycle is significantly impacted by climatic change, which lowers the amount of water resources available in many regions (Groppelli *et al*., 2011). Water is the key ingredient for development processes in both the soil and the plant (Shaxson & Barber, 2003). The main source of water input to the soil is precipitation, although water can also enter the soil through vertical infiltration of rain or snowmelt (Waring & Running, 2007). This water may be retained in the root zone for plant use or move to subsurface water bodies. While a portion becomes available to plants, the remainder can be lost as surface runoff, leading to soil erosion and nutrient loss into streams and other water bodies (Winter *et al.,* 1998). Optimizing fertilizer application rates, pesticide, herbicide, and irrigation water application times requires knowledge of the water state of the soils (Kumar & Bhople, 2017). This information can be used for soil moisture mapping to raise farmers' awareness of the need to save moisture through improved soil management techniques (Akinremi *et al.,* 1997). Also, understanding the soil moisture condition is crucial for planning irrigation schedules or predicting the start of droughts (Woodward *et al.,* 2001). According to the rain water balance for eastern Kenya, 60-70% of the rainfall is lost as runoff, leaving just 20-30% for the production of crops and feed (Kilewe, 1987). This suggests that in order to improve soil moisture levels and storage for crop production as the rains become more unpredictable, soil moisture conservation must be practiced for rain fed cropping systems (Kathuli & Itabari, 2014). Using rainwater effectively for crops and minimizing its loss from the time it reaches the soil's surface are based on the ideas that water loss must be kept to a minimum and crops must utilize it as well as possible (Singh *et al.,* 2015). According to Itabari (1999), the amount of water available for a crop to use is given by the formula Tcrop (mm) = P-R-D-E-s, where T stands for transpiration, P for precipitation, R for runoff, D for drainage, E for evaporation from the soil surface, and s for change in soil water stored within the rooting zone. The equation demonstrates that Tcrop needs to be improved in order for plants to effectively use rainwater. This is only possible if soil management is used to reduce R, D, and E. Soil and water management alternatives are required in order to increase soil's capacity to store water (Saraswati *et al.,* 2022). Assessing soil moisture levels and the water lost via soil evaporation and plant transpiration is crucial for determining the optimal soil water balance to support crop growth (Verstraeten *et al.,* 2008). These measurements are also critical for minimizing soil evaporation, enhancing water availability to plant roots, and guiding decisions on fertilizer application, irrigation scheduling, weather-based management, and overall farm practices.

2.10 Soil moisture conservation practices

Preserving soil moisture serves as a crucial method for maintaining the essential water required for agricultural production and helps reduce the irrigation demands of crops (Lin, 2010). This becomes particularly significant in regions where both rainwater and groundwater resources for irrigation are either scarce or diminishing due to climate change (SUSTAINET EA, 2010). The conservation of soil moisture is considered among the most effective and cost-efficient approaches to augment soil moisture levels (Jamieson *et al.,* 2001). Given the erratic availability of water for coffee production resulting from climate change, farmers are urged to adopt soil conservation practices to enhance soil moisture (Markandya *et al.,* 2015). The following are therefore, some recommended farming practices for soil moisture conservation: -

2.10.1 Agroforestry

Agroforestry is a strategy for managing land use in which trees or shrubs are cultivated next to or amid pastureland or crops (Sanchez, 1995). Shade trees affect the local environment's radiation balance and wind patterns (Monteith *et al.,* 1991; Brenner, 1996). Also, they produce shade, which creates a microclimate that alters the equilibrium of the energy present in the environment and affects the soil moisture use, production, and seasonal patterns of plants in that environment (Baldy & Stigter, 1993). Shade (agroforestry) systems are described by Damatta and Ramalho (2006) as a viable option for sustainability in coffee exploitation. Farmers therefore practice agroforestry to provide shade, timber, firewood, arrest degradation and for maintenance of soil fertility (Verchot, 2007). In addition, shade trees reduce soil evaporation beneath the canopy, lessen radiation and temperature at the soil surface (Partelli *et al.,* 2014). By absorbing water from deep soil layers, they may help improve infiltration and boost rainfall water usage efficiency (Amin, 2017; Sarmiento-Soler *et al*., 2019). Rain-splash erosion reduces because trees reduce the impact of rainfall on the ground. (Beer, 1995). Leguminous trees also fix nitrogen that helps food crops as they recycle nutrients from deep layers of the soil (Beer *et al.,* 1998). However, shade tree may reduce the water that is intended to reach the soil by rainfall interception and utilizing the water that would otherwise be for coffee (Righi *et al.,* 2008). Recently, the National Coffee Research Institute (NaCORI) of the National Agricultural Research Organization (NARO) developed recommendations of site-specific shade trees to be intercropped in coffee in Uganda based on farmer preference, scientific knowledge and not being good alternative hosts of *Xylosandrus compactus* insect pest (Kagezi *et al.,* 2015). Nevertheless, the consequences of these shade trees on the water budgeting was not put into consideration in developing these recommendations, calling for such studies on Robusta coffee in Uganda (Tran *et al*., 2021).

2.10.2 Mulching

Mulch refers to any material placed on the soil surface with the aim of reducing evaporation and managing weed growth (Jamieson *et al.,* 2001). These materials function as barriers, impeding the outward movement of moisture from the soil (Iqbal *et al.,* 2020). Mulches can be categorized as either natural (such as straw, wood chips, peat, and grass) or man-made (including transparent or opaque plastic sheeting) (Jamieson *et al.,* 2001). The application of mulch serves to mitigate soil degradation by preventing runoff and soil loss, reducing weed infestation, and curbing water evaporation (Kumar & Bhople, 2017). Consequently, mulching contributes to an increase in soil moisture retention by approximately 4% to 5.6% (Louise *et al.,* 1999). Additionally, mulch aids in reducing soil temperature by 5.6^{0}C (Louise *et al.,* 1999). Mulches contribute to the enhancement of soil's physical, chemical, and biological properties, introducing nutrients and ultimately fostering crop growth and yield (Telkar *et al.,* 2017). Notably, mulching has been observed to increase coffee yield by 50-60% under rain-fed conditions, leading to larger coffee bean sizes (Abu-Awwad, 1998; Bekeko, 2013). This increase in productivity signifies improved water use efficiency and reduced premature shedding of coffee berries from trees due to insufficient soil moisture (Wangui, 2012). Despite these benefits, the adoption of mulching practices by farmers is hindered by challenges such as the expense and labor intensity associated with obtaining, transporting, and applying mulch to the soil (Jamieson *et al.,* 2001). Moreover, the limited availability of mulching materials presents a challenge, as they are also in demand for livestock feed and energy purposes (Zizinga *et al.,* 2022)

2.10.3 Cover crops

The term "cover crops" refers to plants that cover the soil (Kaspar & Singer, 2011). In past years, cover crops were planted alongside crops to prevent soil erosion on steep slopes and also to control weeds but of recent, they are intercropped with crops to manage nutrients and water relations, in addition to weed management (Mulinge *et al*., 2017). Depending on the climate, biomass production, local soil, cover crops, can increase soil organic matter by 9 to 85%. (Kaspar & Singer, 2011). Leguminous cover crops have the ability to enhance soil structure, nutrient retention capacity and soil compaction (Koudahe *et al.,* 2022). Moreover, in clay loan soils, cover crops have been shown to increase infiltration by 2.8 and 2.2 times as compared to control (Mitchell *et al.,* 2017). In addition, cover crops affect soil temperature and evaporation in the plant root zone as well as soil moisture retention and efficiency of water use (Kahimba *et al.,* 2008). According to a study by Liebig *et al.* (2015), cover crops resulted in a 21% increase in soil water content compared to no treatment. Research studies have shown that even in regions with variable rainfall, long-term use of cover crops improves soil water relations (Basche *et al.,* 2016). However, according to Merrill *et al*. (2007) the varieties of cover crops determines how much water is retained in the soil. Although cover crops have several benefits for improving soil quality and production, they are not commonly used (Singer *et al.,* 2007). This may be partly as a result of cover crops competing with related crops for nutrients and water, harboring pests and diseases, lowering yields, and sometimes climbing related crops. But some research, such as that by Steele *et al.* (2012) and Blanco-Canqui *et al.* (2015), demonstrated that cover crops have little effects on yields. Majority of the published research studies have been conducted on annual crops (Subedi-Chalise, 2017; Krstic *et al.,* 2018), with limited studies on perennials such as coffee. Although, such studies have been conducted on Robusta coffee in other countries (Kiseve, 2012; Biradar *et al.,* 2015; Júnior *et al.,* 2022), similar detailed research is yet to be initiated in Uganda.

Also, there exist other soil water conservation practices including; manuring, rain water harvesting, conservation tillage, crop rotation and construction of contours and ridges, among others (Kumar & Bhople, 2017) which can also be used in coffee agrosystems (Alele *et al.,* 2023). Therefore, there is an urgent need to identify adaptation measures that will increase the climate-resilience of the region's coffee farming systems (Jassogne *et al.,* 2013). Developing climate-smart solutions should be a top concern. Some examples include techniques that help farmers increase crop productivity, adapt to changing climate, and encourage the decrease in emissions of greenhouse gases (FAO, 2018). Considering the extensive information on conservative strategies, there is still an urgent need for site-specific research in various environments and socioeconomic settings.

2.11 Growth habits of *Albizia coriaria*

Albizia coriaria is a deciduous nitrogen-fixing tree in the Fabaceae family that is also known locally as Mugavu in Luganda and Swahili (Katende *et al.,* 1995; Fern, 2014). It grows to a height of 6-36 m free of branches for up to 22 m and up to 100 cm in diameter (Fern, 2014). Young branchlets are hairy whereas, the leaves are bipinnate. It grown at an altitude range of 850-1700m.asl and found on a variety of soil types (Orwa *et al.,* 2009). *A. coriaria* is a slow growing tree with various products and services for example as medicine, fodder for animals and bees and ornamental (Tabuti & Mugula, 2007). In Uganda's indigenous agroforestry systems, *A. coriaria* is one of the most often used multifunctional tree species (Bukomeko *et* *al.,* 2017). *A. coriaria* was purposively selected among all the trees for this particular study because it is one of the major shade trees recommended by NaCORI/NARO in all the Robusta coffee growing regions of Uganda (Kagezi *et al.,* 2015). Secondly, it is the most commonly grown tree species by the farmers (Bukomeko *et al.,* 2017) and then thirdly, because it has a reverse sap flow (Buyinza *et al*., 2019).

2.12 Growth habits of Greenleaf desmodium, *Desmodium intortum*

Greenleaf desmodium, *Desmodium intortum* is a perennial feed legume belonging to the Fabaceae family (Cueva-Chamba *et al.,* 2023). It is a branching, decumbent plant with trailing, ascending, and nodal-rooted long pubescent stems (Heuzé *et al.,* 2017). The stems are 1.5 to 7.5 m long, about 7 mm in diameter, and green or occasionally red. There are several trifoliate leaves on greenleaf desmodium. The ovate leaflets are reddish-brown to purple in color, 2-7 cm long and 1.5-5.5 cm wide. Deep lilac to deep pink flowers are produced on terminal, compact racemes. The narrow, segmented, 5 cm-long pods, which are filled with 8-12 kidney-shaped seeds that firmly cling to hair or clothing, are narrow and segmented. The seeds are around 1.5 mm diameter and 3 mm long. Compared to silverleaf desmodium (*Desmodium uncinatum*), greenleaf desmodium has leaflets that are rounder and more numerous (USDA NRCS, 2012; Cook *et al.,* 2005). In the tropics, it thrives at elevations of 500 to 2500 m. It can be cultivated in regions with annual rainfall range of 900 mm to 3000 mm. It is more vulnerable to drought during the growing season and can withstand flooding and waterlogging better than silverleaf desmodium (Cook *et al.,* 2005). As long as the soil is neither too saline nor too acidic (pH above 4.5-5), greenleaf desmodium can thrive there. It's less tolerant to heavy frosts or fire. It can be planted on coffee plantations because it tolerates the shadow (Ecocrop, 2014). Greenleaf Desmodium is a nitrogen fixing legume that can increase soil nutrient status. It is also employed as a legume feed. It can be used as ground cover because it covers the soil within 4 months and helps to inhibit the growth of weeds (ILRI, 2013). This covercrop can also be used as a ground cover on coffee farms (Maina *et al.,* 2006).

2.13 Research gaps

The production of coffee is becoming severely constrained by climate change, both in Uganda (MWE, 2015; Kagezi *et al.,* 2018; Mulinde *et al.,* 2019) and elsewhere (Msuya, 2013; Haile, 2018; Chengappa & Devika, 2016). Understanding the impact of climate change on soil moisture is essential for effective water resource management and climate adaptation planning (Wang *et al.,* 2019). Climate shifts influence the water requirements of crops in both irrigated and rainfed systems (Saputra *et al.,* 2021). Under changing climate conditions, crop water demand and irrigation needs are expected to rise due to reduced precipitation and higher temperatures (Fader *et al.,* 2016). Elevated temperatures increase evapotranspiration from crops and natural vegetation, accelerating the depletion of soil moisture (Dai *et al.,* 2022). King'uyu *et al.* (2000) highlighted that numerous researches have predicated the effects of climate change on temperature and rainfall, but information on how it will affect other factors, including soil moisture, is still scarce (Nsubuga & Rautenbach, 2018).

Also previous studies have concentrated on the Arabica coffee water use (e.g. Carr, 2001; Jaramillo-Botero *et al.,* 2010; Buyinza *et al.,* 2019) as compared to Robusta coffee (e.g. Tien *et al.,* 2022). However, such research studies are yet to be conducted on Robusta coffee in Uganda despite the fact that it contributes 80% of the export volume (UCDA, 2019a Handbook). Furthermore, despite the various benefits of shade trees (Misgana *et al.,* 2024), they compete with the crop understory (Abdulai *et al.,* 2018). This might restrict adoption of agroforestry by farmers as a climate adaption strategy (Abdulai *et al*., 2018). Therefore, this call for species-specific knowledge on water use to guide in climate smart recommendations (Turyasingura *et al.,* 2024).

Climate change is making water availability for coffee production erratic; therefore farmers need to adapt soil moisture conservation techniques for its improvement (Markandya *et al.,* 2015). The crop water requirements will rise as a result of increased evapotranspiration while the water will be scare (Salman *et al.,* 2020). This will make it impossible for irrigation and thus, add to the challenges farmers are already facing. Thus, there is a critical need for a thorough scientific understanding of both the functioning of the current Robusta coffee agroforestry systems as well as the potential of agroforestry as a method of coping with climate change. NaCORI/NARO has recommended site-specific shade trees to be intercropped in coffee in Uganda based on farmer preference, scientific knowledge and not being good alternative hosts of *Xylosandrus compactus* insect pest (Kagezi *et al.,* 2015). However, there is a need to consider the impacts of these shade trees on the water budgeting so as to develop a complete package for Robusta coffee in Uganda. In addition to agroforestry, research and extension in Uganda and other developing countries are encouraging farmers to apply various practices such as mulches, cover crops to mention a few for conserving soil moisture (Tibanyenda, 1989; UCDA, 2019a Handbook; Nzeyimana *et al.,* 2020) thereby mitigating water stress (Kumar & Bhople, 2017). However, these soil moisture conservation practices have been reported to affect water-soil relations (Dagnachew *et al.,* 2020) and detailed research studies are yet to be conducted on the effects of soil moisture conservation practices in Robusta coffee systems.

CHAPTER THREE: EFFECT OF CLIMATE CHANGE ON SOIL MOISTURE CONTENT IN COFFEE GROWING REGIONS OF UGANDA

3.1 Abstract

In Uganda, coffee, the country's top foreign exchange crop, faces shifts in land suitability due to climate change, impacting over 1.8 million households reliant on it. Previous research has primarily focused on Arabica coffee and considered only rainfall and temperature factors, with limited attention on Robusta coffee and soil moisture content. This study addresses this gap by examining how climate change affects soil moisture in Uganda. Historical soil moisture data (1990-2022) from Terraclimate and future projections (2025-2050) from eight Global Climate Models (GCMs) under two emission scenarios (SSP245 and SSP585) were used. Soil moisture levels were analyzed against coffee crop moisture thresholds to assess suitability under both scenarios. MATLAB live scripts and a set of climatology functions in Climate Data Tool box were employed for soil climatology, while the Mann-Kendall method and Mamdani Fuzzy Inference System (FIS) were used for trend analysis and developing suitability maps respectively. Findings revealed that historically, soil moisture was highest around Lake Victoria (115-143 mm) and lowest in Northern and Southwestern Uganda (<30 mm). SSP245 projections indicate a slight moisture decrease near Lake Victoria but an increase in other regions, with Rwenzori and Kitgum seeing the highest rise (0.08 mm). Under SSP585, soil moisture remains high in Kigezi and Rwenzori with varying yearly patterns. Historically, 71% of Uganda was highly suitable for coffee, but future predictions suggest suitability will rise to 74% under SSP245 and 81% under SSP585, potentially boosting coffee suitability by 10%. This shift calls for tailored soil moisture conservation practices in less suitable areas and further research on how these changes will affect coffee production.

3.2 Introduction

Climate change is projected to significantly impact agriculture worldwide (Gokavi & Kishor, 2020). In Uganda, where Robusta coffee represents 80% of coffee exports and sustains 1.8 million households, the impacts of climate change are expected to be particularly pronounced (Kaufman, 2023). The Intergovernmental Panel on Climate Change (IPCC) projects that global surface temperatures could rise by 0.3-1.7 °C under a moderate scenario or by 2.6-4.8 °C under an extreme scenario this century (Gokavi & Kishor, 2020). Such warming is likely to increase the prevalence of pests, including the coffee berry borer (*Hypothenemus hampei*) and coffee stem borer (*Monochamus leuconotus*), as well as diseases such as coffee leaf rust (*Hemileia vastatrix*), while also affecting coffee tree metabolism, resulting in earlier ripening and reduced yields (Kagezi *et al.,* 2018). Studies in Brazil indicate that coffee yields could decline by roughly 25% by the end of the century (Tavares *et al.,* 2018). In Uganda, temperatures are expected to increase by around 2 °C in the coming decades (Zake, 2015), with each 1 °C rise potentially reducing green coffee yields by 116 kg/ha (Craparo *et al.,* 2012). By 2050, these changes could pose serious challenges to the sustainability of Uganda's coffee industry (IPCC, 2022). As coffee-growing regions shift, suitability for Arabica coffee is likely to decrease in some regions of Africa, Asia, and the Americas, while Robusta coffee may become more viable (Bunn *et al.,* 2015). Currently, 83% of potential coffee-growing areas are suitable for Robusta, compared to just 17% for Arabica (Magrach & Ghazoul, 2015). Timely and effective agronomic interventions are critical for maintaining the long-term sustainability of coffee production (Poitronieri & Rossi, 2016).

Rojas (2012) further predicted that rising temperatures and changing rainfall patterns would negatively affect coffee cultivation, reducing water availability for farming (Bunn *et al.,* 2019). Climate change is also expected to increase evapotranspiration, further limiting water resources (Bunn *et al.,* 2019). Water is a key factor influencing coffee plant phenology, which directly impacts crop success (Silva *et al.,* 2019). In Uganda, most coffee farmers rely on rainwater for production (Sridharan *et al.,* 2019), but the increasing unpredictability of rainfall is likely to lead to greater water stress. Enough water and ideal temperatures are essential environmental conditions for coffee plants. Limitations in temperature and water can significantly impair productivity, output, and growth (Damatta & Ramalho, 2006; Camargo, 2010). When faced with water scarcity, one of the coffee plant's first responses is to close its stomata to reduce water loss through transpiration. However, this reaction also lowers photosynthetic rates by decreasing the amount of CO2 available in the chloroplasts (Damatta & Ramalho, 2006). In order to handle these upcoming difficulties, it is crucial to systematically develop and execute mitigation and adaptation measures (Gokavi & Kishor, 2020).

According to King'uyu *et al.* (2000), numerous studies have forecasted how climate change will impact temperature and rainfall; however, little is known about how it will impact other variables, such as soil moisture (Nsubuga & Rautenbach, 2018). Furthermore, Arabica coffee has been the exclusive focus of the majority of studies on how climate change is affecting Uganda's coffee-growing regions (Markandya *et al.,* 2015). The primary prediction for Robusta coffee comes from Simonett (1989), who produced maps showing a significant reduction in suitable growing areas in Uganda with a 2% increase in temperature. This prediction is outdated, with the most recent study on Robusta suitability conducted in central Uganda by Mulinde *et al.* (2022). These studies on Robusta have mainly considered rainfall and temperature, which don't fully capture the dynamics of water availability in the root zone. A climate change projection suggests that Robusta coffee might shift to higher elevations in southwestern Uganda, near Rwanda and Tanzania, but this remains speculative as no scientific study has confirmed it (Haggar & Schepp, 2012). Therefore, in order to fill in these knowledge gaps, this study set out to forecast how climate change might affect Uganda's soil moisture content.

3.3 Materials and Methods

3.3.1 Study area

The study was conducted across all Robusta and Arabica coffee-growing regions, as well as non-traditional coffee areas in Uganda. All these areas were selected because coffee suitability is projected to shift with climate change, making it important to study both current and emerging zones. The non-traditional areas, in particular, were included in line with government efforts to expand coffee production into new regions beyond the traditional growing areas. Most of Uganda lies between 900 and 1,500 meters above sea level (Bamutaze, 2010). Robusta coffee is typically grown in lower-altitude of Southeastern, Eastern, Central, Western, and regions Uganda, within between 900 and 1,500 masl (Figure 3) (UCDA, 2019a Handbook). In contrast, Arabica coffee is cultivated at higher elevations above 1,400 meters, particularly in the highland regions such as the slopes of Mount Elgon in the east, Mount Rwenzori, Mount Muhavura in the southwest, and in the West Nile region (UCDA, 2019b Handbook). The southern region of Uganda experiences two separate rainy seasons, resulting in a bimodal pattern of increased rainfall from March to May and September to November. There is only one long rainy season in the north, which results in a unimodal rainfall pattern. The far northeastern part of Uganda receives very little rainfall throughout the year. Rainfall across the country ranges from 500 to 2,800 millimeters annually. Uganda's temperatures average around 21 ºC annually, with the lowest monthly temperature being 15 ºC in July and the highest at 30 ºC in February (Irish Aid, 2017).

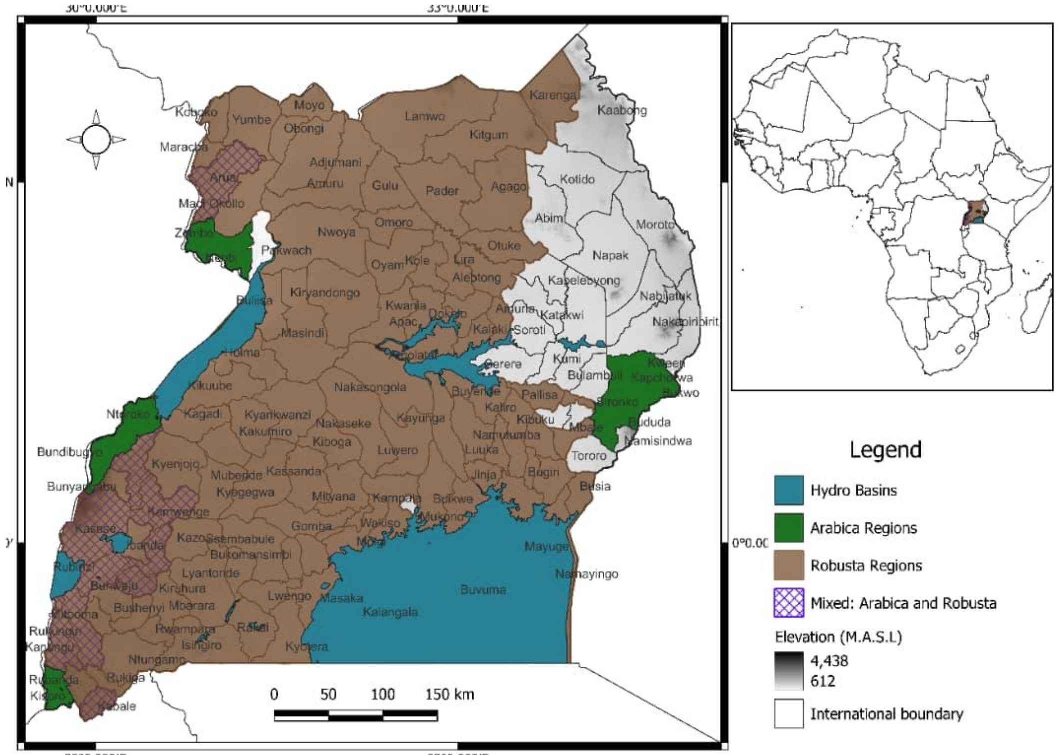


Figure 3: Location of Robusta and Arabica coffee growing areas in Uganda. Map generated using MATLAB

3.3.2 Description of the Soils

Nitisol and Ferralsol soils, which are extremely worn and have a relatively low nutrient content, make up the majority of Uganda's agricultural soils (Henao & Banaante, 1999). Differences in soils influences soil moisture thresholds (field capacity, saturation, permanent wilting point and maximum allowable depletion) differently. According to Grewal *et al.* (1990), knowing these thresholds is crucial for scheduling irrigation, determining how much water plants need, and determining whether the soil is suitable for a given land use. The point of saturation is reached when water fills all of the pores, which are the voids between the solid soil particles

(Datta *et al.,* 2017). Contrarily, field capacity relates to the upper limit of water that is accessible and denotes the soil's moisture content following the gravity-driven drainage of water from macropores (de Oliveira *et al.,* 2015). According to Rai *et al.* (2017), the soil's air and water contents are optimal for crop growth when at field capacity. Permanent Wilting Point (PWP) is the lowest level of soil moisture needed by a plant to avoid wilting (Jin *et al.,* 2018). The soil dries up and the plant is unable to take up more water at the PWP. A plant wilts and loses its ability to regain its turgidity if the moisture content drops below this or any lower level (Jin *et al.,* 2018). The amount of total available water (TAW) that can be drained before plants experience water stress and possible growth loss (and hence yield reduction) is known as management allowable depletion (MAD) (Datta *et al.,* 2017). Water stress increases with depletion until the PWP threshold is achieved and a plant's essential functions are stopped (Datta *et al.,* 2017). A positive correlation was observed between field capacity and permanent wilting point (Figure 4). This means that soils with higher water-holding capacity at field capacity also tend to retain more water at the permanent wilting point. Coffee root zone field capacity is high (110-120 mm) in the area of Mt Elgon, Rwenzori and Kigezi sub-regions. Low field capacity is in the area around Lake Albert, greater Masaka, Ankole sub- regions and area along the Nile in West nile. Saturation is high (150-160 mm) in mt Rwenzori area, and least (<130 mm) in Karamonja sub region, Central, South western, Busoga sub-region and mid north. The maximum allowable depletion was high (12-14 mm) in mid north and westnile sub-region. Least maximum allowable (<8 mm) depletion is in Karamonja, Busoga, greater Masaka, south west sub-region.

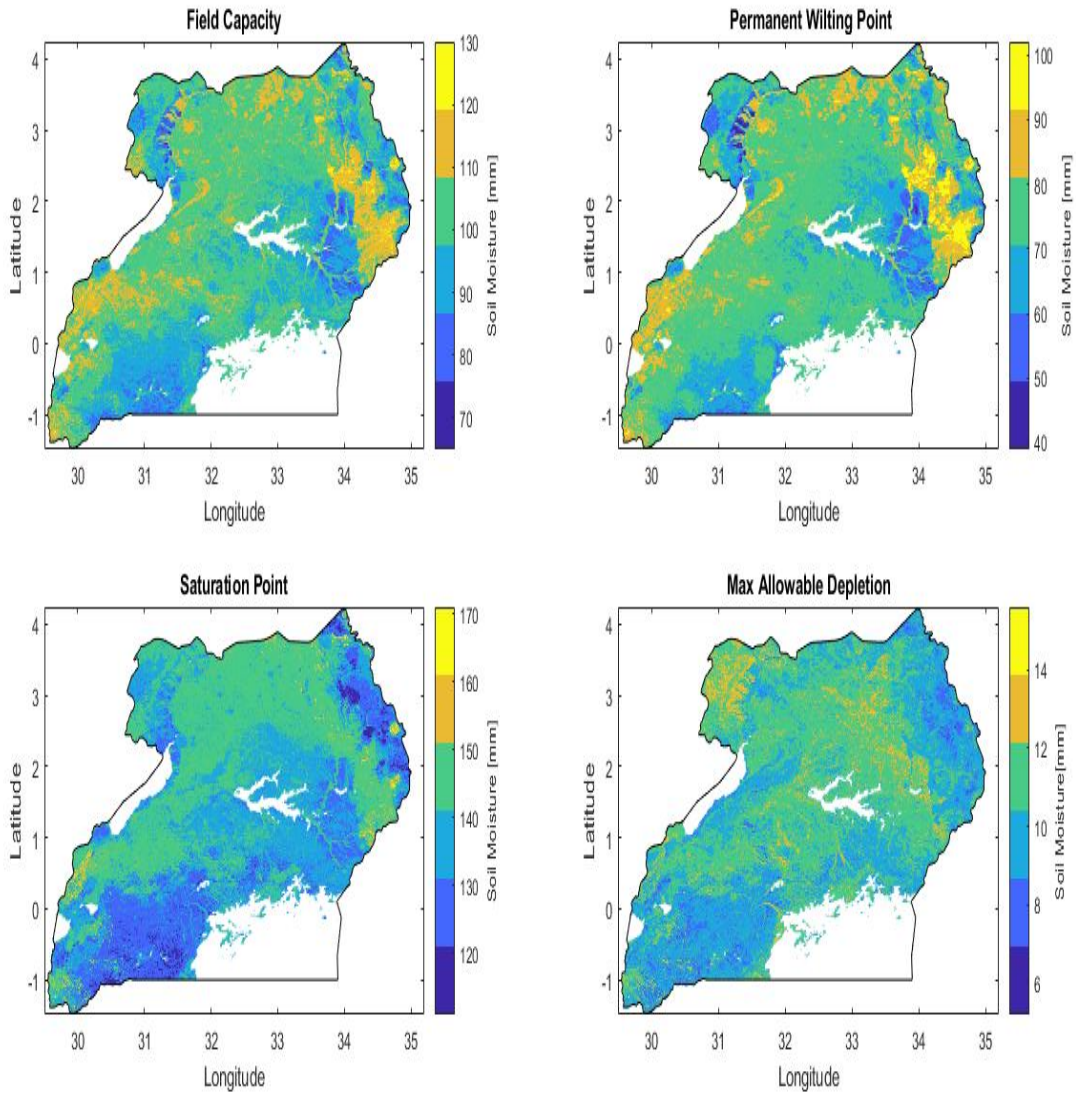


Figure 4: Soil moisture thresholds across Uganda

3.3.3 Data acquisition and analysis

3.3.3.1 Soil moisture Thresholds

Field capacity, permanent wilting point, saturation, and other soil moisture threshold data were taken from https://www.isric.org/explore/soilgrids (Retrieved on October 24, 2023). These datasets were chosen for their high resolution (1km) and reliability. The Management Allowable Depletion (MAD) for coffee was set at 40% of the available water capacity in the root zone, following Allen *et al.* (1998).

3.3.3.2 Historical (1990-2022)

Terraclimate data, accessed from the UofI TERRA CLIMATE's Webpage (northwestknowledge.net) and http://www.climatologylab.org/terraclimate.html on 05.01.2024, were used as the historical soil moisture data for the period 1990-2022. Soil moisture measurements from field sites in Mukono and Mubende were used to adapt these data to match the coffee root zone depth of 0.4 meters. Quality control was performed using the root mean square error (RMSE) at two sampled locations in Uganda, specifically Mukono and Mubende districts. Mubende and Mukono were selected firstly because they are traditional coffee growing areas. Secondly due to difference in amounts of rainfall received. Mukono receives high annual rainfall of about 1400mm to 1600mm while Mubende is located in the cattle corridor with extreme dry spells and an annual rainfall of 560 mm up to 1272 mm. The average annual temperature lies between 15^0C to 28^0C in Mukono while in Mubende its between 17^0C to 29^0C (Krombholz, 2018; Mukono District Local Government, 2015). Soil moisture was measured at Mukono and Mubende districts using a Diviner 2000 device from January 2022 to December 2023 and June 2023 to June 2024 respectively. By contrasting this measured soil moisture content with the Terraclimate data, the RMSE was determined. The findings indicated a 2.80 mm discrepancy in Mukono and a 5 mm discrepancy in Mubende. By dividing the RMSE by the range of recorded soil moisture, the Normalized Root Mean Square Error (NRMSE) was computed (Table 1). The acceptance of the dataset was supported by the Scatter Index, which showed comparatively low errors (Mukono = 3.41% and Mubende = 4.41%). MATLAB was used to perform soil moisture climatology (The MathWorks Inc., 2019). live scripts and climatology functions from the Climate Data Toolbox (CDT) (Greene *et al.,* 2019). Soil moisture climatology means to the long-term average patterns and variability of soil moisture. These tools included methods for analyzing seasonality, climatology, and trends, powered by the Mapping Toolbox, which offers spatial interpolation, overlay, masking, re-projection (to EPSG:4326), and other GIS functions (Figure 5). Four seasons were identified were used: dry (January-February), wet (March-May), dry (June-August), and wet (September-December). Utilizing MATLABR2023b, the Spatio-Mann Kendall method was used for both spatial and temporal analysis. This method is frequently used for trend analysis because it can detect possible trends in meteorological components without requiring the data to follow a particular statistical distribution (Kahya & Kalayci, 2004).

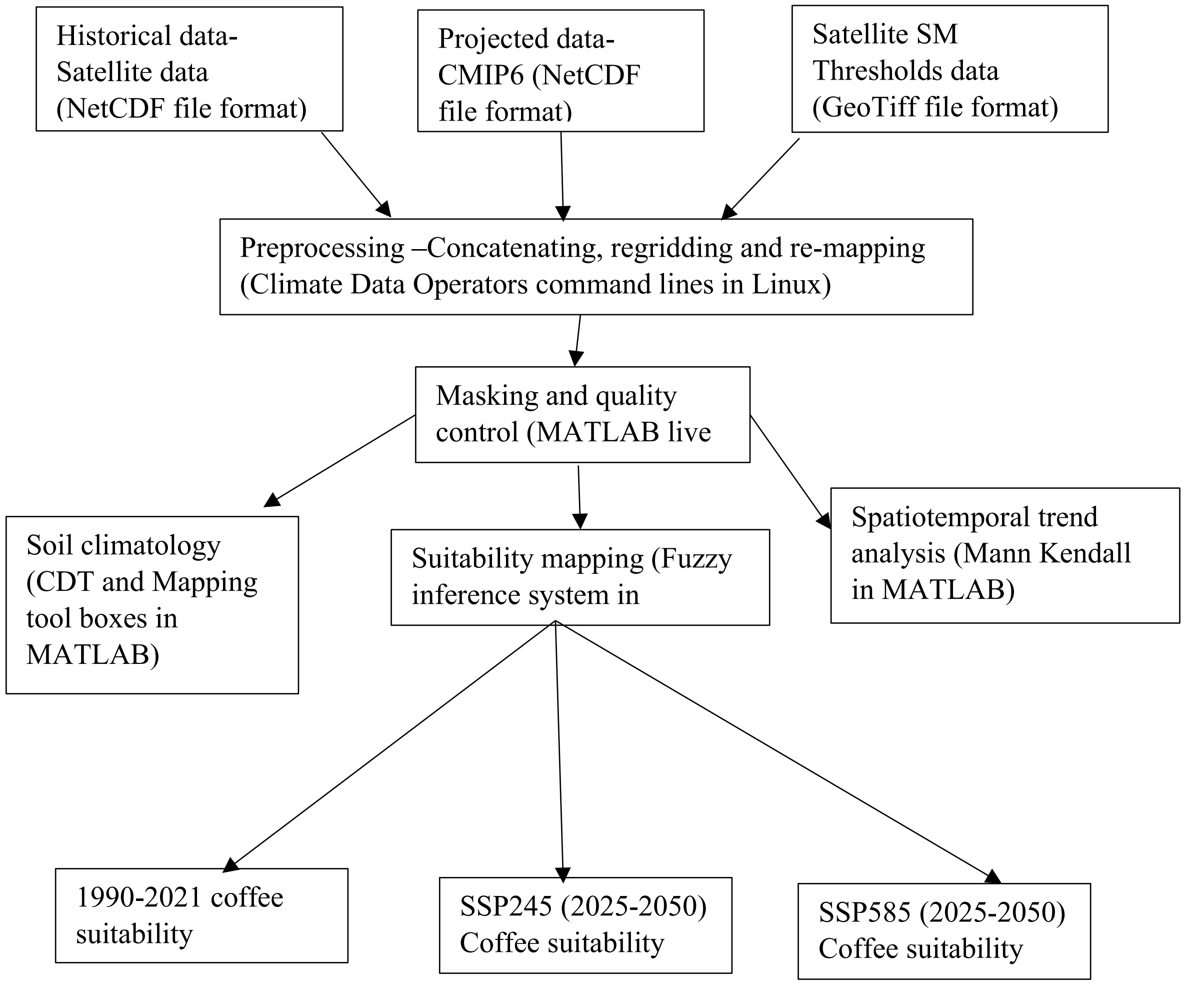


Figure 5: Flow chart of preprocessing and data analysis

Table 1: Soil moisture data validation in Mubende and Mukono district

Performance Metric	Mubende	Mukono
MSE:	24.8992	7.8928
PSNR:	35.1425	39.1585
Rvalue:	0.8303	0.7937
RMSE:	4.989909818	2.8094
NRMSE:	0.0811	0.1303
Mape:	10.6082	7.0237

MSE, Mean Squared Error; PSNR, Peak Signal to Noise Ratio; RMSE, Root Mean Squared Error; NRMSE, Normalized Root Mean Square Error;

3.3.3.3 Future (2025-2050) under two Shared Socio-economic Pathways

In support of Uganda's Vision 2040, soil moisture projections were made for the 2025–2050 timeframe. Eight global climate models (GCMs) under two emission scenarios, SSP245 and SSP585, from the Coupled Model Inter-comparison Project phase 6 (CMIP6), were used to create the future climate projections for this time period (Retrieved on January 16, 2024, from https://esgf-node.llnl.gov/search/cmip6/). These scenarios, which offer alternate future societal evolutions independent of climate change or policy, were created using integrated assessment models (IAMs) based on Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs). Two integrated scenarios were studied: SSP245, which combined SSP2 and RCP4.5, and SSP585, which combined SSP5 and RCP8.5. RCP 4.5 was selected because it is consistent with the particular commitments made by national governments across the globe to cut back on greenhouse gas emissions, which are expected to result in a 2.8 °C rise in global temperature by 2100 (Sanford *et al.,* 2014). In contrast, RCP 8.5 was selected to compare the effects of the two scenarios since it is a "business as usual" scenario and allows for the possibility of significantly higher global temperatures. The reason for excluding RCP 2.6 was its relatively optimistic scenarios, which indicate that there will be little to no global warming beyond the 1.5 °C target in the future. On the other hand, RCP 6.0 does not provide a broad enough range of possible outcomes to fully assess the environment's impact at varying levels of greenhouse gas emissions. SSP 2 “Middle of the road with active mitigation” is considered a modest economic development while SSP 5 “Fossil-fueled development” is considered the strongest economic growth. CMIP6 was chosen for its enhanced understanding of past, present, and future climate changes, supported by a new generation of climate models and scenarios that differ from CMIP5 (Eyring *et al.,* 2016; Oneill *et al.,* 2016). SSP2 represents a middle path where trends continue historically, while SSP5 predicts positive human development trends, including economic growth and robust institutions. RCP4.5 suggests moderate greenhouse gas reductions, leading to some climate changes, whereas RCP8.5 indicates minimal mitigation and more significant global climate shifts (Riahi *et al.,* 2011). As a result, the combination of RCPs and SSPs represents a broad variety of conceivable future scenarios that are made more likely by the integration of socioeconomic development factors and radiative forcing (Doelman *et al.,* 2018), offering a more thorough scenario matrix. Due to the large size of CMIP6 global datasets, climate variables were provided annually and concatenated using Climate Data Operators (CDO)-command lines in Linux to form a comprehensive time series in NetCDF format. Regridding and remapping were performed using conservative first- and second-order methods (Zhang *et al.,* 2011) to account for variations in model grid spacing. The maps were downscaled to 50 km using statistical downscaling method. 50km resolution has been used by various climate change predications such as Sanjay *et al.* (2020). A multi-model ensemble approach (Christensen & Lettenmaier, 2007) was used to combine data from the eight CMIP6 models; BCC-CSM2-MR, CMCC-CM2-SR5, CMCC-ESM2, CNRM-CM6, GDFL-ESM4, CNRM-CM6-1-HR, NorESM2-MM, and CNRM-CM6-1 to reduce uncertainty. According to Anderson *et al.* (2015) and Knutti *et al.* (2017), this method makes the assumption that all models are spread throughout reality, reasonably independent, and similarly credible. The techniques outlined in the preceding section were then applied to these data in order to conduct climatological and trend analysis for the future era.

3.3.3.4 Coffee Suitability Mapping

The appropriateness of coffee for the past and future based on soil moisture was ascertained using a set of rootzone adjusted historical and predicted soil moisture data, as well as soil moisture thresholds over Uganda at uniform grids. The Mamdami Fuzzy inference system (FIS) was used in MATLAB to build suitability maps (Akgun *et al.,* 2012). The use of FIS was justified by the fact that it integrates numerical and categorical data, allows for the explicit expression of system knowledge through fuzzy "if-then" rules, and addresses the subjective uncertainty (fuzziness, vagueness, and imprecision) inherent in the way experts approach their problems (Alvarez Grima, 2000). FIS has been used by several studies on climate change effects as highlighted in the paper by Fallah-Ghalhary *et al.* (2009). The spatial resolution of the suitability map was 4 km. This study examined four different types of suitability: 1) High suitability, which falls between the Total Available Water Holding Capacity (TAW) and field capacity; 2) Average suitability, which falls between the field capacity and Permanent Wilting Point; 3) Low suitability, which falls above saturation; and 4) Unsuitable, which falls below the MAD.

3. 4 Results

3.4.1 Assessing the spatial and temporal patterns of soil moisture climatology

3.4.1.1 Historical Soil Moisture Climatology

The Lake Victoria basin had a higher root zone soil moisture content, according to historical data, particularly in the northern districts of Mpigi, Wakiso and Mityana, Kibaale, Mt Rwenzori subregion, and Mt Elgon sections in the districts that bordered Kenya (Figure 6). The highest soil moisture ranged from 115-143 mm. Low soil moisture was less than 30mm in the areas of Kotido, Moroto, Napak, Nakapiriprit and Amudut in Northen Uganda and Isingiro, Kiruhura and Rakai in south-western region. Furthermore, the areas in Central, Western, Eastern and Northern regions spanning the districts of Mityana, Wakiso (Central), Hoima, Kasese (West), Mbale (East) and Adjumani (North) were associated with the highest interannual variability for the period 1990-2022. For the remaining parts of the country, considerable stability in soil moisture was observed.

However, the data indicated that soil moisture has been significantly increasing each month in Karamojonja areas, Manafa, and Tororo by 1.5 mm, while it has been drastically dropping in the rest of the country and increasing by 0.5 mm in Mukono, Buikwe, Jinja, Bugiri, Busia, Kiruhura, and Lyantonde districts. Root zone soil moisture range was high (224-270 mm) in Kitgum, Kaabong, Mubende, Mityana, Ibanda and Kiruhura (Figure 7). On the other hand, low soil moisture ranges (less than 84 mm) were observed in the districts of Isingiro, Kanungu, Kasese, Mayuge, Iganga, Kaliro, Soroti, parts of Bundibugyo, Kabarole Kyenjojo, Kaberemaido, Soroti, Kaliro, Iganga, Mayuge, Bugiri and Busia

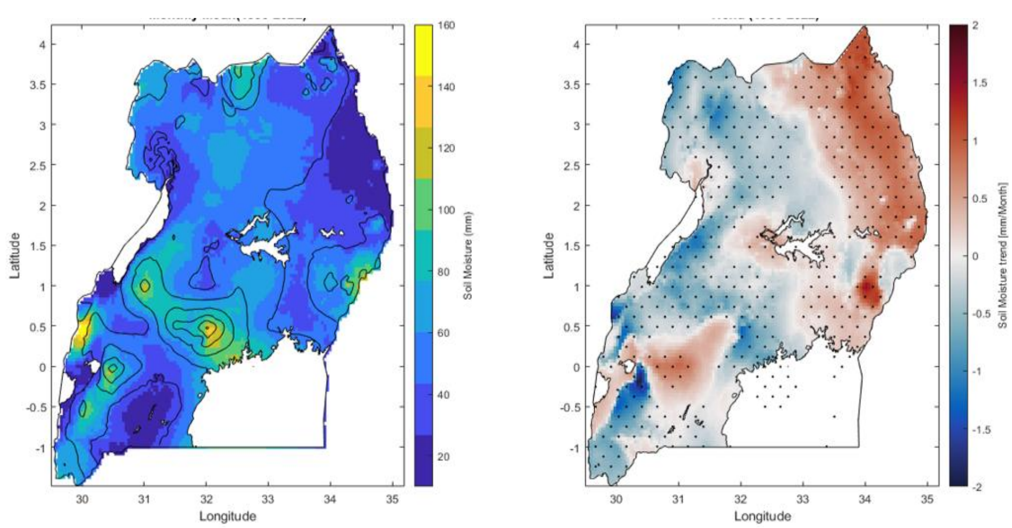


Figure 6: Monthly climatology (left) and long-term trends (right) of root zone soil moisture from 1990-2022

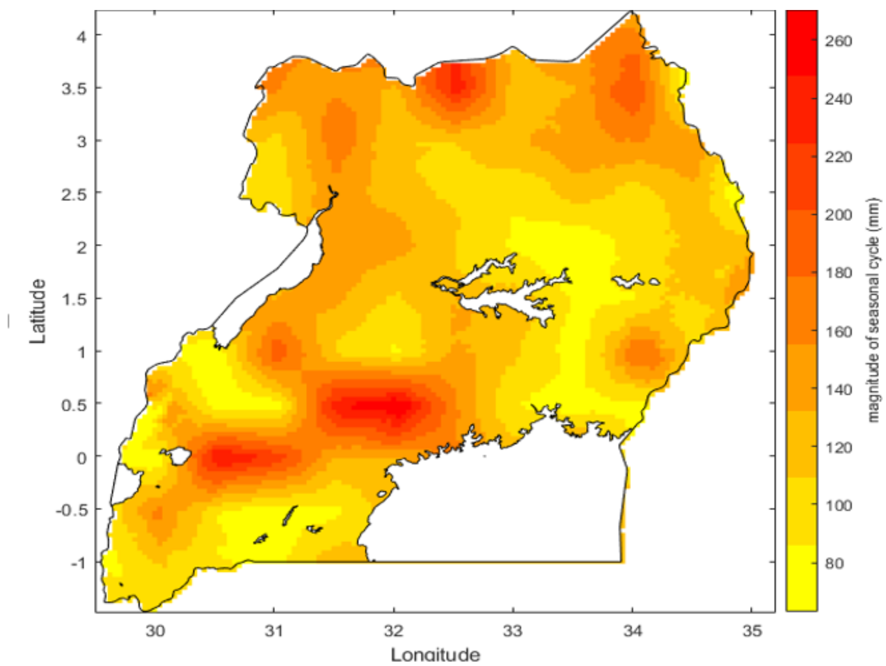


Figure 7: Seasonal range of Root zone soil moisture (1990-2022)

3.4.1.2 Future Soil Moisture Climatology

According to SSP245 projections, Kitgum and Moroto districts will have the lowest soil moisture (72-89 mm), whereas the Kigezi sub-region will have the highest soil moisture (122-135 mm) and the highest fluctuation between years. According to SSP245 estimates, soil moisture content will rise over the rest of the country and fall by 0.02-0.06 mm around Lake Victoria, Kisoro, and Kabale. Kitgum and the Rwenzori sub-region are showing the largest increases, at 0.08 mm (Figure 8). According to SSP 585 projections, the Kigezi subregion will have high soil moisture (119-135 mm), with significant annual fluctuation. The Rwenzori sub-region will likewise have high soil moisture, albeit this will not change from year to year. There will be low soil moisture (74-89 mm) in the districts of Kitgum, Kaabong, and Moroto. According to SSP585, soil moisture would rise nationwide, with Moroto and Amudat experiencing the largest increases at 0.2-0.25 mm per month, while Lake Victoria, Kisoro, and Kabale saw virtually no change. (Figure 9). SSP245 and SSP585 give the same predication for soil moisture. Projection under SSP245 showed that the ranges for soil moisture between 2025-2050 will be more (67-80 mm) around Lake Victoria and south-western regions while, SSP585 showed that only areas of Mpigi, Kabale and Kisoro will have the highest soil moisture ranges of 69-85 mm. On the other hand, SSP245 showed that there will be least soil moisture (38-47 mm) in the stretch starting from Moroto, through Serere up to Tororo while SSP585 showed that low soil moisture (42-51 mm) will start from Kitgum, through Nakasongola up to Tororo (Figure 10).

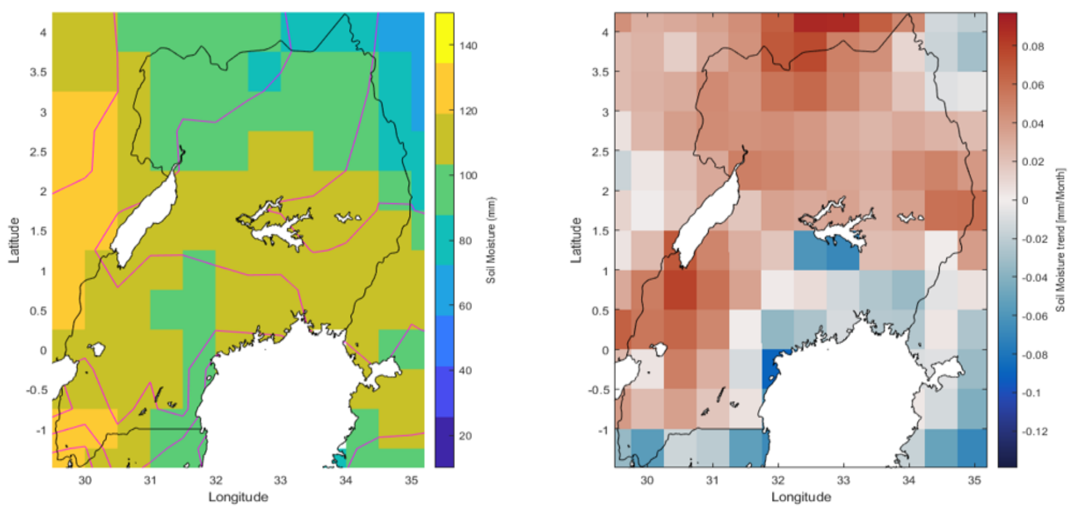


Figure 8: Monthly climatology (left) and long-term trends (right) of root zone soil moisture under SSP245 over Uganda

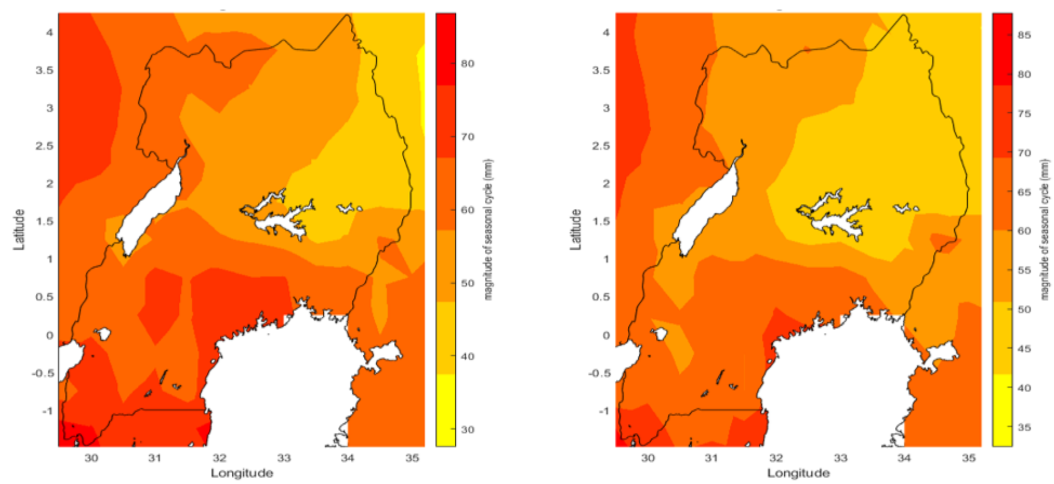


Figure 9: Seasonal range of soil moisture (2025-2050) under SSP245 (left) and SSP585 (right) under SSP245 (Left) and SSP585 (Right)

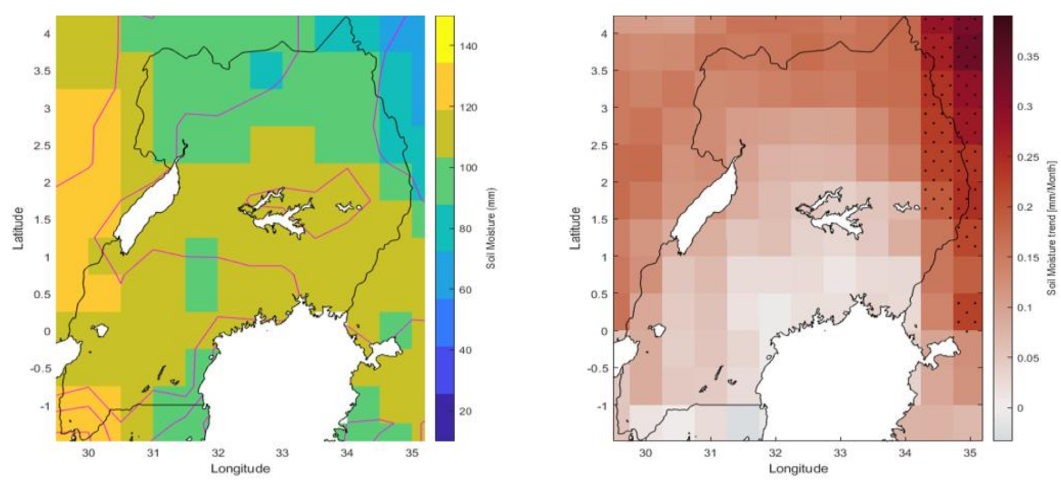


Figure 10: Monthly climatology (left) and long-term trends (right) of root zone soil moisture under SSP585 over Uganda

3.4.2 Seasonal characteristics of soil moisture

3.4.2.1 Historical soil moisture

Historical data from 1990 to 2022 revealed that in the regions of Mount Elgon, Rwenzori subregion, Mpigi, Mityana, Mubende, Kibaale, and Bushenyi, the root zone's soil moisture was high (100–150 mm) during all seasons. Throughout all seasons, the Karamoja subregion, Isingiro, Rakai, Pakwach, Nebbi, and Ntoroko had the lowest soil moisture levels (less than 33 mm). (Figure 11). During the months of January and February, interannual soil moisture was variable in the districts of Wakiso, Mityana and Mubende while, the rest of the country it was stable. Furthermore, there was high variability among years in the months of March, April and May in districts of Wakiso, Mityana, Mubende, Masaka, Rakai, Kaboong, Kitgum, Mt Elgon, Kyenjojo, Kibaale, Ibanda, Bushenyi, Ssemabule, Kiruhura and Ntungamu. In June, July and August and September, October, November and December seasons, there was similar trends in variability in the districts of Wakiso, Mityana, Mubende, Ibanda and Kitgum.

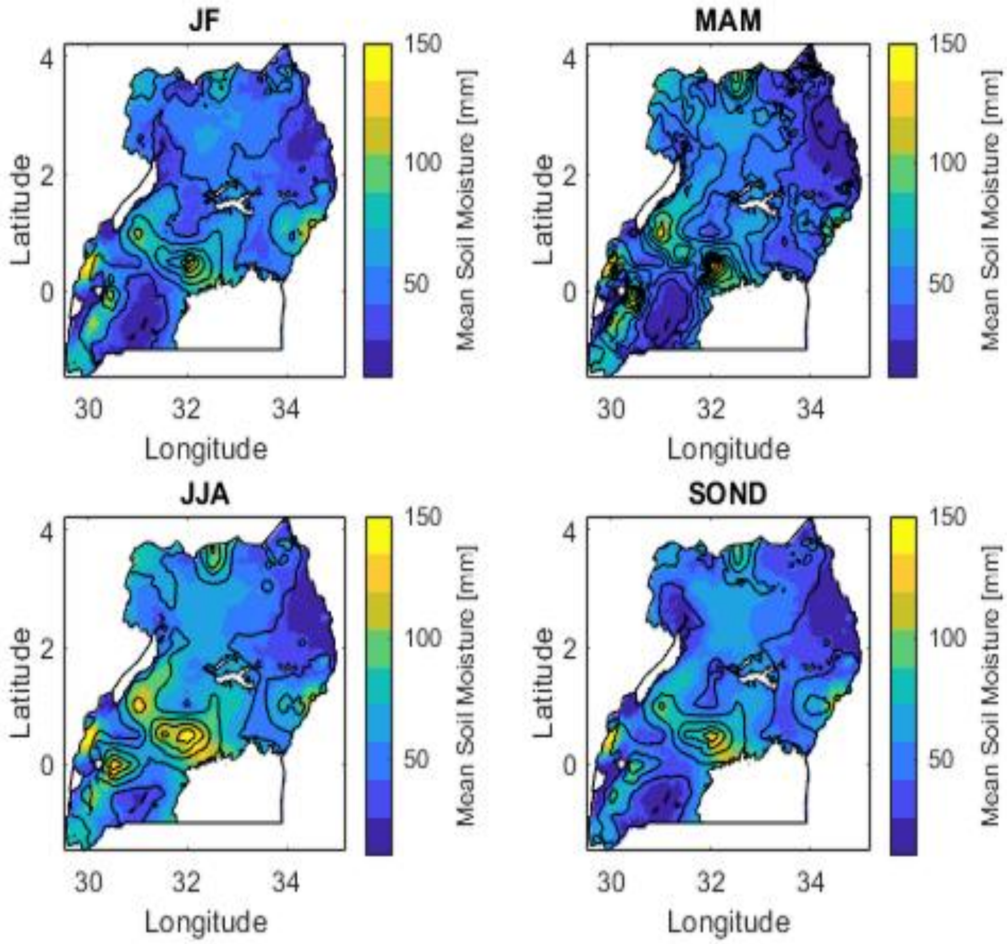


Figure 11: Average seasonal root zone soil moisture and its spatiotemporal variability (1990–2022), represented as contours.

JF=January, February; MAM=March, April, May; JJA=June, July, August; SOND=September, October, November, December.

3.4.2.2 Future soil moisture

Forecasts based on SSP 245 indicated that in Kabale, Kisoro, Kalungu, Masaka, Lwengo, and Rakai, there would be a significant (100-120 mm) variance in soil moisture between years, and that this range would be consistent across the seasons. The rest of the country, soil moisture will be similar among years. Throughout all seasons, the areas in the north, west Nile, Karamojonga, and a small portion of Rakai will have the lowest soil moisture (80-100 mm) (Figure 12). SSP585 has made similar predictions, with the exception of the January-February season, when the soil moisture in the vicinity of Rakai, Sembabule, Mubende, Kiruhura, Wakiso, and Luwero is +20 mm higher than in previous seasons (Figure 13).

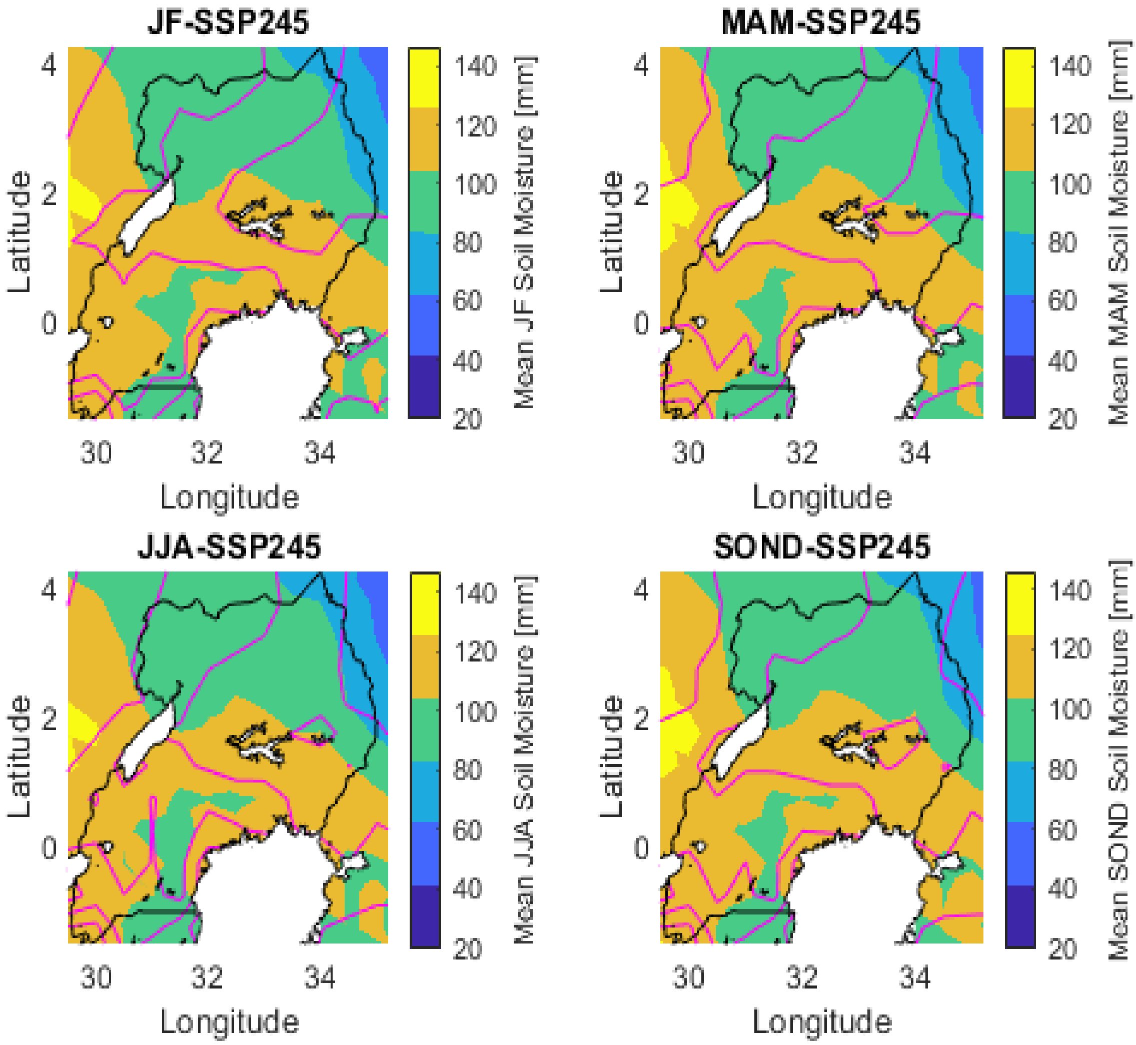


Figure 12: Average seasonal root zone soil moisture and its spatiotemporal variability (2025–2050), represented as contours under SSP245

JF=January, February; MAM=March, April, May; JJA=June, July, August; SOND=September, October, November, December.

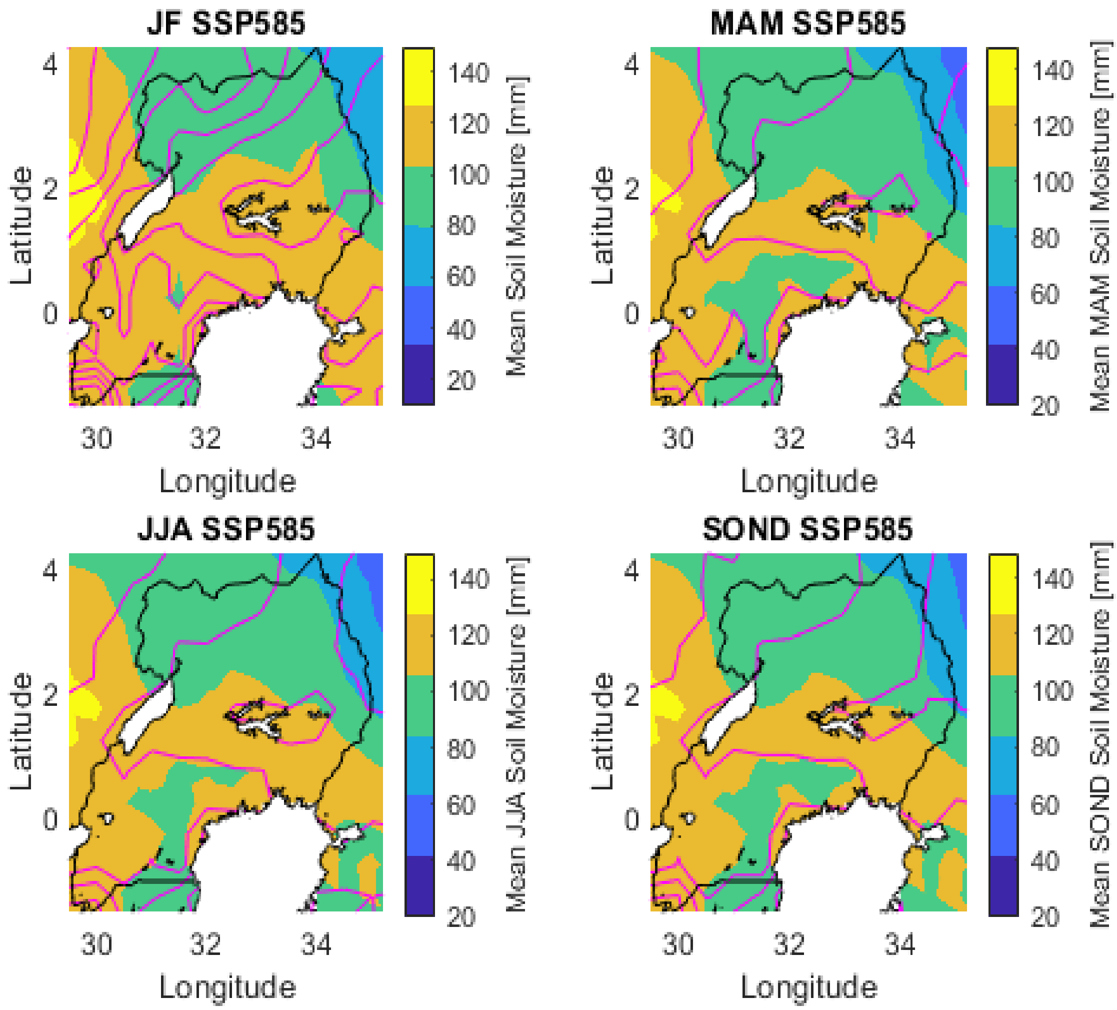


Figure 13: Average seasonal root zone soil moisture and its spatiotemporal variability (2025-2050), represented as contours under SSP585

JF=January, February; MAM=March, April, May; JJA=June, July, August; SOND=September, October, November, December.

3.4.3 Present and future coffee suitability as determined by soil moisture content

Historical soil moisture content data indicated that while parts of Ntoroko are low suitability for growing coffee, areas of Isingiro, Kiruhura, Nebbi, parts of Adjumani, Aura, Bulisa, Kitgum, parts of Kabong, Kotido, Abim, Moroto, Napak, Katakwi, Nakapiripirit, Amudat, Nakasongola, Nakaseke, Kasese, and Rubirizi are unsuitable (Figure 14). Of the total area, 71% is highly suitable, <1% has low suitability, and 28% is unsuitable (Figure 15).

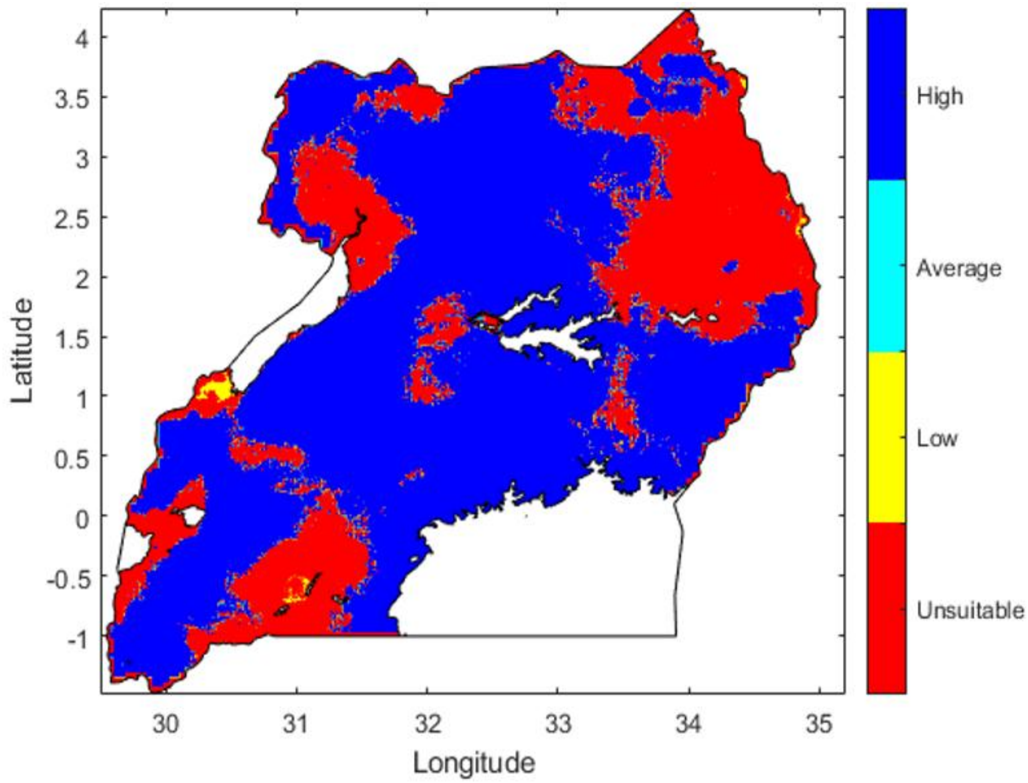


Figure 14: Coffee production suitability across Uganda from 1990 to 2022

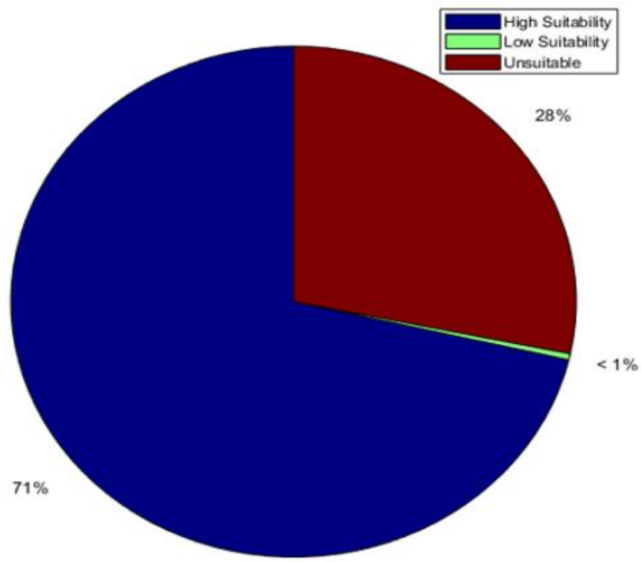


Figure 15: Share of land suitable for coffee cultivation between 1990 and 2022.

Coffee suitability will decline in the West Nile and mid-northern regions of Uganda and increase in the central, western, eastern, and Karamoja subregions in the future, according to SSP245 (Figure 16) and 585 (Figure 17). According to SSP245 and SSP 585, the area suitable for coffee growth will be 74% and 81%, respectively (Figure 18).

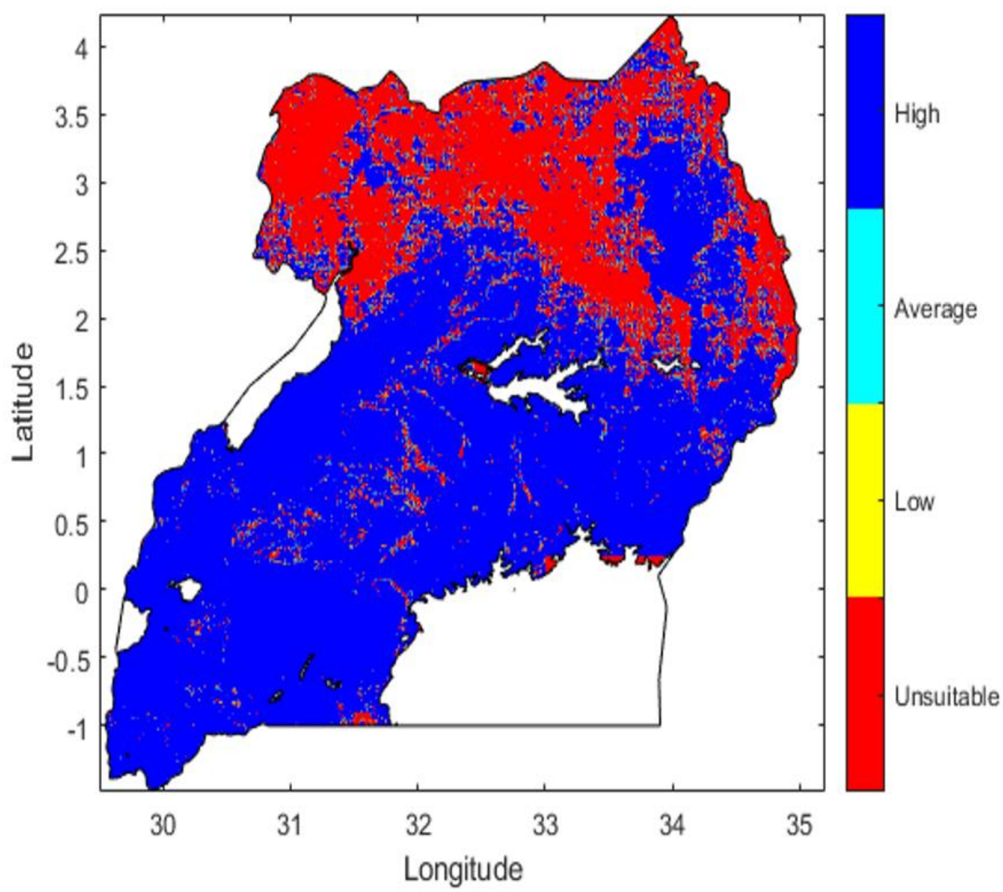


Figure 16: Projected coffee suitability in Uganda for 2025-2050 under SSP245

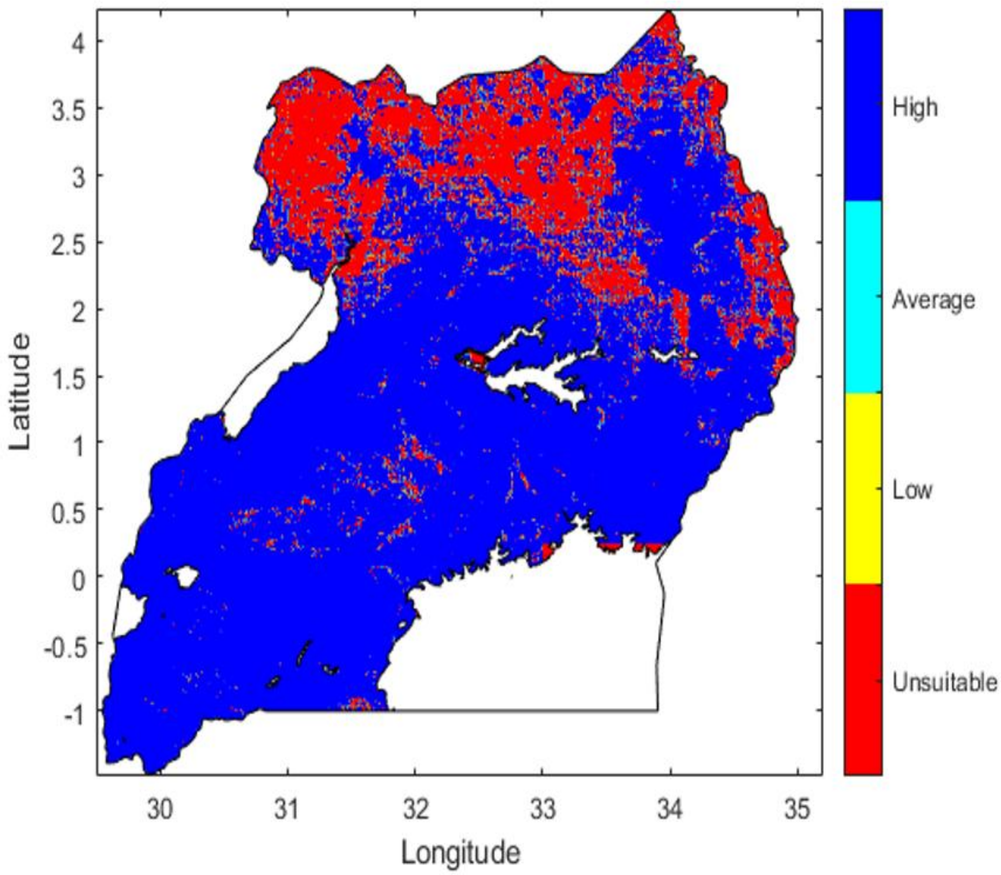


Figure 17: Projected coffee suitability in Uganda for 2025-2050 under the SSP585 scenario

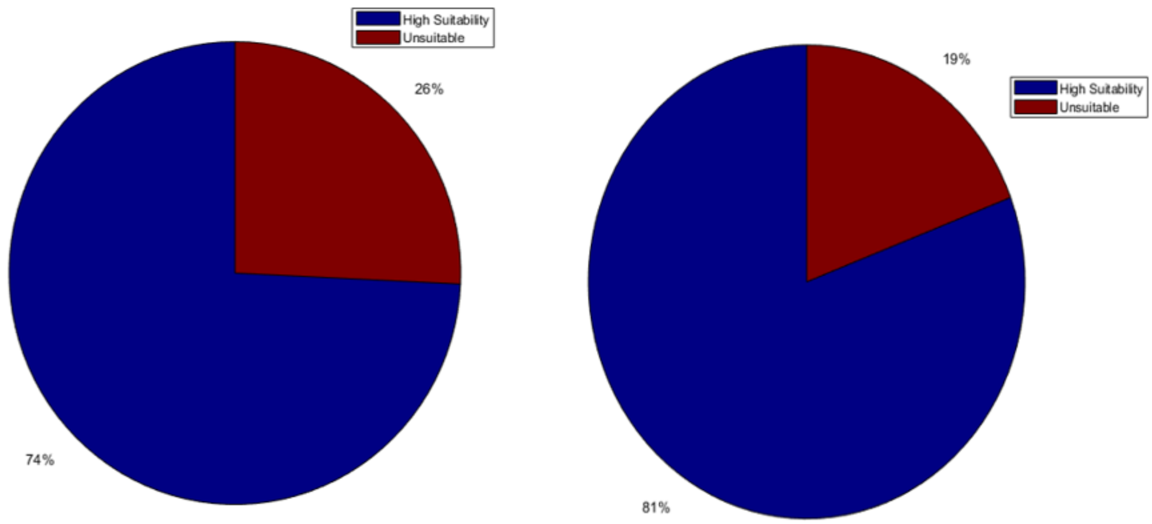


Figure 18: Share of land area suitable for coffee cultivation (2025–2050) under SSP245 (left) and SSP585 (right)

3.5 Discussion

3.5.1 Assessing the spatial and temporal patterns of soil moisture climatology

The root zone soil moisture content is higher in the Lake Victoria basin (especially in the northern districts of Mpigi, Wakiso, and Mityana), Kibaale, the Mt. Rwenzori subregion, and the Mt. Elgon parts in the districts that border Kenya. These findings are consistent with those of Jury (2015), who discovered that rainfall in the vicinity of Lake Victoria was more than 2 m/yr compared to 1.5 m/yr in other locations. Furthermore, according to GOU (2007), Uganda's wetter regions, particularly those east of the country and in the Lake Victoria basin, are trending toward increasing wetness due to an increase in rainfall. The regions east of the Lake Victoria and Lake Kyoga basins are also exhibiting positive trends in wetting tendencies, according to the NBI (2020) and UNESCO (2020); this may also help to explain the recent increase in lake levels and the landslide incidents that have been occurring in the Lake Kyoga basin around Mount Elgon. Additionally, historical data indicated that the soil moisture was low in the southwest regions of Rakai, Kiruhura, Isingiro, and northeastern Uganda. These results are consistent with earlier studies that show Karamonja, in northeastern Uganda, was the area most affected by climate change and most vulnerable to drought (USAID, 2017; Kakumba, 2022). This is because it receives the highest temperatures and the least amount of precipitation throughout the year, the northeast region of Uganda has the lowest soil moisture levels (CDKN, 2015). When temperatures rise and precipitation levels fall, the moisture content of the soil reduces (Afolabi *et al.,* 2009; Omona, 2023). According to studies (e.g. Eltahir, 1998; Dai *et al.,* 2022), there is a negative correlation between soil moisture content and air temperature and a significant and positive correlation between soil moisture content and precipitation. Additionally, WRMD (2004) revealed that water stress was present in parts of the country's southwest and northeast. It is important to note that these areas are a part of the Cattle Corridor, which crosses diagonally through Uganda, making up about 35% of the nation's total geographical area. It runs from southwest to northeast. Numerous semi-arid traits, such as prolonged droughts and low, erratic rainfall, are present in the corridor (Mayanja *et al.,* 2020). Also, MWE (2015) and GOU (2015) reported that the frequency and duration of droughts are on the rise, particularly in the western, northern, and north-eastern regions, with an average annual damage of US$237m in the past decade.

Conversely, the findings also indicated that the soil moisture content has been considerably reducing throughout the country and growing by 1.5 mm each month in the Karamojonja areas, Manafa, and Tororo, while dropping by 0.5 mm in the districts of Mukono, Buikwe, Jinja, Bugiri, Busia, Kiruhura, and Lyantonde. In line with this, Diem *et al.* (2014) reported that seasonal rainfall significantly decreased between 1983 and 2012 in the western and central regions of Uganda. While considerable increases in annual rainfall patterns were recorded in the Mpologoma catchment in Eastern Uganda by Mubialiwo *et al.* (2020) for the years 1948-2016.

Soil moisture content was projected by SSP245 and SSP 585 to be high in Kigezi and Rwenzori sub regions but changing variably between years and not varying between years respectively. By the end of the century, rainfall in the country's southern and western regions is expected to increase by up to 8 mm, according to SSP245 predictions (Ngoma *et al.,* 2022). This explains the rising trends of soil moisture in these regions. Additionally, SSP245 forecasts indicate that soil moisture will increase in the rest of the nation and drop by 0.02-0.06 mm around Lake Victoria, Kisoro, and Kabale. In consistent with our study, Kisakye and Van der Bruggen (2018) reported that Lake Victoria might experience a substantial decrease in rainfall (-20% from present), coupled with a 1 ºC temperature increase, impacting the lake water level. These climatic shifts are expected to contribute to reduced soil moisture in around lack Victoria. Lower rainfall directly decreases the amount of water infiltrating into the soil profile, while rising temperatures accelerate evapotranspiration, thereby intensifying water loss from both soil. Kitgum and the Rwenzori sub-region are will have the highest increases, measuring upto 0.08 mm. Accordingly, Jury (2024) forecasted that the Rwenzori subregion will see an increase in rainfall, with more equatorial and less subtropical rainfall being driven by a quicker Hadley circulation. According to the Ministry of Foreign Affairs (2018), the north of the country will receive more rainfall, while the southeast will receive less. According to earlier rainfall forecasts, yearly precipitation will somewhat decline across most of the country, with slightly wetter circumstances expected in the west and north-west under RCP 4.5 and RCP 8.5, respectively.

3.5.2 Seasonal characteristics of soil moisture

The high soil moisture found in the Mt. Elgon and Rwenzori subregion and the low soil moisture found in the Karamonja subregion, Isingiro, Rakai, Pakwach, Nebbi, and Ntoroko subregion throughout the year are supported by prior research by Basalirwa (1995). According to this study, low places like Uganda's cattle corridor are seeing greater drying conditions, whereas high ground areas are experiencing an increase in rainfall of roughly 10% to 20%. Throughout the year, the Karamonja sub-region, Isingiro, Rakai, Pakwach, Nebbi, and Ntoroko experience low soil moisture due to a combination of high temperatures and low rainfall (Mayanja *et al.,* 2020). According to Lui *et al.* (2022), temperature and precipitation are the primary drivers of the long-term dynamics of soil moisture droughts. In Uganda's various areas, Ogwere (2021) showed, that the yearly and seasonal soil moisture content generally declined across all soil depths. In the majority of the country, MAM shows notable yearly fluctuations in soil moisture content. This could be due to the interannual variation in rainfall reported by Jury (2015).

With the exception of a few areas in Rakai, Northern, West Nile, and Karamojonga regions will have the least amount of soil moisture under the SSP245 over all seasons. SSP585 has made similar predictions, with the exception of the January-February season, when there is +20 mm of soil moisture in Rakai, Sembabule, Mubende, Kiruhura, Wakiso, and Luwero districts. According to Markandya *et al.* (2015) and Nsubuga and Rautenbach (2018), the December-January-February (DJF) season is predicted to become significantly wetter, due to a prolonged wet season from September-October-November (SON) towards DJF. These modifications, in addition to significant temperature rises, particularly during the March-April-May (MAM) and June-July-August (JJA) seasons, call for a variety of adaption techniques. The seasonal differences in predication by SSP 245 (similar soil moisture from January to December) and SSP585 (similar soil moisture from March to December) could be due to the differences in assumptions of the two scenarios. In this study, soil moisture content ranges for every season under SSP 245 and SSP 585 were the same because by 2050, it is predicted that rainfall will increase by 5-20% in drier seasons (Hulme *et al.,* 2001; IPCC, 2007). In many Ugandan locales, Goulden's (2008) study found significant percentage increases in rainfall for normally dry seasons. Unlike Nandozi (2012), who predicted that between 2071 and 2100, precipitation will stay consistent and seasonal. While Collins *et al.* (2013) and Markandya *et al.* (2015) highlighted that rainfall variability is expected to intensify between wet and dry seasons, resulting in an overall decrease in rainfall for most of Uganda (-5 to -30mm per month). Similar soil moisture in all season could have an effect on coffee yields as coffee requires a period of water stress to initiate flowering (Carr, 2001)

3.5.3 Present and future coffee suitability as determined by soil moisture content

According to historical data on soil moisture content, parts of Ntoroko have low suitability for coffee growing, while areas of Isingiro, Kiruhura, Nebbi, parts of Kabong, Aura, Kitgum,parts of Adjumani Bulisa, Nakapiripirit, Kotido, Abim, , Napak, Amudat, Katakwi, Moroto, Kasese, Nakaseke, Nakasongola, and Rubirizi are unsuitable. The unsuitability could be because these areas are in the cattle corridor expressing low soil moisture. Numerous semi-arid traits, such as prolonged droughts and low, erratic rainfall, are present in the corridor (Mayanja et al., 2020). MWE (2013) also noted that the Rift Valley and the north-east experience an annual deficit, reaching over 600 mm/year. Coffee has an annual water requirement of 951mm, meaning that the rainfall being received can't met the crop water requirements for coffee therefore affecting productivity (Wintgens, 2004). In 2017, coffee yields in greater Luwero areas dropped by 60% due to drought (MCDonnel, 2017). Also, Matyanga (2023) noted that the recurrent droughts in Isingiro district have reduced coffee production in the area

The future unsuitability of northern region as predicted by both SSP 245 and SSP585 could be due to the low soil moisture in these areas (Moat *et al.,* 2017). Due to protracted dry spells, Swaibu *et al.* (2014) reports that coffee production in northern Uganda is restricted to one season annually, although most of the nation's main coffee-growing regions have two seasons (UCDA, 2019a Handbook). According to SSP245 and SSP 585, the area suitable for coffee growth will increase to 74% and 81%, respectively. However, it is likely that 1% of the land will be marginally suitable, and 26% and 19% will likely be not suitable for coffee cultivation. Its projected that there will be changes in areas suitable for growing coffee in Uganda by 2050 (UCDA, 2019a Handbook). In the central, western, eastern, and Karamoja sub-regions, there will be a rise in coffee suitability, which suggests that these places will see an increase in Robusta suitability in the future. A suitability study conducted by Nandozi (2012) discovered that, based on projected climate data (rainfall and temperature), 84% of the coffee-prone areas are predicted to be suitable for coffee growth in the future. However, projections of both SSP 245 and SSP 585 show that the suitability of Robusta in the mid-north will decrease, as will the suitability of Arabica, which is grown in the West Nile. This outcome supports the forecast made by Von Loeben *et al.* (2023) that by the end of the century, the West Nile districts that are today suited for Arabica coffee would no longer be so. Consequently, farmers might have to move to more climate-resilient coffee species or varietals, such Robusta coffee.

Furthermore, these authors predict that the Northern region will experience an increase in the frequency of hot days and nights as well as notable temperature variations. There may be a risk to the government's intentions and initiatives to boost coffee output in Northern Uganda and other unconventional coffee-growing areas (Coffee Roadmap, 2017). Previous research by CIAT (2013) and Jassogne *et al.* (2013) indicates that the number of regions that are entirely unsuitable for producing Arabica will significantly decline by 2050, while the number of areas that are completely unsuitable for producing coffee will significantly increase by 2030. Simonett (1988) provides the first illustration of an impact study evaluating how climatic change is affecting *C. canephora* output in Uganda. According to the maps in this study, a 2% increase in temperature has resulted in a significant reduction in Uganda's acceptable growing area. Robusta coffee in Uganda is expected to move to higher elevations in the southwest, where it borders Tanzania and Rwanda, according to Haggar and Schepp's (2012) projections. This suggests that the region is more suitable for growing Robusta coffee. Von Loeben *et al.* (2023) came to similar results regarding the displacement of Robusta coffee from the interior of Uganda to the shores of Lake Victoria under all possible circumstances.

Furthermore, according to statistics from Kenya and Uganda, Robusta production will move to areas with higher rainfall, and climate change would raise the minimum altitude needed for Arabica production by as much as 400 meters (Haggar and Schepp, 2012). Should the sustainability of their coffee-growing regions shift, the nations that grow coffee might experience a decrease in export revenue (Bilen *et al.,* 2023). A growing number of smallholder farmers in particular regions are dependent on coffee earnings, therefore in order for them to continue growing coffee, they will need to employ soil moisture conservation techniques (Bracken *et al.,* 2023).

CHAPTER FOUR: WATER USE EFFICIENCY OF ROBUSTA COFFEE AT VARIOUS PHENOLOGICAL STAGES UNDER *ALBIZIA CORIARIA* AND OPEN SUN SYSTEMS

4.1 Abstract

Investigating how agroforestry systems influence water use efficiency (WUE) in coffee is essential, as it provides insights for optimizing water use and promoting sustainable farming practices. This study therefore assessed the WUE of Robusta coffee at different phenological stages under coffee under *Albizia coriaria* and open sun coffee systems. A randomized complete block design was established with two systems *A. coriaria* coffee system (ACS) and open sun coffee system (COSS) and three coffee varieties. Water use by coffee and shade trees was monitored using sap flow meters. Additional measurements included the duration from inflorescence emergence to ripening, berry size from yellow stage to ripening, coffee growth and yield parameters, leaf area index, and photosynthetically active radiation. Differences in water use were analyzed using an F-test at a 5% significance level. Water use varied by phenological stage, clone, and system. Coffee grown in open sun used significantly more water per day (1.43 l/day) compared to shaded coffee (0.62 l/day, $p<0.001$). Differences in water use per unit leaf area were also significant, with ACS using 0.12 mm/day and COSS 0.10 mm/day. There was non-significant difference in WUE per fruit phenological stage per system. However, at yellow stage, ACS was more water efficient (434.9 cm3/mm), at 10-50% COSS was water efficient (1411cm3/mm), at 50-90% ACS was water efficient (2472 cm3/mm), and at 100% to ripening COSS was more water efficient (309 cm3/mm). The system and varietal effect on coffee water use suggests a competition for water between coffee and *A. coriaria*. Similarly, there was a varietal and system effect on coffee bean weight and coffee growth response. Recommend that *A. coriaria* should be optimally used as a way for improving WUE of fruit development without compromising on bean weight and yield.

4.2 Introduction

Producing crops efficiently per unit of water is a major global concern, as freshwater resources are limited (Hogeboom, 2020), particularly in densely populated regions, and the demand is expected to rise with population growth (Mulwa & Fangninou, 2021). Water use efficiency (WUE) is therefore crucial for assessing plant adaptation and productivity in water-limited environments, both under current climate conditions and future global changes (Xu & Hsiao, 2004). A key question is how plants will respond to shifts in temperature, precipitation, and atmospheric carbon dioxide (CO2), which directly influence WUE (Hatfield & Dold, 2019). Therefore, improving crop WUE is mandatory for global food production (Zahoor *et al*., 2019). Agroforestry is widely regarded as a key component of sustainable farming systems, capable of improving the efficient use of water and nutrients while supporting global food production (Pinho *et al.,* 2012). Shade trees can help reduce evaporation, increase water retention in the upper soil layers, and enhance water use efficiency (Padovan *et al.,* 2018). However, they can also increase transpiration and intercept rainfall, which may reduce water availability for understory crops (Padovan *et al.,* 2015). Additionally, a dense tree canopy limits light penetration, potentially restricting water use by crops like coffee (Muñoz-Villers *et al.,* 2020). The competition for water between shade trees and crops can therefore be a significant constraint on the effectiveness of agroforestry as a climate adaptation strategy, especially under extreme conditions (Abdulai *et al.,* 2018). The National Agricultural Research Organization (NARO) has recommended and is currently promoting region-specific shade trees to each of the six coffee growing regions of

Uganda to be intercropped in the coffee agrosystems. Selection of these trees was based on farmer preference, scientific knowledge and not being good alternative hosts of *Xylosandrus compactus* insect pest in Uganda (Kagezi *et al.,* 2015). However, there is limited knowledge on water use of the recommended shade tree species, particularly in the Robusta coffee agrosystems.

In Uganda, research on water use in coffee agroforestry systems has largely focused on Arabica coffee (Buyinza *et al.,* 2019; Sarmiento-Soler *et al.,* 2019), while studies on Robusta coffee remain limited. Robusta coffee is gaining increasing importance for the global coffee trade because of the species' relative resilience to climate shocks, and the crop's increasing livelihood contribution is several economies such as Vietnam (Amarasinghe *et al*., 2015 Byrareddy *et al*., 2020) and Uganda (Musoil *et al.,* 2001; Masiga & Ruhweza, 2007). For instance, Uganda's Robusta-dominated coffee sector earnings increased from 5.41 million 60-kilo bags worth US$ 513.99 million in 2020 to 6.13 million bags worth over US$ 1.14 billion in the financial year 2023/24 (UCDA, 2020; UCDA, 2024). Despite the importance of Robusta coffee to smallholder farmers in Uganda, limited studies exist on its WUE, but, some research has been conducted in other Robusta coffee growing countries like Vietnam (Byrareddy *et al*., 2020; Tran *et al*., 2021). Understanding the water use of trees is a crucial step toward enhancing complementarity and stability in food production within smallholder agroforestry systems (Buyinza *et al.,* 2019). Research on tree water use physiology has become increasingly important due to environmental pressures such as land-use change (Ellison *et al.,* 2017), agricultural land degradation (Muthuri *et al.,* 2005), and climate change (Strobl *et al.,* 2017), all of which have significant implications for household food security. Water availability is critical for coffee farming, as it influences plant phenology, productivity, quality, and economic viability (Silva *et al.,* 2019). Coffee's water requirements vary with phenological stage, atmospheric humidity, soil properties, and management practices (DaMatta & Ramalho, 2006; DaMatta *et al.,* 2007). Understanding how climate change affects coffee phenology will therefore provide information on how these effects ultimately affect the yield and quality of coffee berries (Wangui, 2012). This study therefore aimed at estimating the water use efficiency of Robusta coffee at various phenological stages under coffee *Albizia coriaria* and open sun Robusta coffee systems. The specific objectives were to determine effect of systems on; 1) duration of coffee fruit phenological stages, 2) coffee water use, 3) WUE of coffee fruit phenological stages, 4) coffee berry weight. It was hypothesized that Robusta coffee under *A. coriaria*; 1) takes a longer time per coffee fruit phenological stage, 2) uses less water 3) has heavier beans compared to coffee under open sun systems, 4) has a better WUE under different coffee fruit phenological stages. Understanding water use efficiency provides insights into the water needs of the different components within farming systems and helps identify the most effective management practices for farmers facing water stress (Buyinza *et al.,* 2019).

4.3 Materials and methods

4.3.1 Study area

The study took place at the National Coffee Research Institute (NaCORI) in Mukono district, located within the Lake Victoria crescent agroecological zone, approximately 35 kilometers east of Kampala, Uganda's capital. Mukono lies in Uganda's low-to-medium altitude range, at about 1,200 meters above sea level. The NaCORI is located at $0^0$15'26.9874"N and $32^0$47'27.69648"E (Kobusinge *et al.,* 2023) (Figure 19). The yearly rainfall is bimodal, varying between 1,400 and 1,600 mm. The region experiences two primary rainy seasons, from March to May and from September to November. Annual minimum temperatures range between 15 °C and 18 °C, while maximum temperatures vary from 25 °C to 28 °C (Kobusinge *et al.,* 2023; Mukono District Local Government, 2015). According to Kobusinge *et al.* (2023) and Mukono District Local Government (2015), Ferralsols (sandy clay-loams), are the major soil types in Mukono. NaCORI was purposively chosen to allow the experiment to be conducted under a controlled setting compared to farmers' fields which have high variability in terms of management, coffee age and soils. Besides, the study shade tree and study Robusta coffee varieties were already established at NaCORI.

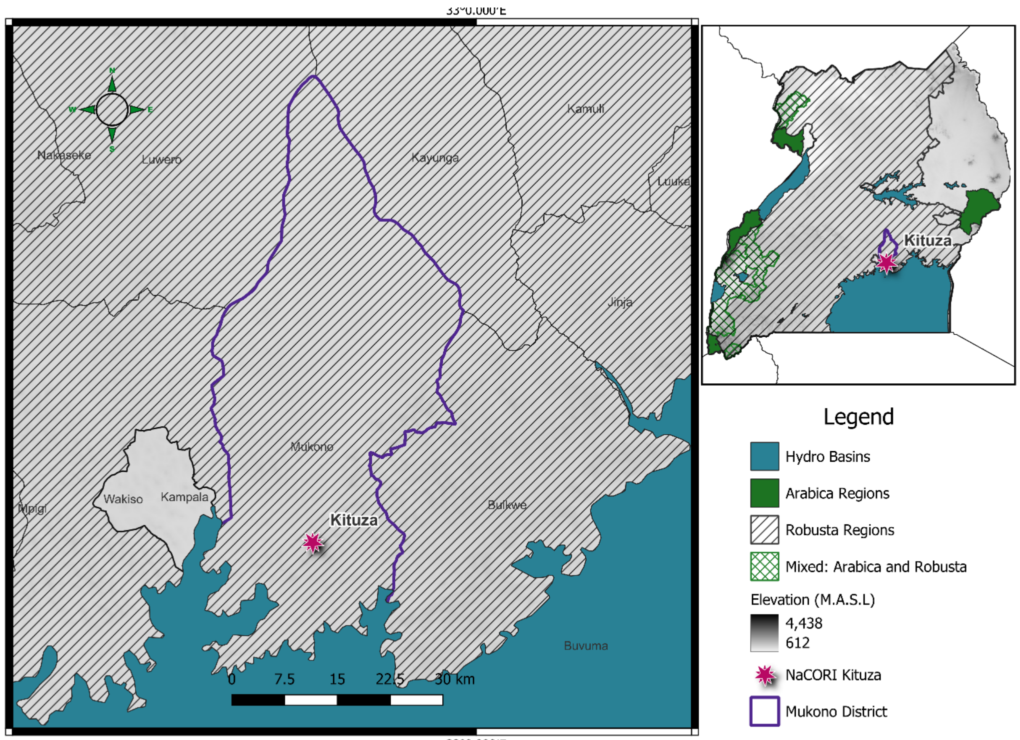


Figure 19: Study site at the National Coffee Research Institute (NaCORI), Kituza, Mukono district, Central Uganda. Map generated using MATLAB

4.3.2 Research design

A Randomized Complete Block Design with four seasonal replications was used to assess significant differences between the two coffee systems. The experiment was conducted within a coffee plantation established in 2009, with Robusta coffee trees last stumped in 2019. The study involved a breeding population segregating for Coffee Wilt Disease (CWD) resistance (UCDA, 2019a Handbook). Coffee plants were spaced 3 m × 3 m, while shade trees were spaced 15 m × 15 m, and each study plot measured 81 m². Two contrasting coffee systems were evaluated: the open sun coffee system (COSS) and the coffee–Albizia coriaria system (ACS). Within each system, three coffee clones (MFCT1, J24/13/20/4, and 203/32/2) were planted around the shade trees. All plots received uniform management practices, including weeding, fertilizer application, and pruning, differing only in the system type. Weeds were controlled manually using hand hoes, and NPK 25:5:5 fertilizer was applied at a rate of 250 g per plant once during the rainy season. The coffee plants were pruned regularly to prevent sucker development and were solely rain-fed throughout the study.

4.3.3 Methods of data collection

4.3.3.1 Climatic data

Climatic data (minimum temperature, maximum temperature, relative humidity at 9 hours, relative humidity at 15 hours and rainfall) were obtained from Uganda National Meteorological Authority (UNMA) station located at NaCORI. The weather station is situated about 0.5 km from the study site. The temperature and relative humidity created by the different systems were measured using i-button readers which were installed at 1.3 m height of coffee. This microclimate data were then used to calculate the vapor pressure deficit (VPD) (Equation 1 & 2) of the different systems using a formula by CronkLab (2015).

$SVP = 610.7 \times 10^{(7.5T/(237.3+T))}$ ……………………………… ………………Equation 1

and $VPD = [(100 - RH)/100] \times SVP$ ……………………………………………………Equation 2

where SVP is saturated vapor pressure (Pa), T is temperature (ºC), VPD is vapor pressure deficit (kPa), and RH is relative humidity (%).

4.3.3.2 Photosynthetic Active Radiation and Leaf Area Index

PAR and LAI were measured every two weeks in every system using Ceptometer LP-80 in the morning hours. For coffee and shade tree, two measurements were taken, one above the canopy and one below the canopy. The Ceptometer was first placed above the coffee canopy to measure the above canopy PAR then randomly placed under the coffee canopy at four points (East, West, South and North direction) and the average calculated automatically by the instrument. The above and below canopy PAR per plant was taken at the same sunshine intensity. In case of change of sunshine intensity after measuring the above canopy PAR, it was repeated at the new sunshine intensity. The change in sunshine intensity was observed visually. Based on light intercepted by the plant, LAI was calculated using the Ceptometer. For the *A. coriaria* system, measurement above the coffee canopy captured the shade tree LAI while the one below the coffee canopy captured the system (shade tree and coffee tree) LAI. The difference between the two measurements gave the coffee LAI.

4.3.3.3 Coffee growth and yield parameters

Growth parameters were measured once every dry and wet season for a period of 20 months. Same coffee trees used for sap flow measurements (water use) were used for growth and yield parameters. Growth parameters measured included: stem girth (SG), number of stem internodes (SI), stem Length (SL), canopy height (CH), canopy diameter (CD), number of primaries branches (NP), number of primary branches in bearing head (PBH), length of longest primary branch (LP), number of primary branch internodes (PI). The measurements were made in reference to Ferrao *et al*. (2019) and Bote (2016)

4.3.3.4 Water use measurement

4.3.3.4.1 Research design and instrumentation

SFM1 Sap Flow Meters (ICT International, Armidale, Australia) was used to assess water use for a period of 20 months. The meters are designed to rely on heat ratio method for measuring sap flow. This non-destructive method can measure both low and reverse flow rates over long periods (Burgess *et al.,* 2001). The meters were installed on three Robusta coffee plants in open sun, three Robusta coffee plants under *A. coriaria* tree and on one *A. coriaria* tree. An individual coffee plant was the observational unit and considered as a replicate per system. The sap flow meters were placed on one of the coffee stems and on the shade tree, giving a total of seven sap flow meters installed (Figure 20). Sap flow measurements serve as an indicator of plant water use (Burgess *et al.,* 2001).

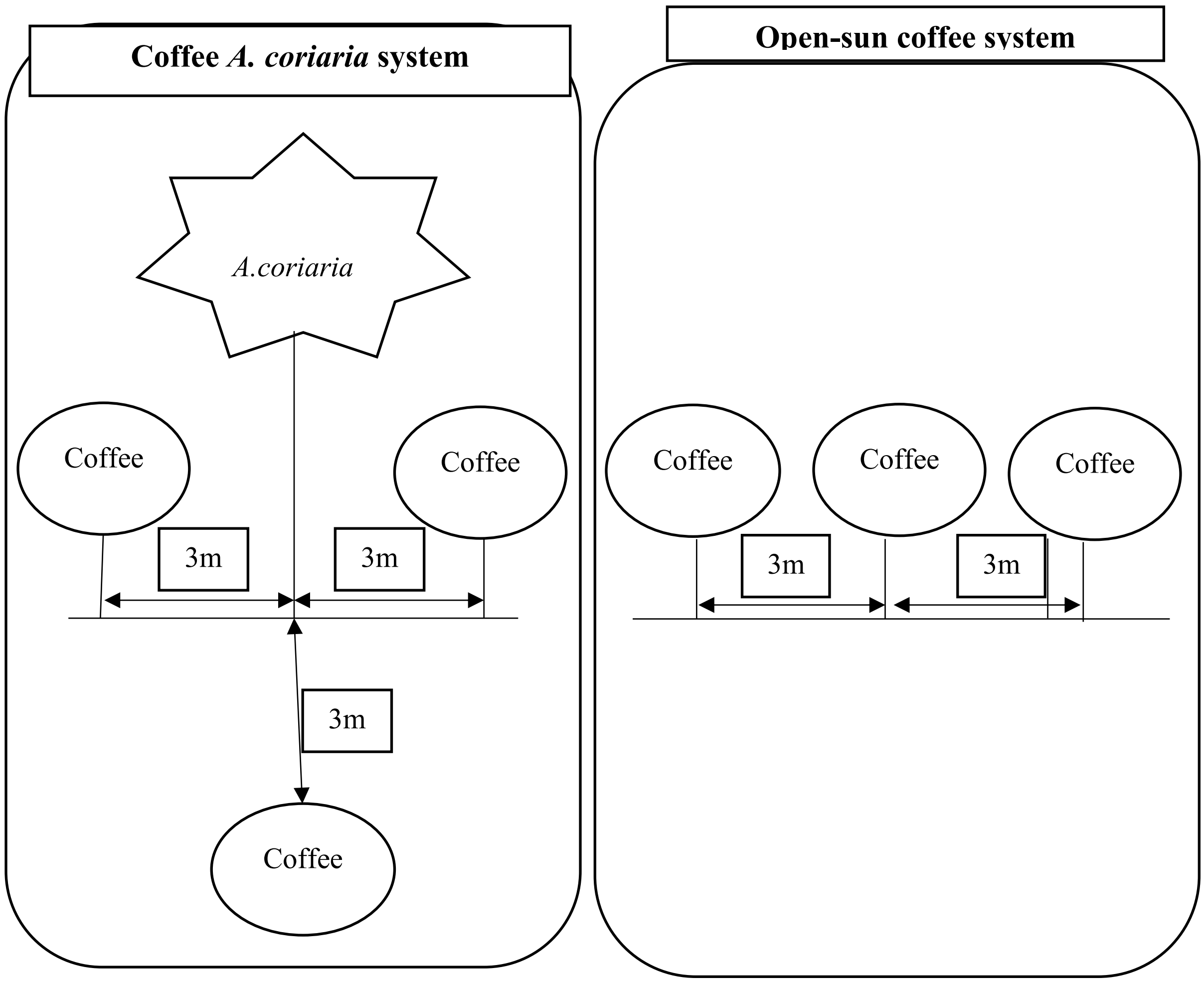


Figure 20: Experimental set up at the National Coffee Research Institute (NaCORI), Mukono district, central Uganda for assessing water use under two contrasting coffee systems.

4.3.3.4.2 Sap wood diameter and bark depth

Destructive sampling was employed to measure coffee bark depth and sapwood area (Buyinza *et al.,* 2019), whereas an increment borer was used to assess the sapwood and heartwood thickness of the shade trees (Buyinza *et al.,* 2019). For the shade tree bark depth, a flat blade screw driver was pushed inside the bark using a hammer until a hard surface was reached and a change in sound was noticed as the blade hits the sap wood. Then the edge of the tree on the screwdriver was marked, removed and the distance measured using a centimeter ruler. Iodine dye was used to differentiate bark depth, sap wood and heart wood for the cut coffee stems and the stem materials that came with the increment borer. The bark turned orange; sap wood light black; while the heart wood was dark black. The diameter of these stem parts were measured using a ruler in centimeters (Table 2).

Table 2: Characteristics of the coffee system studied at the National Coffee Research Institute (NaCORI), Mukono district, central Uganda

	System	
Parameter	**ACS**	**COSS**
Plot Area (m^2)	81	81
Coffee Spacing	3m x 3m	3m x 3m
A.coriaria spacing	15m x 15m	-
Coffee plant density (tree ha^{-1})	1,111	1,111
A.coriaraia density (tree ha^{-1})	44	-
A.coriaria Stem Diameter (cm $stem^{-1}$)	29.9	-
Coffee in open sun Stem Diameter (cm $stem^{-1}$)	2.83±0.50	3.3±1.53
A.coriaria Bark depth (cm $stem^{-1}$)	2.25	-
Coffee Bark depth (cm $stem^{-1}$)	0.14	0.14
A.coriaria sap wood diameter (cm)	2.1	-
Sapwood diameter (cm $stem^{-1}$)	1.3	1.3
A.coriaria Stem height (cm)	1023	

Coffee Stem height (cm)	255±9.75	281±15.53
A.coriaria No. of stem/tree	1	
Coffee No. of stem/tree	3.67±0.33	3.67±0.33
A.coriaria canopy diameter (cm)	904	
Coffee Canopy diameter (cm)	382±26.65	345±51.83
Age of coffee plants (years)	15	15
Age of *A.coriaria* (years)	15	

ACS, coffee Albizia coriaria system; COSS, open sun coffee system; m, meter; cm, centimeter; ha, hectare

4.3.3.4.3 Installation of the sap flow meters

For each tree, a healthy, straight stem was selected, and bark thickness was measured prior to installing the sap flow meters. Sapwood depth was determined using an increment borer (Buyinza *et al.,* 2019) to ensure proper radial placement of the sap flow probes within the tree's water-conducting tissue. Probes were installed at approximately 1.3 m above the ground, corresponding to the diameter at breast height (DBH) for both tree trunks and coffee stems. Bark was removed at this height to allow direct insertion of the probes into the xylem. A metal drill bit guide (ICT International, Armidale, Australia) was used to ensure perpendicular drilling and accurate spacing. After drilling, the three needles were lightly coated with inert silicon vacuum grease to improve thermal contact and then inserted into the pre-drilled xylem holes, with two measurement needles positioned 0.5 cm above and below the central heater. The ratio of heat transfer between these symmetrically positioned temperature needles was used to calculate the magnitude and direction of water flux. Each sap flow meter was connected to a solar panel to trickle-charge its internal battery. Sap flow was continuously recorded every 30 minutes over a period of 20 months.

4.3.3.5 Coffee fruit development

Data were collected from coffee stems equipped with sap flow meters. For each treatment, three stems were selected, and four primary branches oriented toward the four cardinal directions (North, West, East, and South) in the upper third of each stem were tagged. Flower buds on these primaries were monitored through to ripening, and the duration of each phenological stage was recorded according to the

Biologische Bundesanstalt, Bundessortenamt, and Chemische Industrie (BBCH) scale (Table 3). Every new inflorescent stage was followed to ripe cherries for the study period by further tagging on the already tagged primaries. Observations on these primaries were done on a daily basis. The length, width and thickness of randomly selected 20 pinheads was measured until the coffee ripens using a vernier caliper in centimetres (cm) per system every week. Volume of the fruits was computed by multiplying length x breadth x thickness x 0.52 as standardised by Reddy (1976). All the observations and data herein refer to berry development in the tagged primaries. Dates for change of phenological stage were taken when more than 50 % of the berries under a previous stage have changed to the next.

Table 3: Selected fruit phenological growth stage and Biologische Bundesantalt Bundessortenamt and CHemische Industries (BBCH) identification keys used in the study (Arcila-Pulgarin *et al.,* 2002)

Code	Description
Principal growth stage 5: Inflorescence emergence	
51	Swelling of the inflorescence bud at leaf axils
53	The inflorescence buds have burst, covered in brown mucilage, with flowers absent
57	Flowers can be seen, still closed and closely grouped, borne on inflorescences containing 3–4 flowers each
58	Flowers are visible but not tightly clustered, remaining closed with green petals measuring 4–6 mm in length, indicative of the dormant stage

59	Flowers have elongated petals measuring 6–10 mm, remain closed, and are white in color.
Principal growth stage 6: flowering	
69	90% of the flowers are open
Principal growth stage 7: Development of fruit	
70	Small yellowish berries visible
71	Fruit set: Initial stage of berry growth, with fruits attaining about 10% of their final size (pinhead stage)
73	Light green fruits with liquid-crystalline contents, ~30% of full size
75	Light green fruits with liquid-crystalline contents, ~50% of full size
77	Light green fruits with liquid-crystalline contents, ~70% of full size
79	Light green fruits with liquid-crystalline contents, ~90% of full size
Principal growth stage 8: Ripening of fruit	
88	Fruit has reached full ripeness and is ready for harvest

4.3.3.6 Coffee Kiboko weight per bean

Since coffee plants had differences in ripening, and were ripening throughout the year, coffee yield data were collected for a period of one year. Coffee berries picked were dried in a solar dryer to 14% moisture content, then weighed using a weighing scale (Model Renznov SF-400) and then counted to get the weight per bean. Data were collected per coffee tree.

4.3.3.7 Water use efficiency per phenological stage

Total number of primaries were determined. Similarly, the number of primaries with yellow berries, 10-50%, 60-90% and 100-ripening was determined and the percentage of primaries with a particular phenological stage determined. This data was collected on biweekly basis on each of the three coffee stems per system with the sap flow meters The BBCH identification key was used to identify the different phenological stages (Arcila-Pulgarin *et al.,* 2002). To determine the total number of phenological stage on the whole stem, tagged primaries used for coffee fruit development were used for data collection. The number of clusters per phenological stage was determined. A sample cluster with more than 50% of particular phenological stage was selected; and yellow berries, 10-50%, 60-90% and 100-ripening berries were counted. The berry volume previously determined in the coffee fruit development section was used to calculate the change in berry volume. The inflorescence and flowering stage were left out because it was not practical to determine their change in volume.

4.3.4 Data analysis

4.3.4.1 Duration (in days) of each coffee fruit phenological stage

Data were analyzed using R software version 4.2.3. A two-way ANOVA was performed with the aov() function to determine significant differences in the number of days per phenological stage among clones and between systems, with a significance threshold of 5%

4.3.4.2 Change in berry size among fruit phenological stages, clones and systems

Significance of differences among clones, phenological stages and between systems for coffee berry length, width, thickness and volume were determined using F-test at 5 % error margin. Pearson correlation matrix was drawn using ggcorrplot package in R. Correlations were done between cherry berry dimensions, water use and dry weight.

4.3.4.3 Measurement of daily water use per unit ground area, transpiration per unit leaf area, and flow rate

Regression between daily water use and variables (rainfall, temperature, relative humidity, LAI) was carried out using the ggpubr and ggplot packages in R. A three-way ANOVA was conducted in R using the aov() function to assess the effects of system, clone, and season, including their interactions, on mean daily water use per ground area and transpiration per unit leaf area. Daily water use for individual coffee trees was calculated by multiplying the daily water use of a single stem by the total number of stems per tree (l day^{-1}). These values were then converted to millimeters by scaling to the number of trees per hectare and dividing by the area.

4.3.4.4 Water use efficiency for each phenological stage across different systems

Modified version of yield WUE was used where it was defined at it as the change in berry volume per water used during that fruit phenological stage. Change in volume was determined as the difference in volume at the start of the stage and its end. Since this change in volume was determined on berry basis, total change in volume of the whole plant was calculated by total number of berries which were in that stage multiplied by the berry volume. Total water used per phenological stage was determined by summing up the amount of water used during that particular stage. T-test was used to ascertain the significance of difference between systems for water use efficiency per phenological stages at 5% error margin. Linear regression analysis was done between water use efficiency and change in volume; and water used and selected climatic factors using the ggpubr package. Water Use Efficiency (WUE in cm^3 mm^{-1}) was calculated using equation 3

$$WUE = \frac{\Delta V}{Total\ water\ used\ (mm)}$$ ………………………………………….............................Equation 3,

Where ΔV is change in volume of a phenological stage (cm^3).

4.4 Results

4.4.1 Effect of system on coffee growth and yield parameters

Table 4 below summarizes the relationship between the coffee systems, clone and seasons. Results showed that there was no significant difference ($p \geq 0.05$) between the systems for all the growth and yield parameters. All the growth and yield parameters were higher under open sun coffee system (COSS) than *Albizia coriaria* coffee system (ACS), apart from number of berries per cluster (NBC) and number of clusters per primary branch (NCP). However, there was a significant ($p \leq 0.05$) interaction between the system and the clones for canopy diameter (CD), number of internodes on stem (SI) and stem length (SL). Furthermore, for coffee growing under ACS system, a significant difference ($p \leq 0.05$) between clones was observed only in case of the number of primaries (NOP) and stem length (SL). The highest NOP (59.5) was recorded under clone J24/13/20/14 and the lowest (17.5) was under clone MFCT1 whereas, the highest SL (174.8) was observed under clone 203/32/2 and the lowest (250.0) was under clone MFCT1. On the other hand, for coffee growing under COSS, a significant difference ($p \leq 0.05$) between clones was observed only in case of the canopy diameter (CD) and stem length (SL). The highest CD (430.0) was again recorded under clone J24/13/20/14 and the lowest

(266.5) was under clone MFCT1 whereas, the highest SL (339.5) was observed under clone J24/13/20/14 and the lowest (252.0) was under clone MFCT1

Table 4: Coffee growth and yield parameters under *Albizia coriaria* coffee system and coffee open sun system at the National Coffee Research Institute, Mukono district, central Uganda

System	Clone	CH	CD	NBC	NCP	NOP	NAB	PI	SI	SG	SL	LP
	203/32/2	107.5±39.5	350.5±39.5	26.5±4.5	13±2.0	48.5±7.5a	34.0±1.6	26.5±3.5	65.0±9.0	5.5±0.4	274.8±0.2a	101.5±8.5
ACS	J24/13/20/14	143.0±1.0	323.0±3.0	14.5±2.5	8.0±1.0	59.5±0.5a	43.5±1.5	22.0±9.0	54.0±4.5	5.85±0.1	252.0±2.0b	110.25±6.2
	MFCT1	105.5±16.5	250.5±6.5	6.5±6.5	4.5±0.5	17.5±5.5b	8.5±1.5	10.5±2.5	48.0±2.5	4.0±0.6	250.0±7.0b	80.5±27.5
p value		0.552	0.112	0.127	0.261	**0.02425 ***	0.152	0.274	0.212	0.098	**0.04292 ***	0.523
cv		29.46	10.64	42.76	48.27	18.18	45.97	41.41	13.28	11.53	2.3	24.67
	203/32/2	137.0±12	266.5±4.5b	14.0±8.3	4.5±4.5	41.0±4.0	27.0±6.0	23.5±1.5	48±1.0	5.1±0.2	287.5±11.2b	103.2±5.2
COSS	J24/13/20/14	179.5±6.5	430.0±22.0a	7.0±3.0	5.5±0.5	58.0±9.0	30.0±9.3	41.0±5.0	61.5±4.5	6.55±0.3	339.5±9.5a	167.5±22.5
	MFCT1	61.5±48.5	275±35.0b	13.5±1.5	9.5±0.50	45.0±8.0	32.0±1.0	26.0±2.0	61.5±3.5	4.25±0.9	252.0±11.0b	89.5±6.5
p value		0.134	**0.02818***	0.814	0.461	0.359	0.643	0.057	0.1	0.15	**0.02325***	0.054
cv		32.65	10.48	102.21	57.22	21.58	16.74	15.13	8.29	15.9	5.16	16.31
ACS		118.7±13.5	308±21.5	15.83±4.3	8.5±2.0	41.83±8.3	28.67±7.8	19.67±4.0	55.67±3.9	5.12±0.4	258.9±5.4	97.4±9.4
COSS		126±25.4	323.8±35.3	11.5±4.0	6.5±1.5	48.0±4.6	29.67±1.8	30.17±3.8	57.0±3.22	5.3±0.5	293.0±16.8	120.1±16.4
p system		0.804	0.71	0.474	0.449	0.531	0.903	0.083	0.798	0.782	0.082	0.259
p system*C		0.325	**0.019***	0.387	0.126	0.071	0.081	0.113	**0.029***	0.589	**0.004****	0.23
p season		0.501	0.13	0.924	0.249	0.249	0.374	0.668	0.593	0.231	0.416	0.257

C, Clone; S, Season; CH, canopy height in centimetres (cm); CD, canopy diameter in cm; NBC, number of berries per cluster; NCP, number of clusters per primary branch; number of primary branches; NAB, number of primary branches in bearing head; PI, number of internodes on primary branch; SI, number of internodes on stem; SG, stem girth in cm;

SL, stem length in cm; LP, length of longest primary branch in cm; ACS, Albizia coriaria coffee system; COSS, open sun coffee system. Letters indicate mean separation within a system

4.4.2 Effects of coffee system on Photosynthetic Active Radiation and Leaf Area Index of three coffee Clones

The effect of coffee systems on the PAR and LAI for the different clones and seasons is summarized in table 5 below. Results showed that there was no significant ($p \geq 0.05$) interaction between the seasons and system as well as the seasons and the clones for both LAI and PAR. In the dry season, LAI did not vary significantly ($p \geq 0.05$) across the clones for both ACS and COSS, but, the highest LAI for both ACS (2.08) and COSS (2.04) was recorded under clone J24/13/20/4. In the wet season, LAI varied significantly ($p = 0.002757$) across the clones for ACS, with the highest (2.66) being recorded for clone 203/32/2. For COSS, no significant ($p \geq 0.05$) variation of LAI was observed across the coffee clones, though, the highest (1.89) was recorded under clone 203/32/2. On the other hand, the intercepted PAR did not significantly ($p \geq 0.05$) vary across the clones for both systems and seasons. However, the highest PAR for both ACS (75.06) and COSS (71.06) was observed under clone J24/13/20/4 in the dry season, whereas, in the wet season, the highest for both ACS (77.33) and COSS (71.28) was recorded under clone 203/32/2.

Table 5: Effects of system on Photosynthetic Active Radiation and Leaf Area Index of three coffee clones

Clones	LAI				Intercepted PAR (%)			
	Dry season		Wet season		Dry season		Wet season	
	ACS	COSS	ACS	COSS	ACS	COSS	ACS	COSS
203/32/2	1.75±0.27	1.80 ±0.30	2.66±0.13a	1.89±0.15	70.28 ±5.28	66.68±3.69	77.33±2.57	71.28±2.70
J24/13/20/4	2.08±0.27	2.04±0.30	2.14±0.13b	1.77±0.15	75.22 ±5.28	71.06 ±3.69	73.72±2.57	69.12±2.70
MFCT1	1.68±0.27	1.82±0.30	1.96±0.13b	1.74±0.15	63.99±5.28	69.16±3.69	68.40±2.57	67.30±2.70
p value: C	0.54963	0.828	**0.002757 ****	0.75438	0.345	0.707	0.0637	0.5868
cv	39.06	42.16	20.34	28.18	20.0	14.17	12.14	13.52
Mean system	1.84±0.17	1.89±0.17	2.25±0.10a	1.80±0.10b	69.83±2.70	68.97±2.70	73.15±1.94	69.23±1.94
p value: system	0.832		**0.002511 ****		0.823		0.158	
S	0.2522				0.5043			
S*system	0.07545				0.5707			
S*C	0.20743				0.5127			

C, Clone; S, Season; ACS, Albizia coriaria coffee system; COSS, open sun coffee system

4.4.3 Duration (in days) of each coffee fruit phenological stage

Table 6 presents the duration of coffee fruit phenological stages across systems and clones. Overall, coffee grown under the Albizia coriaria system (ACS) required significantly more time from inflorescence to ripening (397.8 days) compared to the open sun system (COSS), which took 350.9 days ($p<0.001$). Among clones, J24/13/20/4 had the longest duration under COSS (354.8 days), while MFCT1 took the most time under ACS (438.8 days); however, differences between clones within each system were not statistically significant ($p\geq0.05$). Two sigmoid growth trends were observed for all the coffee clones. There was a slow growth under inflorescence stage followed by a fast flowering and a slow growth at yellow berries. The second scenario was characterized by slow growth under 10 to 50% berry size, then a fast growth from 60% to 90% and a slow growth under 100% to ripening. Significant differences ($p \leq 0.05$) across clones for both COSS and ACS were observed for inflorescence, yellowing, 10-50% and 100-ripening stages. For inflorescence stage, the highest duration under COSS was recorded on clone MFCT1 (69.0 days) and under ACS, was on clone J24/13/20/4 (89.9 days). During the yellow berries stage, the highest duration under COSS was on clone 203/32/2 (75.0 days) whereas, under ACS, was on clone MFCT1 (68.0 days). In addition, for the 10-50% stage, the highest duration was recorded on clone J24/13/20/4 (106.3 days) and under ACS, was on clone MFCT1 (112.0 days). For the 100-ripening stage, the highest duration was observed on clone 203/32/2 for both COSS (133.1 days) and ACS (149.2 days). On the other hand, significant differences ($p \leq 0.05$) across clones for the flowering and 60-90% stages were observed only under ACS. The highest duration for flowering stage was on clone J24/13/20/4 (5.4 days) and for 60-90 stage, it was on clone MFCT1 (41.9 days). Results further showed that significant differences ($p \leq 0.05$) in the duration of coffee fruit phonological stages between the two systems were observed for only inflorescence, 60-90% and 100-ripening. For all the three stages, the duration was higher for coffee growing under ACS (77.4, 32.5 and 141.9 days, respectively) than under COSS (58.8, 28.1 and 115.4 days, respectively).

Table 6: Differences in the duration of coffee fruit phenological stages across systems and clones at the National Coffee Research Institute, Mukono District, central Uganda

Stage	System	Clone (C)			p value: C	c.v. %	mean System	p value: System	p value: C* System
		MFCT1	**J24/13/20/4**	**203/32/2**					
Inflorescence	COSS	69.0±3.15a	57.5±3.1b	44.8±4.c	**0.0001417 *****	23.18	58.8±2.3	**6.589e-08 *****	**4.674e-05 *****
	ACS	72.0±3.2b	88.9±3.1a	69.9±3.2b	**0.0001513 *****	17.96	77. 4±2.1		
Flowering	COSS	3.3±0.8	3.3±0.5	4.0±0.6	0.8337	63.84	3.5±0.4	0.3920	0.08161
	ACS	3.7±0.6ab	5.4±0.7a	2.6±0.7b	**0.04048 ***	62.82	3.5±0.4		
Yellow berries	COSS	41.6±2.8c	51.1±2.8b	75.0±3.5a	**1.68e-08 *****	22.59	53.2±2.4	0.5900	**2.321e-11 *****
	ACS	68.0±3.2a	44.1±2.8b	51.7±2.8b	**2.627e-05 *****	25.26	54.8±2.2		
10-50%	COSS	81.54±2.8b	106.3±2.8a	70.8±3.5c	**8.74e-10 *****	13.71	88.4±2.7	0.3505	**2.321e-11 *****
	ACS	112.0±6.4a	85.8±3.9b	90.8±4.1b	**0.002858 ****	19.02	92.1±2.7		
60-90%	COSS	28.12±1.6ab	30.8±1.6a	23.9±2.1b	0.05287	25.20	28.1±1.3	**0.02538 *4**	**0.04343 ***
	ACS	41.9±3.6a	33.1±2.1b	28.3±2.2b	**0.006124 ****	29.05	32.5±1.3		
100-Ripening	COSS	116.8±8.9b	105.8±4.0b	133.1±5.1a	**0.0005683 *****	15.000	116.4±2.7	**1.777e-09 *****	0.0843
	ACS	134.0±3.9b	136.7±1.7b	149.2±1.8a	**2.148e-05 *****	5.46	141.9±2.4		
Total	COSS	348.3±13.1	354.7±6.2	348.3±9.3	0.542	7.45	350.9±5.9	**2.966e-06 *****	10.07225
	ACS	438.8±17.4	390.4±9.7	392.1±10.1	0.056	8.76	397.8±6.0		

ACS, Albizia coriaria coffee system; COSS, open sun coffee system

4.4.4 Effects of coffee systems and clone on coffee fruit development

Figure 7 below shows that generally, the coffee berry length, width, thickness and volume increased with phenological stage under the different coffee systems. Generally, coffee berry length was more under COSS except at 50% berry size (Figure 21a). On the other hand, at yellow berry, length was more under MFCT1 under COSS and least under J24/13/20/4 under ACS. As the berry developed, 203/32/2 under COSS had the highest berry length until 100% except for at 50%, where it was more under 203/32/2 under ACS (Figure 21b). Furthermore, COSS had the highest coffee width until 70% berry size (Figure 21c) whereas, MFCT1 under COSS had the highest width until 10%. At 30% J24/13/20/4 had the highest width. Clone 203/32/2 had the least berry width at yellow berries and gradually increased in size surpassing all the varieties at 70% (Figure 21d). Berry thickness was highest under COSS until 50% (Figure 21e). From yellow berries to 30% berry size, J24/13/20/4 under COSS had the highest thickness while 203/32/2 under ACS had the highest thickness at 50% after which MFCT1 under ACS had the highest thickness. J24/13/20/4 under ACS, had the lowest thickness among all clones until 70% berry size where it had the highest (Figure. 21f). In addition, berry volume was more under COSS throughout berry development expect for 50% and 100% berry size (Figure 21g). J24/13/20/4 under COSS had the highest volume until 30% and 203/32/2 under ACS had the highest volume at 50%. MFCT1 under ACS and 203/32/2 under COSS gradually increased in volume surpassing other varieties at 70% berry size (Figure 21h)

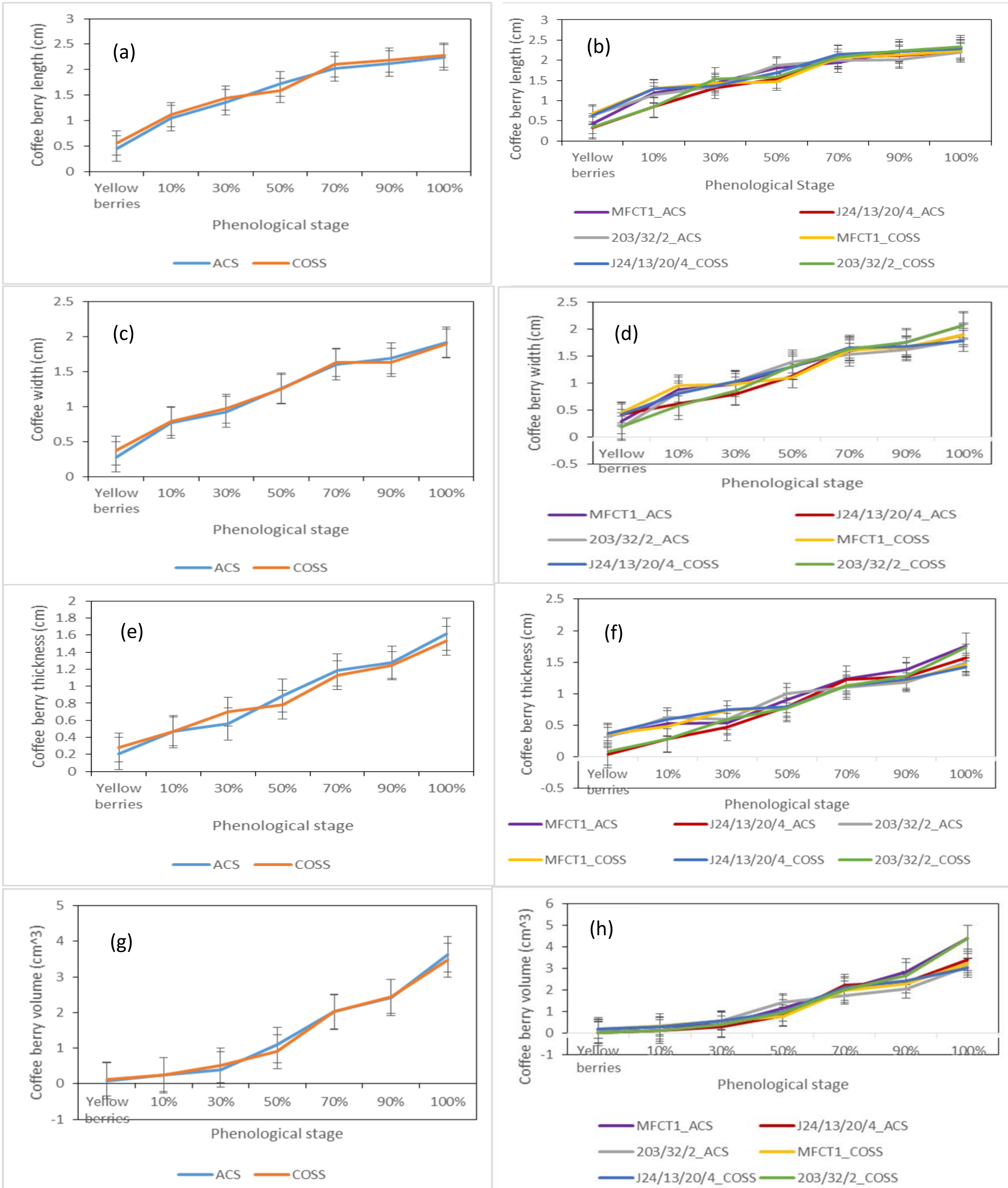


Figure 21: Change in coffee berry length (a, b), width (c, d), thickness (e, f) and volume (g, h) across phenological stages among systems at the National Coffee

Research Institute (NaCORI), Mukono district, central Uganda. *ACS, Albizia coriaria coffee system; COSS, coffee open sun system*

4.4.5 Water use per coffee phenological stage

Figure 22 illustrates water use per coffee phenological stage for each coffee system. The results indicated that water use during berry development was influenced by both the clone and the system. In the *Albizia coriaria* system (ACS), water use differed significantly among clones and stages ($p<0.001$), with clone 203/32/2 consistently using more water than the other clones across all fruit stages ($p\leq0.05$). In ACS, clones 203/32/2 and MFCT1 used the most water at flowering and 30% berry size, and the least at yellow berries and ripening. Clone J24/13/20/4 used the most water at flowering and ripening, and the least at yellow berries, 10%, and 50% berry size. Specifically, at flowering, 203/32/2 used 1.16 l/day and MFCT1 0.48 l/day; at 30% berry size, 203/32/2 used 0.88 l/day and MFCT1 0.36 l/day. At ripening, 203/32/2 used 0.77 l/day and MFCT1 0.17 l/day, while at yellow berries, 203/32/2 used 0.77 l/day and MFCT1 0.26 l/day. Clone J24/13/20/4 used 1.09 l/day at flowering, 0.37 l/day at yellow berries, 0.29 l/day at 10%, 0.30 l/day at 50%, and 0.59 l/day at ripening.

Under the open sun system (COSS), clone J24/13/20/4 generally used the most water, while MFCT1 used the least across phenological stages. J24/13/20/4 used the highest water amounts at flowering (0.94 l/day) and 30% berry size (0.75 l/day).

Clone 203/32/2 used the most water at 30% berry size (1.36 l/day), and MFCT1 at ripening (1.35 l/day). The lowest water use occurred at 10% berry size for 203/32/2 (1.01 l/day), 70% for MFCT1 (0.49 l/day), and 50% for J24/13/20/4 (1.81 l/day).

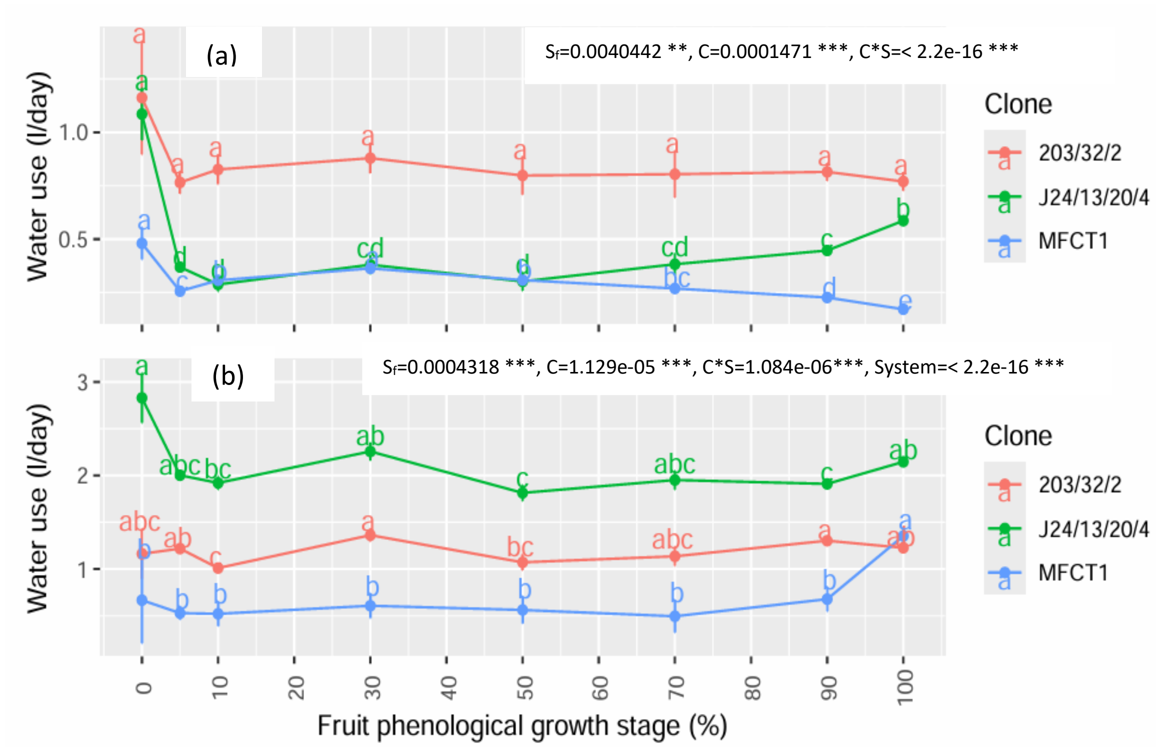


Figure 22: Water use across coffee phenological stages under ACS (a) and COSS (b). Panels a and b represent the two coffee systems. Stage codes: 0, flowering; 5, yellow berries; 100, ripening. Values sharing the same letters within a clone and treatment are not significantly different. S_f, fruit phenological stage; C, clone; ACS, *Albizia coriaria* coffee system; COSS, open sun coffee system.

4.4.6 Assessment of water use across different coffee systems

The change in water flow rate in relation to change in vapour pressure deficit (VPD) and temperature per system is summarized in figure 23 below. The change in water flow rate with the time of the day followed the same trend as the VPD and temperature under both ACS and COSS. Flow rate was generally higher for coffee under COSS as compared to ACS. In the first 8 hours, water flow rate was very low and almost equal under both systems. Thereafter, it increased reaching a peak of 0.065 l/hr-0.064 l/hr between 12-14 hours at temperature of 28.75 ºC-30.67 ºC and VPD of 1.3 kPa-1.67 kPa for COSS and a peak of 0.042 l/hr at 14 hours at temperature of 27.62 ºC and VPD of 1.21 kPa for ACS. It then decreased again.

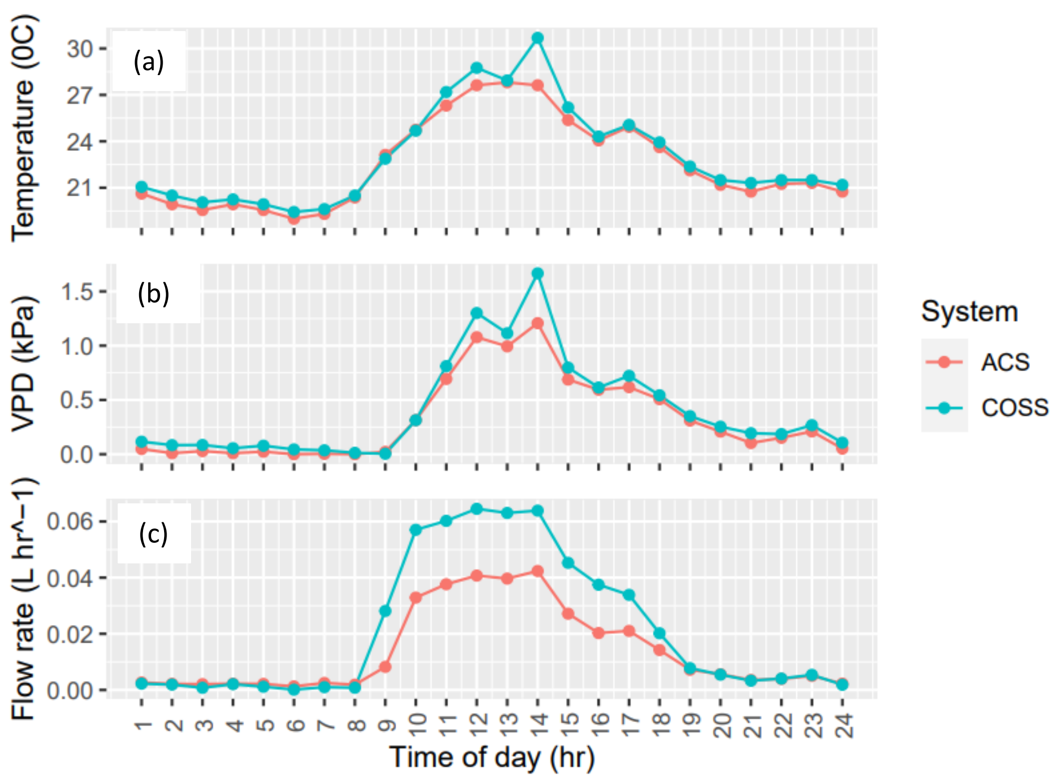


Figure 23: Variation in water flow rate (c) with respect to vapor pressure deficit (VPD) (b) and temperature (a) across systems. Data represent mean values for June

2022 from three coffee plants per system. ACS = coffee *Albizia coriaria* system; COSS = open sun coffee system.

There were significant differences ($p < 0.001$) in coffee water use across seasons, systems, and varieties (Table 7). Coffee grown under the open sun system (COSS) used significantly more water per day (1.43 l/day) than coffee under the *Albizia coriaria* system (ACS), which used 0.62 l/day. Daily water use also varied significantly ($p \leq 0.05$) among coffee varieties within both systems and seasons. In ACS during the dry season, clone J24/13/20/4 had the highest daily water use (1.25 l), while MFCT1 used the least (0.37 l). In the wet season, clone 203/32/2 used the most water per day (0.77 l), and MFCT1 the least (0.27 l). Under COSS, J24/13/20/4 used the most water during the dry season (2.57 l) and wet season (1.88 l), whereas MFCT1 had the lowest usage (0.74 l dry season; 0.67 l wet season).

Water use per unit leaf area varied significantly between systems ($p < 0.001$). The *Albizia coriaria* coffee system (ACS) recorded higher water use per unit leaf area (0.12 mm/day) compared to the open sun system (COSS), which used 0.10 mm/day. Within ACS, clones used more water during the dry season, whereas in COSS, higher water use occurred during the wet season. Differences among clones were significant ($p \leq 0.05$). In ACS, clone J24/13/20/4 had the highest water use per unit leaf area in the dry season (0.35 mm/day) and MFCT1 the lowest (0.15 mm/day), while in the wet season, clones J24/13/20/4 and 203/32/2 used 0.05 mm/day compared to 0.04 mm/day for MFCT1. Under COSS, clone J24/13/20/4 consistently had the highest water use per unit leaf area across both seasons (0.15 mm/day).

No significant difference ($p = 0.05$) was observed in water use per ground area between systems. However, water use per ground area varied significantly ($p \leq 0.05$) among coffee varieties. In ACS, J24/13/20/4 had the highest water use in both the dry (0.25 mm) and wet (0.15 mm) seasons, while MFCT1 used the least (0.15 mm dry; 0.10 mm wet). Similarly, under COSS, J24/13/20/4 had the highest usage (0.29 mm dry; 0.21 mm wet), whereas MFCT1 used the least (0.08 mm dry; 0.07 mm wet).

Figures 24 and 25 show that daily water use in both systems was influenced by rainfall, with COSS consistently using more water throughout the study period. Shade tree water use declined as the rainy season approached, with evidence of reverse water flow observed in late December 2023 and January 2024. Similar trends were recorded in 2022 and 2023, with water use gradually decreasing from July in both years. Gaps in the data correspond to periods of equipment malfunction

Table 7: Water use per coffee plant, transpiration per unit leaf area, and transpiration per unit ground area across systems and varieties

System:	**ACS**		**COSS**	
Season:	**Dry**	**Wet**	**Dry**	**Wet**
Water use per coffee plant (l/day)				
203/32/2	1.11±0.03b	0.77±0.01a	1.39±0.03b	1.10±0.03b
J24/13/20/4	1.25±0.03a	0.37±0.01b	2.57±0.03a	1.88±0.03a
MFCT1	0.37±0.03c	0.27±0.01c	0.74±0.04c	0.67±0.03c
Shade tree	25.59±0.46	18.2±0.64		
p value: C	**< 2.2e-16 *****	**< 2.2e-16 *****	**< 2.2e-16 *****	**< 2.2e-16 *****
cv	29.77	30.95	21.42	29.42
Mean Season	0.91±0.05	0.44±0.04	1.69±0.03	1.24±0.03
Mean system	0.62±0.03		1.43±0.02	
p value: System	**< 2.2e-16 *****			
p value: S	**< 2.2e-16 *****		**< 2.2e-16 *****	
p value: S*C	**< 2.2e-16 *****			
p value System*S	**0.7376**			
C*System	< 2.2e-16 ***			
System Transpiration per unit leaf area (mm/day)				
203/32/2	0.19±0.02b	0.05±0.002a	0.09±0.003b	0.07±0.004b
J24/13/20/4	0.35±0.02a	0.05±0.001a	0.15±0.003a	0.15±0.004a
MFCT1	0.15±0.02b	0.04±0.002b	0.05±0.003c	0.04±0.004c
Shade tree	0.06±0.002	0.04±0.002		
p value: C	**2.199e-09 *****	**0.01157 ***	**< 2.2e-16 *****	**< 2.2e-16 *****
cv	92.72	39.14	30.74	59.96
Mean Season	0.23±0.01a	0.05±0.01b	0.11±0.01	0.09±0.004
Mean system	0.12±0.006		0.10±0.004	

p value: System	5.412e-05 ***			
p value: S	**< 2.2e-16 *****		0.0001634 ***	
p value: S*C	1.280e-07 ***			
p value System*S	**< 2.2e-16 *****			
C*System	0.210063			
System Transpiration per ground area (mm/day)				
203/32/2	0.23±0.005b	0.12±0.004b	0.15±0.003b	0.12±0.003b
J24/13/20/4	0.25±0.005a	0.15±0.004a	0.29±0.003a	0.21±0.002a
MFCT1	0.15±0.005c	0.10±0.004c	0.08±0.004c	0.07±0.003c
Shade tree	0.11±0.002	0.08±0.003		
p value: C	**< 2.2e-16 *****	**< 2.2e-16 *****	**< 2.2e-16 *****	**< 2.2e-16 *****
cv	20.79	36.61	21.42	29.42
Mean Season	0.21±0.01	0.12±0.004	0.19±0.003	0.14±0.003
Mean system	0.16±0.004		0.16±0.003	
p value: System				0.392
p value: S	**< 2.2e-16 *****		**< 2.2e-16 *****	
p value: S*C	**< 2.2e-16 *****			
p value System*S	3.045e-08 ***			
C*System	< 2.2e-16 ***			

ACS, Albizia coriaria coffee system; COSS, open sun coffee system; C, Clone, S, season

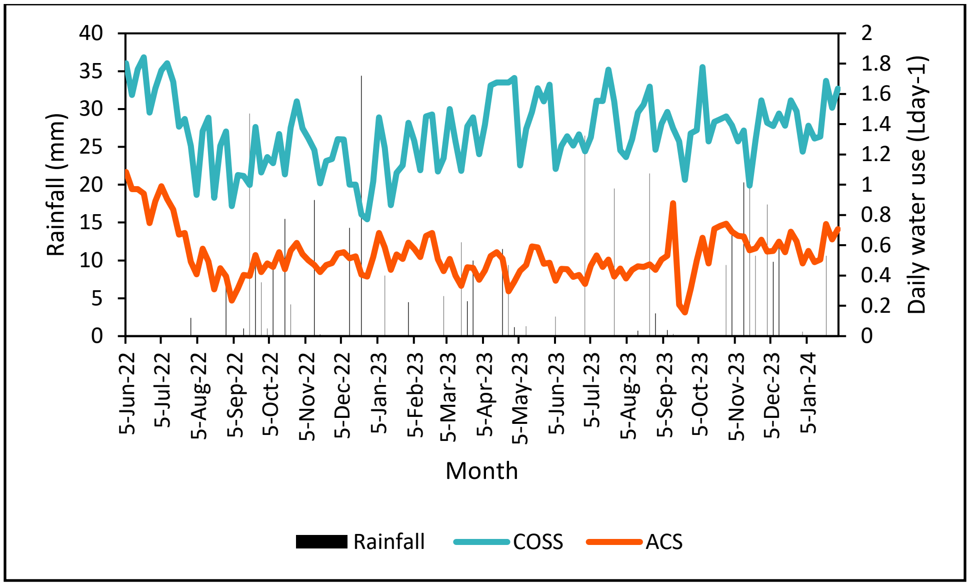


Figure 24: Seasonal variation in daily mean coffee water use and rainfall. Daily water use values represent the average of coffee plants per system over one year. ACS, *Albizia coriaria* coffee system; COSS, open sun coffee system.

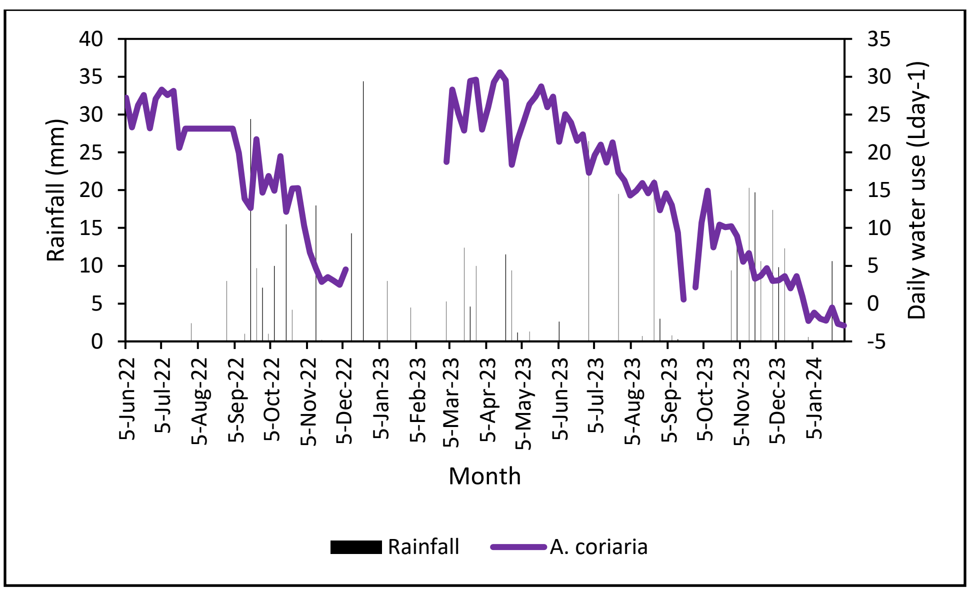


Figure 25: Daily variation in water use by *Albizia coriaria* and corresponding rainfall.

4.4.7 Relationship between water use and coffee berry parameters

Figure 26 illustrates the relationship between water use efficiency (WUE) and coffee berry characteristics. Significant positive correlations were observed between water use and dry cherry weight ($R^2 = 0.68$, $p = 0.055$), cherry width and cherry thickness ($R^2 = 0.79$, $p < 0.05$), cherry volume and cherry thickness ($R^2 = 0.93$, $p < 0.01$), and cherry volume and cherry width ($R^2 = 0.94$, $p < 0.01$).

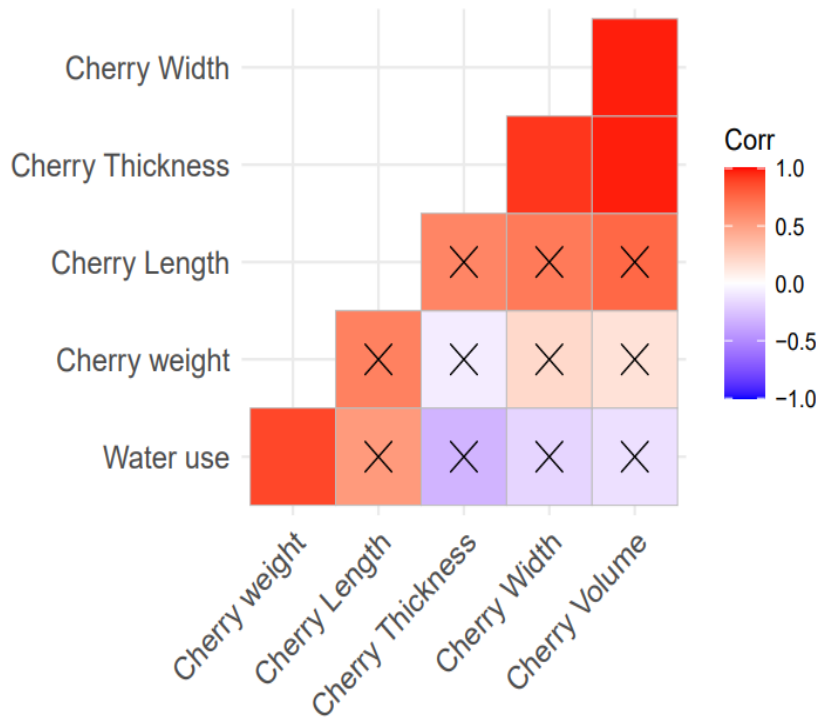


Figure 26: Correlation matrix between water use and coffee berry parameters

Corr; correlation coefficient key; X, nonsignificant

4.4.8 Relationship between water use and climatic factors

There was a significant positive linear relationship between potential evaporation and water use (R^2=0.22, p<0.001) (Figure 27a), maximum temperature and water use (R^2=0.024, p<0.001) (Figure 27b) and water use and minimum temperature

(R^2=0.013, p<0.001) (Figure 27c). There was also a linear negative relationship between water use and rainfall (R^2=0.022, p<0.001) (Figure 27d), water use and relative humidity at 15 hrs R^2=0.046, p<0.001) (Figure 27e) and water use and relative humidity at 9hrs (R^2=0.029, p<0.001) (Figure 27f).

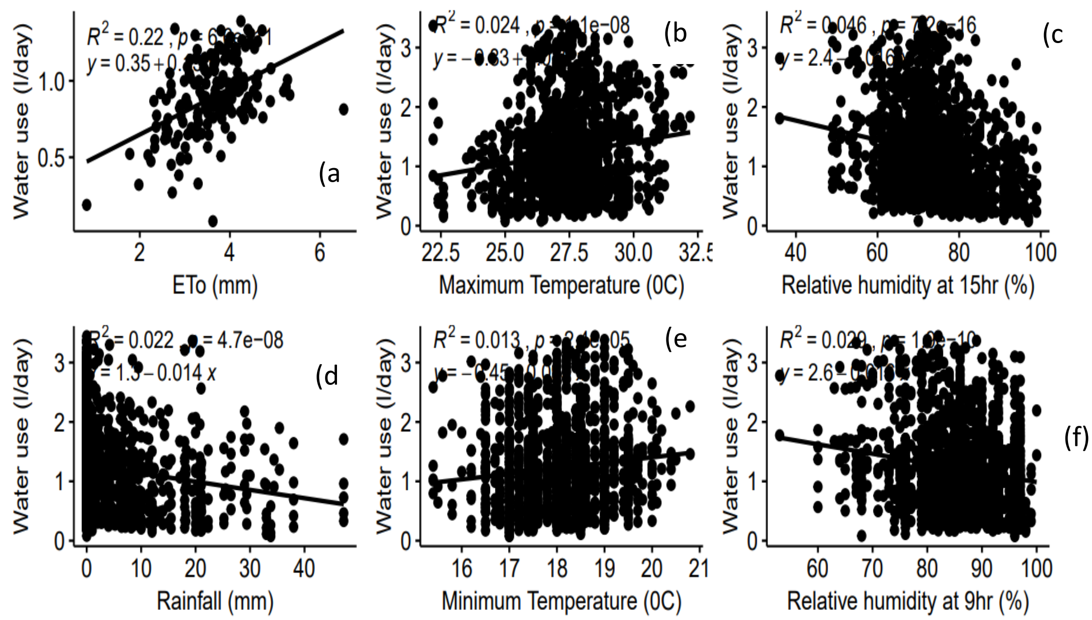


Figure 27: Linear relationship between water use and climatic factors. The data points represent both water use for all varieties and systems

4.4.9 Water use efficiency per coffee fruit phenological stage per system

There was no significant difference in water use efficiency (WUE) per fruit phenological stage per system (Table 4.7). Overall, ACS was more water use efficient (1054 cm^3/mm) than COSS (974 cm^3/mm). The same trend was observed for the yellow berries and 60-90% stages where WUE was higher under ACS (434.9 and 2472 cm^3/mm respectively) than COSS (273.5 and 1903 cm^3/mm respectively).

Contrary, COSS was more water use efficient for 10-50% and 100-ripening stages (1411 and 309 cm^3/mm respectively) than ACS (118 and 120.6 cm^3/mm, respectively). Furthermore, linear regression analysis results showed that WUE increases significantly (R^2=0.36, $p<0.01$) with the change in berry volume of the whole coffee plant (Figure 28).

Table 8: Water use efficiency of coffee fruit phenological stages per coffee plant

Stage	System	Total Change in size (cm^3)	Total water used (mm)	WUE (cm^3/mm)
Yellow berries	ACS	985±924.7	1.94±2.23	434.9±332.9
	COSS	4129±3284	9.15±1.82	273.5±271.9
	p value	0.588	0.213	0.6555
	cv	198.08	80.06	139.28
10-50%	ACS	4036±3074	2.07±2.07	1188±655.1
	COSS	9973±3952	5.87±1.69	1411±534.9
	p value	0.412	0.374	0.809
	cv	90.1	61.67	70.1
60-90%	ACS	4237±2125	2.88±1.46	2472±1356
	COSS	13880±7839	8.31±3.16	1903±1356
	p value	0.493	0.357	0.767
	cv	135.47	89.18	90.03
100-ripening	ACS	577±504.5	5.99±2.09	120.6±72.37
	COSS	2371±1668	3.56±2.56	309±219.3
	p value	0.545	0.515	0.625
	cv	174.66	72.11	162.55
Mean	ACS	2459±2754	2.863±1.55	1054±434.8
	COSS	7588±2248	7.327±1.27	974±355.1
	p value	**0.019***	0.166	0.889
	cv	68.29	140.67	122.27

ACS, Albizia coriaria coffee system; COSS, open sun coffee system; WUE, water use efficiency

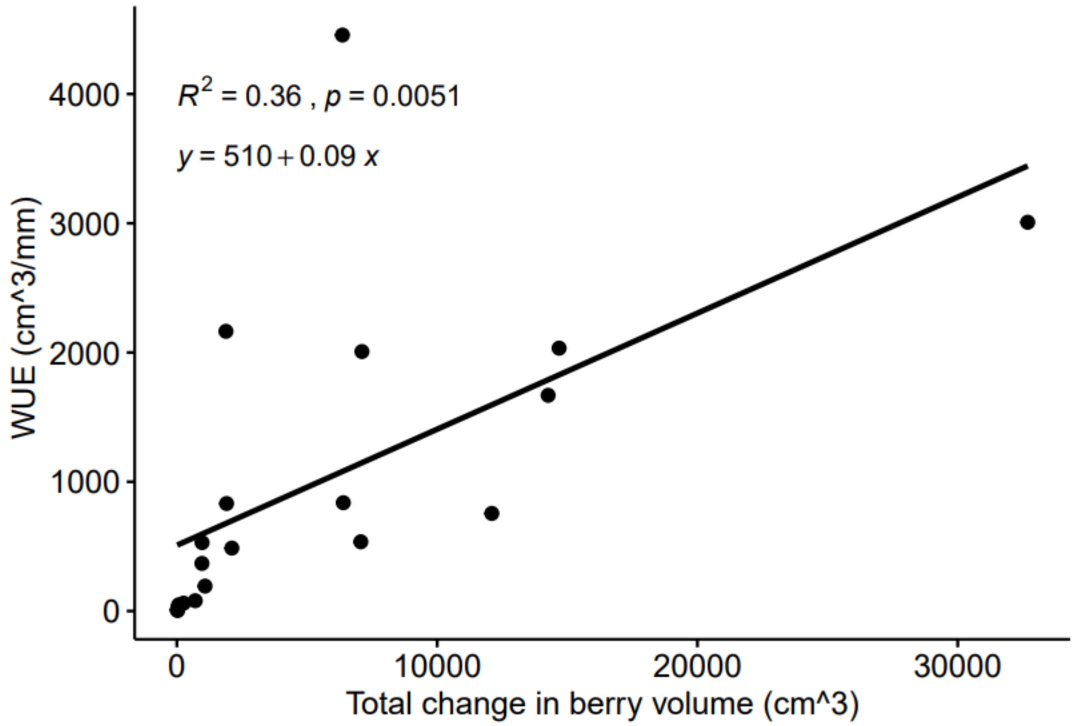


Figure 28: Relationship between water use efficiency (WUE) and change in berry volume of the whole coffee plant

4.4.10 Dry berry weight (g) per clone per system

Table 9 below summarizes the coffee dry weights by system by varieties. Overall, the dry weight of the coffee growing under COSS (0.48g) was significantly (p=0.0008883) higher than for the coffee growing under ACS. There was a significant difference (p<0.001) in dry berry weight of the varieties across systems except for clone MFCT1. For all the varieties, berries harvested from coffee growing under COSS were heavier than under ACS.

Table 9: Dry berry weight per system in grams

System	203/32/2	J24/13/20/4	MFCT1	Mean
COSS	0.50±0.03a	0.45±0.02a	0.48±0.06	0.48±0.02a
ACS	0.29±0.03b	0.33±0.02b	0.46±0.10	0.35±0.03b
p value: System	**5.317e-06 *****	**3.743e-05 *****	0.69833	**0.0008883 *****
cv	28.75	19.62	55.79	38.56
Mean C	0.41±0.03ab	0.39±0.03b	0.48±0.03a	
p value C	**0.0349417 ***			
P value C*System	0.1111339			

ACS, Albizia coriaria coffee system; COSS, open sun coffee system; C, Clone

4.4.11 Coffee plant parameters as water use predictors

Coffee water use models (l/day/coffee stem) developed based on coffee plant parameters are shown in Table 10. Results showed that models containing the length of the longest primary (LP) emerged superior. The best model for predicting water use using coffee plant parameters was therefore, model 10 with a coefficient of determination (R^2) of 0.83.

Table 10: Models for predicting coffee water use based on coffee growth parameters

Model	Estimate	se	R^2	*p* value
Model 1: $W=a_1+b_1SG+e$				
Intercept, a_1	-0.66	0.27	0.46	0.002
Slope, b_1	0.19	0.05		
Model 2: $W=a_2+b_2SG+b_3SL+e$				
Intercept, a_2	-1.01	0.40	0.48	0.004

Slope, b_2	0.002	0.07		
Slope, b_3	0.13	0.002		
Model 3: $W=a_3+b_4SL+b_5CH+e$				
Intercept, a_3	-0.81	0.39	0.58	0.002
Slope, b_4	0.003	0.002		
Slope, b_5	0.003	0.001		
Model 4: $W=a_4+b_6SL+b_7PI+e$				
Intercept, a_4	-0.90	0.39	0.53	0.002
Slope, b_6	0.003	0.002		
Slope, b_7	0.02	0.006		
Model 5: $W=a_5+b_8LP+e$				
Intercept, a_5	-0.371	0.10	0.80	0.000
Slope, b_8	0.006	0.001		
Model 6: $W=a_6+b_9PI+b_{10}LP+e$				
Intercept, a_6	-0.43	0.11	0.81	0.000
Slope, b_9	0.01	0.001		
Slope, b_{10}	0.01	0.005		
Model 7: $W=a_7+b_{11}CH+b_{12}SG+b_{13}L+b_{14}LP+b_{15}PI+e$				
Intercept, a_7	-0.402	0.163	0.83	0.000
Slope, b_{11}	0.000	0.001		
Slope, b_{12}	-0.023	0.047		
Slope, b_{13}	0.000	0.000		
Slope, b_{14}	0.005	0.001		
Slope, b_{15}	0.007	0.005		
Model 8: $W=a_8+b_{16}SL+b_{17}CH+B_{18}LP+e$				

Intercept, a_8	-0.52	0.001	0.79	0.000
Slope, b_{16}	0.001	0.001		
Slope, b_{17}	0.001	0.001		
Slope, b_{18}	0.005	0.001		
Model 9: $W=a_9+b_{19}L+e$				
Intercept, a_9	0.043	0.12	0.34	0.008
Slope, b_{19}	0.001	0.000		
Model 10: $W=a_{10}+b_{20}LP+b_{21}L+e$				
Intercept, a_{10}	-0.4	0.09	0.83	0.000
Slope, b_{20}	0.000	0.000		
Slope, b_{21}	0.005	0.001		
Model 11: $W=a_{11}+b_{22}CH+b_{23}L+e$				
Intercept, a_{11}	-0.14	0.13	0.49	0.004
Slope, b_{22}	0.000	0.000		
Slope, b_{23}	0.003	0.001		
Model 12: $W=a_{12}+b_{24}SL+b_{25}CH+b_{26}S+b_{27}LP+e$				
Intercept, a_{12}	-0.53	0.287	0.77	0.000
Slope, b_{24}	0.001	0.001		
Slope, b_{25}	0.001	0.001		
Slope, b_{26}	0.001	0.001		
Slope, b_{27}	0.005	0.001		
Model 13: $W=a_{13}+b_{28}CH+b_{29}SG+b_{30}SL+b_{31}L+b_{32}LP+e$				
Intercept, a_{13}	-0.59	0.273	0.80	0.000
Slope, b_{28}	0.000	0.001		
Slope, b_{29}	-0.006	0.049		

Slope, b_{30}	0.001	0.001		
Slope, b_{31}	0.000	0.000		
Slope, b_{32}	0.005	0.001		
Model 14: $W=a_{14}+b_{33}SL +e$				
Intercept, a_{14}	-1.04	0.44	0.37	0.006
Slope, b_{33}	0.005	0.002		
Model 15: $W=a_{15}+b_{34}CH+e$				
Intercept, a_{15}	-0.1	0.134	0.46	0.002
Slope, b_{34}	0.004	0.001		
Model 16: $W=a_{16}+b_{35}PI+e$				
Intercept, a_{16}	-0.21	0.165	0.44	0.002
Slope, b_{35}	0.022	0.006		

a, intercept; b, slope; e, random error; R^2, coefficient of determination; W, Water use per stem; SG, stem girth; CH, canopy height; L, total number of leaves on a plant; LP, length of the longest primary; PI, number of primary internodes; SL, stem length

4.5 Discussion

4.5.1 Effect of system on Photosynthetic Active Radiation, Leaf Area Index, coffee growth and yield

Results of the study indicated no significant differences in coffee growth and yield between the systems, likely due to minimal variation in light intensity among them, as previously noted by da Silva Neto *et al.* (2018). However, the ACS system produced slightly more berries per cluster and a higher number of clusters compared to COSS. This aligns with findings from Durand-Bessart *et al.* (2020) and Diriba *et al*. (2021), who reported that shade can influence the average number of fruits per cluster. While coffee grown under full sun may show initially high production, yields often decline over time (Delarozza *et al.,* 2017). Shade can positively impact yield if the canopy coverage ranges between 15% and 54%; beyond this, it may negatively affect coffee yield (Gao, 2018). Yet, Long *et al.* (2015) observed no difference in fruit set between shaded and unshaded sites. Reduced berries per cluster may result from competition for water and nutrients between shade trees and coffee shrubs (Durand-Bessart *et al.,* 2020), which could explain why COSS had relatively more primaries in the bearing head than ACS.

Leaf area index (LAI) and photosynthetically active radiation (PAR) also varied between coffee systems and clones, consistent with previous studies (Ricci *et al.,* 2013; Sarmiento-Soler *et al.*, 2019). Higher LAI under shade indicates greater potential for CO_2 assimilation and dry matter production compared to unshaded plants (McNaughton & Jarvis, 1983; Bote & Struik, 2011). Shaded leaves typically have increased leaf area per unit mass due to lower photon flux density, which is an adaptive strategy to capture maximum light under low-intensity conditions (Assefa & Gobena, 2009). Conversely, sun-exposed leaves are smaller, as their mesophyll structure enhances air contact, facilitating latent heat loss and efficient foliar cooling (Rubio-de-Casas *et al.,* 2007).

Even when LAI was high during the wet season, low PAR values were recorded due to reduced sunlight intensity. In ACS, light transmittance is influenced by the structure and thickness of shade tree branches and leaves, as well as crown density and width (Suryanto & Tohari, 2005). Solar radiation intercepted by coffee plants affects tissue development, photosynthesis, storage of photo-assimilates, flowering, and the allocation of energy required for flowering, fruit set, and yield (Lopez *et al.,* 2021).

4.5.2 Impact of system on coffee fruit developmental stages

Understanding the phenology of coffee fruits is essential for effective harvest planning (Damatta *et al.,* 2007). The total number of days per phenological stage was generally similar across systems and varieties. All coffee varieties exhibited two sigmoid growth curves, as also reported by Fernandes *et al.* (2017) and Salazar *et al.* (2019). The first sigmoid extended from inflorescence emergence to yellow berries, characterized by a long inflorescence stage, rapid flowering, and an extended yellow berries stage. The second sigmoid, from 10-50% berry size to ripening, showed a longer 10-50% phase, faster 60-90% growth, and a prolonged 100% to ripening phase. This differs from Salazar *et al*. (2019), who reported that the first sigmoid ends at flowering and the second continues to 100% berry size. ACS plants spent more days in the inflorescence stage (79.75 days) compared to COSS (58.79 days), consistent with observations by Kimenia and Njoroge (1988) and Severino and De Oliveira (1999). Significant differences were also noted between varieties, as reported by Salazar *et al*. (2019), with Robusta taking longer in the inflorescence stage than Arabica. Variation in this stage may be influenced by soil moisture affecting floral bud development (DaMatta *et al.,* 2007).

The duration of the yellow berries stage was not significantly different between systems but varied among varieties within a system. Under COSS, clone 203/32/2 had the longest duration (75 days) while MFCT1 had the shortest (41.6 days). Under ACS, clone 203/32/2 again took longer (51.74 days) compared to clone J24/13/20/4 (44.09 days). These durations align with the 42-70 days reported by DaMatta *et al*. (2007) but can vary with climate (Sureshkumar *et al.,* 2013). In Robusta, the yellow berries stage may last two to three months until soil moisture is adequate for pinhead development.

No significant differences were observed in the 10-50% berry size stage between systems, though significant differences existed among varieties. Clone J24/13/20/4 took the longest under COSS (106.27 days) and 203/32/2 the longest under ACS (90.75 days).

Similarly, the 60–90% stage showed no significant differences, with rapid cell expansion and accumulation of organic compounds characterizing this growth (De Castro & Marraccini, 2006; Salazar *et al.,* 2019). Coffee under ACS required significantly more days (142.80) to reach ripening from 100% berry size than under COSS (116.43 days), a delay attributed to lower average temperatures in shaded systems (DaMatta *et al.,* 2007). Clone 203/32/2 took the longest under both systems (COSS: 133.14 days; ACS: 149.21 days). Comparatively, Salazar *et al.* (2019) reported ripening durations of 57 days for Robusta and 88 days for Arabica. Differences in ripening duration in this study may reflect that the measurement included the period from 100% berry size to full ripening. Robusta coffee generally requires 9-11 months (270-330 days) from flowering to fruit maturity (Dinh *et al.,* 2022). In this study, ACS averaged 390.4-438.8 days from inflorescence to ripening, while COSS averaged 348.3-354.7 days, consistent with previous reports of delayed maturation under shade (Kimenia & Njoroge, 1988; Severino & Oliveira 1999; Ronchi *et al.,* 2007). Prolonged maturation under shade improves cup quality and market value (DaMatta *et al.,* 2017).

Varietal differences were evident, with clone J24/13/20/4 taking longer under COSS and MFCT1 longer under ACS, supporting Dinh *et al.* (2022) and Pohlan and Janssens (2010), who noted that the duration from flowering to ripening varies with variety and site. Shading modifies the microclimate, particularly temperature, and, due to genetic plasticity, affects coffee anatomy, physiology, floral induction, differentiation, and anthesis (Lopez *et al.,* 2021).

Berry growth followed a linear increase in length and width up to 50% berry size, after which expansion slowed, while thickness and volume increased gradually, accelerating at ripening. These growth patterns were consistent across varieties and systems. Berry dimensions were initially larger under COSS up to 30% size. Rapid increases in length, width, thickness, and volume from 10-50% were driven by size and fresh mass gains (DaMatta *et al.,* 2007), consistent with findings from Karnataka, India, where fruit size increases linearly up to 90 days in C. arabica and 150 days in *C. canephora* (Sureshkumar *et al.,* 2013). Differences among varieties persisted throughout berry development except around 70% growth. From 70% to ripening, berry volume increased by 44% under ACS and 41% under COSS, reflecting dry mass accumulation (DaMatta *et al.,* 2007). During ripening, pericarp size and dry mass increase, influenced by soil moisture (Sureshkumar *et al.*, 2013). Varietal differences in final berry volume were observed, with MFCT1 having the largest berries under ACS and 203/32/2 under COSS (Sualeh & Dawid, 2014).

4.5.3 Assessment of water use across different coffee systems

Water use per coffee phenological stage was influenced by both clone and system, aligning with the observations of Carr (2001). In the *Albizia coriaria* system (ACS), clone 203/32/2 exhibited higher water consumption, whereas under the open sun system (COSS), clone J24/13/20/4 used more water during berry development. Similarly, Sarzynski *et al.* (2021) reported variation in water use among Coffea arabica hybrids grown in agroforestry systems. Righi *et al.* (2008) also noted that shaded coffee plants typically display lower water use efficiency (WUE) compared to monocropped plants. Within ACS, flowering and the 30% berry stage recorded the highest water use, while yellow berries and ripening stages used the least, except for clone J24/13/20/4. Under COSS, clone J24/13/20/4 consumed the most water at flowering and 30% berry size, clone 203/32/2 at 30% berry size, and MFCT1 at ripening. This aligns with Dang *et al.* (2014), who noted that flowering requires the greatest water. Minimal water use occurred at 10% berry size for 203/32/2, 70% for MFCT1, and 50% for J24/13/20/4, as yellow berries remain dormant and have low water demands (Dinh *et al.,* 2022). As berries expand, water requirements rise (Carr, 2001; Dinh *et al.,* 2022), emphasizing the need for this stage to coincide with the wet season (DaMatta *et al*., 2007). Petek *et al*. (2009) also highlighted that water availability influences ripening, with low water potentially accelerating the process. Based on growth parameters, clone 203/32/2 efficiently used water for berry development, producing the highest number of berries (11,713) while consuming less water than J24/13/20/4 (5,046 berries). Under COSS, MFCT1 had the highest berry count and lowest water use, demonstrating efficient water use. Studies of water use in agroforestry systems are important for understanding shade tree–understory crop interactions (Sarmiento-Soler *et al*., 2019).

Daily water use per coffee tree was higher under the open sun system (COSS) compared to the ACS across both seasons and all clones. The greater water use in unshaded coffee is likely due to the absence of competition for soil water and increased exposure to radiation (Sarmiento-Soler *et al.,* 2019), while the reduced water use under ACS is associated with the cooler microclimate provided by shade trees (Sarmiento-Soler *et al.,* 2019). Daily water use by coffee trees ranged from 0.37 to 2.57 l/day, which is similar to values reported for Arabica coffee 0.7-2.2 l/day (Buyinza *et al.,* 2023) and 0.9–1.6 l/day (Sarmiento-Soler *et al.,* 2019) with differences likely reflecting varietal variation.

Transpiration per leaf and per ground area was generally higher under ACS, except during the wet season for clone J24/13/20/4. Clone J24/13/20/4 consistently used more water across systems and seasons, whereas MFCT1 used the least. This may relate to tree size, as J24/13/20/4 had a higher DBH (3.6-3.8 cm) than MFCT1 (2.1-3.2 cm), and tree water use is proportional to size (Phillips *et al.,* 2003). MFCT1 also had a lower LAI than other clones in both seasons. Despite LAI variations, J24/13/20/4 maintained high water use, consistent with Tausend et al. (2000). High transpiration per leaf area under ACS could result from higher LAI and contributions from shade trees (Sarmiento-Soler *et al.,* 2019), whereas previous studies reported higher transpiration under COSS due to higher LAI (Siles, 2007). Low transpiration under COSS during the dry season may reflect higher leaf temperatures and vapor pressure deficit (VPD), which strongly influence stomatal conductance (Gates, 1968; Hernandez *et al.,* 1989; McAdam & Brodribb, 2015; Van Kanten & Vaast, 2015). Transpiration per leaf area in this study was lower than previously reported (Padovan *et al.,* 2018; Sarmiento-Soler *et al.,* 2019), and per ground area, no difference was found between ACS and COSS, potentially due to the lower coffee density (1,111 trees/ha versus 1,875-4,000 trees/ha in other studies). In ACS, most transpiration originated from coffee plants rather than shade trees, reflecting their higher density. Coffee contributed 53.1% and 55.6% of water use per ground area in the dry and wet seasons, respectively (Padovan *et al.,* 2018). MFCT1's low water use suggests it is suitable for drought-prone areas. During the wet season, COSS used more water per leaf area than ACS, contrary to Odeny (2016).

Mean temperature and VPD were higher under COSS, consistent with Sarmiento-Soler *et al.* (2019) and Cassamo *et al.* (2023). Increased temperature elevates VPD, enhancing water flow, while shade reduces both, leading to lower water use and higher leaf water potential (Rahman *et al.,* 2018). Lower VPD increases stomatal aperture, facilitating CO_2 diffusion (Bote & Struik, 2011). Water flow reduction under COSS at 1.67 kPa aligns with Padovan *et al.* (2018), suggesting a mechanism to reduce internal water stress. Flow rates peaked between 12-14 hrs due to increased irradiance and VPD (Carelli *et al.,* 2000) and decreased after 19 hrs as sunlight declined and stomata closed.

Water use decreased with rainfall and increased during dry periods, consistent with Sarmiento-Soler *et al.* (2019). Higher transpiration during the dry season results from increased evaporative demand and exploitation of soil water reserves (O'Grady *et al.,* 1999). Between September and October 2023, rainfall was <40 mm, but COSS coffee used ~54 mm, relying on stored soil moisture. *A. coriaria* exhibited negative water flow in late December 2023 and January 2024, coinciding with leaf shedding in the dry season, consistent with Buyinza *et al.* (2023). Reverse water flow occurs under low soil water potential, driven by water movement toward areas of lower potential, a process known as hydraulic redistribution (Smith *et al.,* 1999; Hafner *et al*., 2017).

4.5.4 Impact of coffee system on water use efficiency at each fruit phenological stage

Water use efficiency (WUE) varied according to the coffee fruit's phenological stage (Kouadio et al., 2021). At the yellow berry stage, ACS exhibited higher WUE, while at the 10-50% stage, COSS was more efficient. At 60-90%, ACS again showed greater efficiency, and from 100% to ripening, COSS was more efficient. Overall, ACS demonstrated higher water use efficiency (1054 cm^3/mm) compared to COSS (974 cm^3/mm). Padovan et al. (2018) observed that agroforestry systems are generally more efficient in water use than open-sun coffee systems, as a larger share of rainfall is utilized in transpiration rather than lost through soil evaporation. This contrasts with findings by Righi et al. (2008) and Getachew et al. (2022), who reported that shaded coffee had lower WUE than monocropped systems.

4.5.5 Effect of coffee system on coffee bean weight

Generally, coffee under COSS had heavier beans as compared to ACS, agreeing with research studies by Campanha *et al.* (2004). This is in contrast with Bote and Struik (2011), Etafa (2022) and Mengistu (2023), who found out that coffee weight was more under the tree canopy than in open fields. But also, Diriba *et al.* (2021) and Ehrenbergerová *et al.* (2021), found non-significant difference in coffee weight between shade and unshaded systems.

Nevertheless, shade effects on coffee depend on the tree species used and the physical features of the site (Sarmiento-Soler *et al.,* 2020). Higher water use translated into increased berry dry weight among systems with the COSS having heavier beans compared to ACS. This is confirmed by the high correlation between cherry dry weight and water use (r=0.87). However, there was no defined varietal effect on berry weight and water use. Much as J24/13/20/4 used the most water, it had less bean weight under COSS but, MFCT1 had the heaviest beans under ACS and had the least water use.

Even though under COSS, MFCT1 used the least amount of water both as a whole plant, during the fruit phenological stages, 203/32/2 had heavier beans. With the results of our study, we can explain why many researches show a heavy bean under open conditions and others a decrease. This large variation of results is a function of the type of Robusta coffee clone and the level of shade. Therefore, the need for research to combine the two so as to break the paradigm existing that shading in coffee Robusta is synonymous of less yield.

CHAPTER FIVE: EFFECT OF SELECTED SOIL WATER CONSERVATION PRACTICES ON SOIL-WATER RELATIONS IN ROBUSTA COFFEE AGRO-SYSTEMS

5.1 Abstract

Uganda is the 7th largest producer of coffee in the whole world. Coffee is not only of great importance to the country but also to the small holder farmers who earn twice a year from it. Despite its importance its production is still below average of 2.2t ha^{-1} because of poor management, low soil fertility, pests and diseases and now climate change. Climate change characterized by erratic rains and droughts affects soil water recharge which in turn affects plant water use. Adoption of suitable soil water conservation practices (SMCPs) is proving to be an effective means in mitigation of water stress induced by climate change. However, they also influence soil water relations differently. Therefore this study determined the effect of SMCPs on soil water relations. The study was conducted at National Coffee Research Institute (NaCORI) and Kaweri Coffee Plantation Limited (KCPL). Four systems where studied; open sun coffee (COSS), coffee cover crop (CCS) coffee mulch (CMS), and coffee-*Albizia coriaria* (ACS). An incompletely randomized block design was used at NaCORI while at KCPL, we used a completely randomized block design. Soil moisture, coffee growth and yield data was collected. Coffee rootzone actual crop evapotranspiration (ETa) was calculated using the water balance equation. Results showed that there was no significant ($p \geq 0.05$) in ETa across the SMCPs at NaCORI but significant ($p<0.001$) between dry and wet season. However, the highest ETa was recorded under CMS (6.34 mm) and the lowest under ACS (6.19 mm) in the wet season while in the dry season, the highest ETa (1.87 mm) was observed under CCS and the lowest under CMS (1.73 mm). Also at KCPL, there was no significant differences in ETa among SMCPs in both dry and wet season. CMS had a high ETa during the wet season (7.27 mm) while in the dry season ETa was high under ACS (1.19 mm). CMS increased soil moisture significantly ($p<0.05$) by 45.32% at NaCORI followed by CCS at 13.68%; while ACS decreased soil moisture by 29.32% within the coffee root zone. At KCPL, there was no significant difference in the efficiency of SMCPs in conserving soil moisture though CMS increased soil moisture by 19.95% followed by ACS (18.73%) and least was at CCS (17.38%). CMS influenced the soil water relations better compared to other SMCPs at NaCORI. At KCPL, CMS, ACS and CCS improved soil moisture conservation compared to COSS. This highlights that the effect of SMCPs on soil water relations is site specific. Therefore the need for site specific studies when recommending SMCPs that farmers can adopt as they adapt to the effects of climate change.

5.2 Introduction

Climate change has caused fluctuations in coffee yields in Uganda (Jassogne *et al.,* 2013). Currently, the average clean (green) Robusta coffee yield is around 0.6 t ha^{-1}, which is nearly four times lower than the attainable yield of 2.2 t ha^{-1} (Kobusinge *et al.,* 2023). Climate change manifests through erratic rainfall, higher temperatures, and droughts, among other factors (Gokavi & Kishor, 2020). Low and irregular precipitation alters soil moisture recharge patterns and limits water uptake by plants (Reynolds *et al.,* 2004; Oki & Kanae, 2006). Atmospheric drought conditions can further increase the evaporative demand, raising transpiration and causing water loss from plants, potentially leading to wilting. Even a temperature rise of less than 1°C can increase transpiration rates by up to 30% in some crops (Msuya, 2013), with forecasts predicting temperature increases of around 2°C.

Additionally, coffee cultivation has expanded into areas less suitable for its growth, negatively impacting productivity (DaMatta & Ramalho, 2006). This shift is driven by land-use changes, higher temperatures, and more frequent water deficits (Easterling *et al.,* 2000; IPCC, 2007), putting pressure on irrigation systems that rely on overexploited aquifers with slower recharge rates than withdrawals (Kumar & Bhople, 2017). Coffee, a key income source for many smallholder farmers in Uganda (NCP, 2013), is now increasingly grown in marginal areas where meeting water requirements is challenging (Jassogne *et al.,* 2013). Even in traditional production zones, rainfall has become unpredictable, exposing coffee plants to frequent and severe droughts. Coffee is particularly vulnerable as a water-intensive perennial crop that remains in the field year-round (Thi & Chaovanapoonphol, 2014). Most Ugandan coffee farmers rely solely on rainfall and lack alternative coping mechanisms (MAAIF, 2010).

Adoption of soil water conservation practices has proven effective in mitigating water stress caused by climate change (Kumar & Bhople, 2017), although such practices may compete with coffee plants for available soil moisture. Measuring soil moisture and water loss through evaporation and transpiration is critical for optimizing soil water balance, planning sowing, fertilizer application, and irrigation under varying climatic and management conditions (Kumar & Bhople, 2017). This approach minimizes soil evaporation and maximizes water availability for plant roots. While global studies have assessed climate change impacts on soil water (e.g., Berg *et al.,* 2017; Eitzinger *et al.,* 2003), less attention has been given to local variations in soil water patterns driven by soil and climate variability. Long-term soil moisture patterns are influenced by interactions between climate and soil water retention capacity (Salley *et al.,* 2016), highlighting the need for region-specific management strategies.

Therefore, this study aimed to evaluate the effects of soil water conservation practices on soil water relations in Robusta coffee systems. The findings will provide insights into coffee systems that are more resilient to climate change in terms of water conservation, supporting stakeholders in adopting adaptive strategies that enhance yields, farmer incomes, and overall livelihoods

5.3 Materials and methods

5.3.1 Study area

This study was conducted at two locations, National Coffee Research Institute (NaCORI) and Kaweri Coffee Plantation Limited (KCPL). NaCORI served as the main study site, while KCPL was used to validate selected results. Both sites were also included for comparison to assess whether soil moisture conservation practices (SMCPs) influence soil water relations similarly across different locations.

NaCORI is located at Kituza village, Ssaayi parish, Ntenjeru-Kisoga Town council, Mukono district of the Lake Victoria crescent agroecological zone (Figure 29). The district is situated 35 kilometers from the eastern section of Kampala, the capital city of Uganda. Mukono is located in Uganda's low- to medium-altitude areas and is roughly 1,200 meters above sea level (m.a.s.l). NaCORI's rainfall is bimodal. Total rainfall received during the study period was 2030.6mm (Figure 31a) while the mean temperature was 27.69 ^{o}C (Figure 31b). Mukono receives two main rainy seasons, the first of which lasts from March to May and the second lasting from September to November (Kobusinge *et al.,* 2023; Mukono District Local

Government, 2015). The major soil types of the study area are Ferralsols (sandy clay-loams) (Kobusinge *et al.,* 2023; Mukono District Local Government, 2015).

KCPL on the other hand, is located in Naluwondwa parish, Madudu sub-county and part of Kitenga sub-county, Buwekula county, Mubende district (Figure 29). KCPL lies between latitudes 0^0 35’ and 0^0 40’N and between longitudes 31^0 25’ and 31^0 30’E while NaCORI is located at $0^0$15'26.9874"N and $32^0$47'27.69648"E (Kobusinge *et al.,* 2023). KCPL lies at an average of 1,300 meters above sea level. KCPL received total rainfall of 1020 mm (Figure 32b) and with mean temperature of 26.79 ^oC during the study period (Figure 32a). The soils are red ferralitic and sandy loams, characterized by large amounts of iron oxides (Kaweri Coffee Plantation Ltd, 2001). KCPL experiences severe drought during the dry season. The planation still grows the old six commercial lines of Robusta coffee grown together with naturally regenerated trees preserved at no clear spacing pattern. NaCORI’s study sites had a slope of 5% while KCPL’s study plots slope ranged from 5-17%.

NaCORI and KCPL were purposively selected because the experiment needed to be conducted under a controlled setting compared to farmers’ fields which have high variability in terms of management, coffee age and soils. Temperature and rainfall were recorded at the study sites. The study site study periods depended on the coffee main season in the areas.

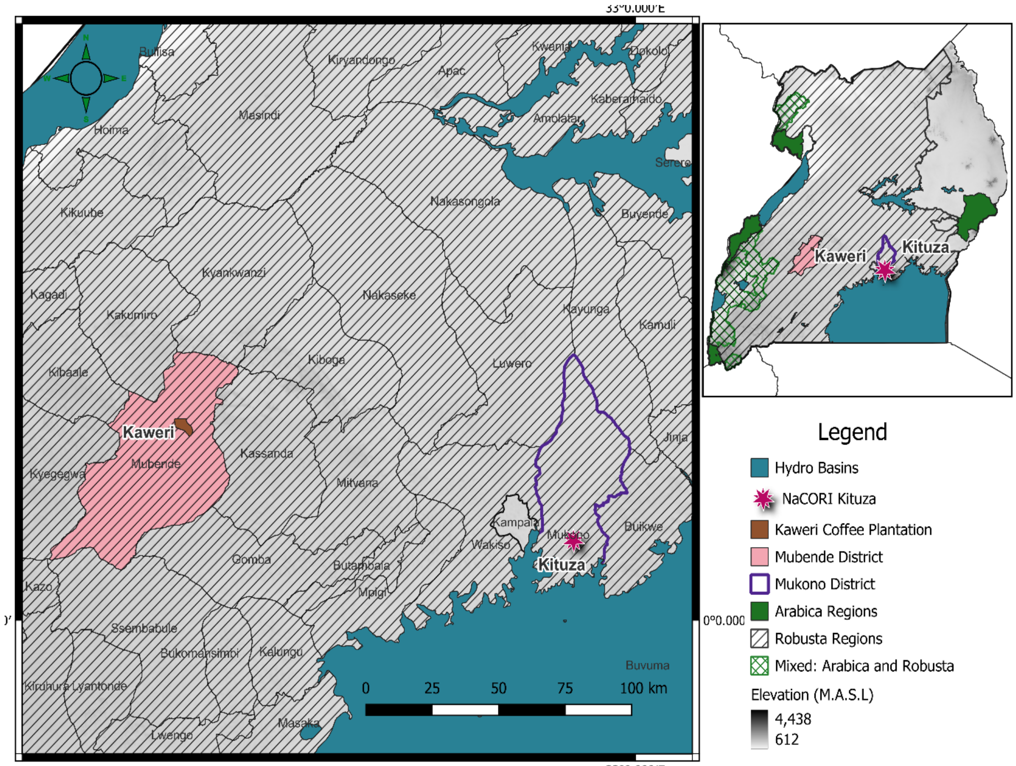


Figure 29: Location of KCPL and NaCORL within Kaweri, Mubende and Kituza, Mukono districts respectively in Uganda. Map generated using MATLAB. KCPL, Kaweri Coffee Plantation Limited; NaCORI, National Coffee Research Institute.

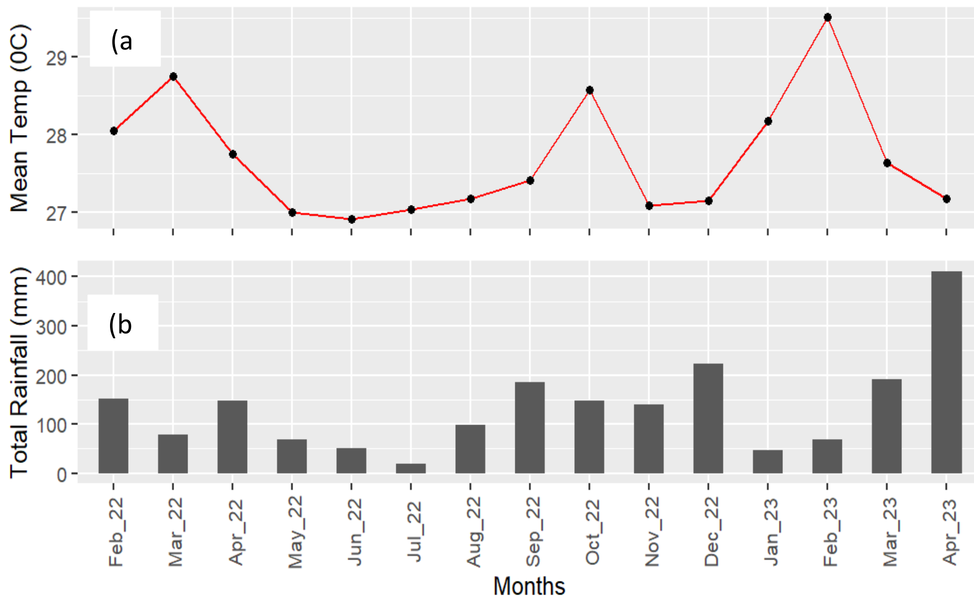


Figure 30: Rainfall (a) and mean temperature (b) for the National Coffee Research Institute, Mukono, Uganda during the study period (February 2022-April 2023). *Feb, February; Mar, March; Apr, April; Jun, June; Jul, July; Aug, August; Sep, September; Oct, October; Nov, November; Dec, December, Jan, January*

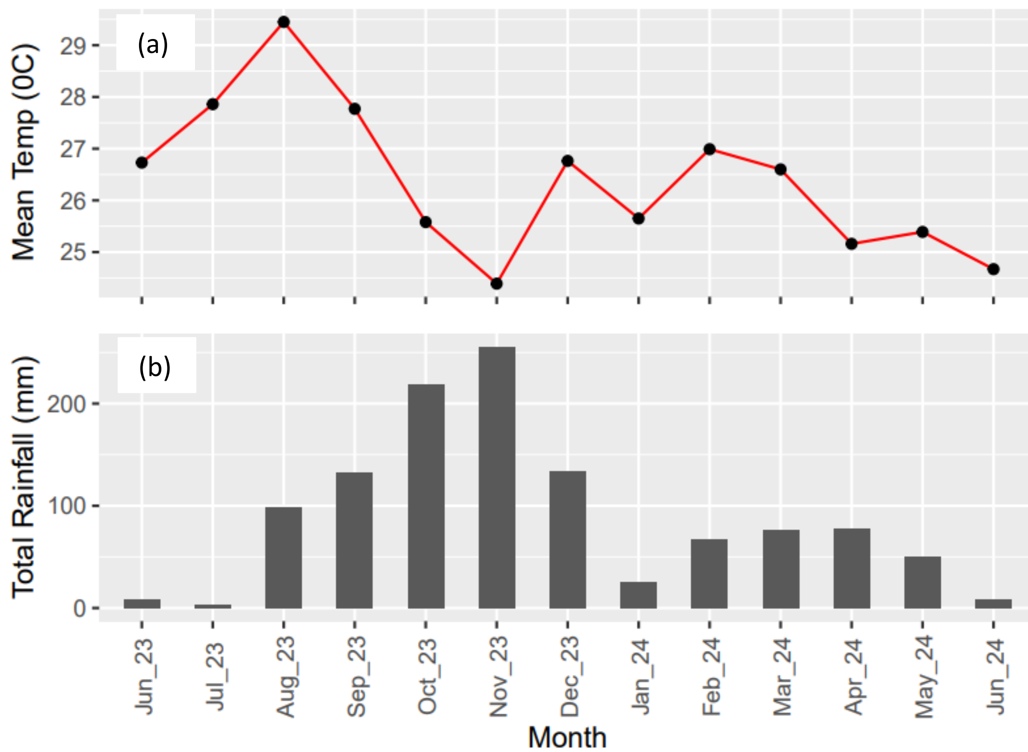


Figure 31: Rainfall (a) and mean temperature (b) for Kaweri Coffee Plantation Limited, Mubende, Uganda during the study period (June 2023-June 2024)

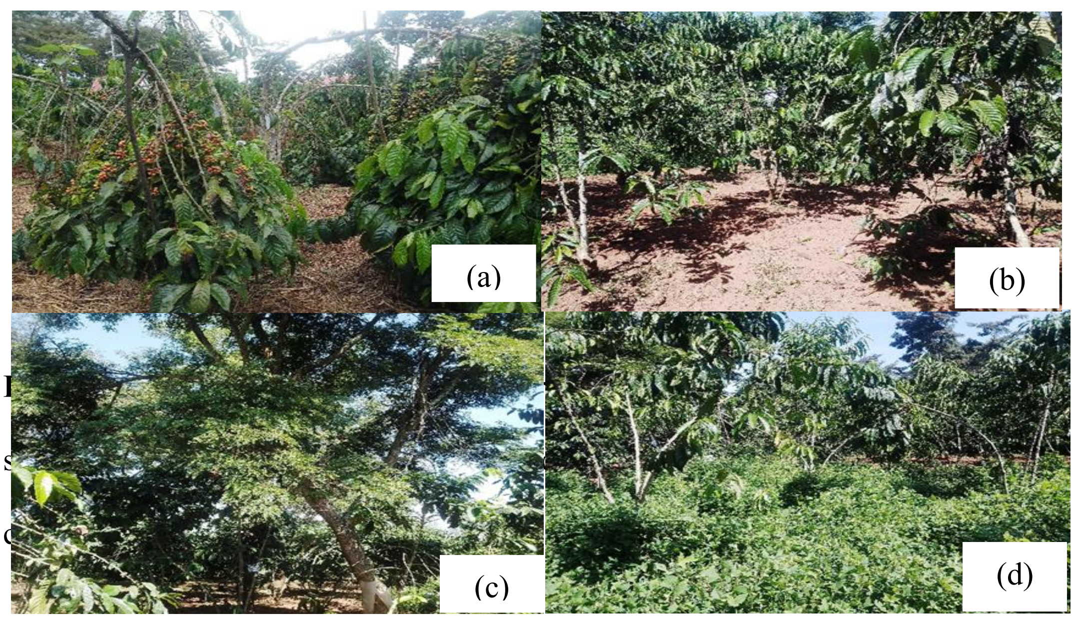
Feb, February; Mar, March; Apr, April; Jun, June; Jul, July; Aug, August; Sep, September; Oct, October; Nov, November; Dec, December, Jan, January

5.3.2 Research design

An incomplete randomized block design was used at NaCORI since A. coriaria was present in only two of the replicates while a completely randomised block design was used at KCPL.

5.3.2.1 Experimental design at NaCORI

Four systems (thereafter referred to as: soil moisture conservation practices, or SMCPs) including: coffee mulch, *Miscanthidium violoceum* (CMS) (Figure 33a), open sun coffee (COSS) (Figure 33b), coffee-*Albizia coriaria* (ACS) (Figure 33c), and coffee cover crop, *Desmodium intortum* (CCS) (Figure 33d) measuring 81 m^2 each, were used in the experiment. The 81 m^2 was determined based on the already existing experimental design of the field. Each system was repeated three times along the slope. The experiment ran from February 2022 to April 2023.. The experiment was superimposed on an already existing a breeding population of Robusta coffee plants that was used to select the Ugandan commercial Coffee Wilt Disease resistant Robusta coffee types (CWD-r) (UCDA, 2019a Handbook). Coffee plants are spaced at 3 m by 3 m while shade trees are spaced at 15 m by 15 m. The plots within a replicate are separated by 3 m while blocks are separated by 15 m. Three to four stems were maintained per coffee plant. The experimental field of the coffee together with *A. coriaria* was established in 2009 on a 2.2 acre field along a slope of 4% and the coffee plants were last stumped in 2019. The cover crop was established in November 2020, while mulch was first applied in August 2021. Basing on recommendations from UCDA (2019a Handbook) and Kakaire *et al.* (2015), mulch was kept at a thickness of 10 cm. All plots were managed in the same way throughout the study time; the only differences were in the targeted systems. During the rainy seasons, 250 g of NPK 25:5:5 fertilizer were applied to all the coffee plants to meet the nutrient needs. Weeds were managed by hand hoeing. In addition, coffee was regularly pruned to prevent the growth of suckers. However, the plots were completely rain-fed with no external application of water. Soil moisture content, diviner (2000) device was used to measure the soil moisture content for study period. Thermochron i-Button, Cold chain (Hygrochron Hi-Res (-20 ºC to +85 ºC) Acc 0.5 ºC) was used to measure air relative humidity and temperature. On the other hand, AccuPAR/LAI Ceptometer LP-50 was used to measure the photosynthetic active radiations and Leaf Area Index (LAI) in each system. The slope was measured using sunnto PM-5 hand-held clinometer.



5.3.2.2 Experimental design at Kaweri Coffee Plantation Limited

Four coffee systems (thereafter referred to as: soil moisture conservation practices, or SMCPs) replicated three times; Coffee *Albizia coriaria*, coffee mulch-*Miscanthidium violoceum*, coffee cover crop- *Desmodium intortum* and open sun coffee. The SMCPs were distributed in two sections of KCPL; Rep 1 was found in Kitagweta section (4 plots each containing a SMCP) while rep 2 and 3 are in Luwunga section (8 plots). The selection of the study sites, placement of access tube was purposive based on the presence of the SMCPs. The plot size was 24m x 9m. Three access tubes were installed diagonally in each plot. Mulch was also maintained at a depth of 10 cm whereas, the cover crop was planted in June 2023. Soil moisture was measured using diviner 2000. Fields were maintained regularly by slashing, hand hoeing and desuckering. The study sites were last stumped in 2019 and the experiment ran from June-June 2024. The site was completely rainfed.

5.3.3 Methods of data collection

5.3.3.1 Soil physical properties

In each plot, a trench of 1 m × 1 m × 1.2 m was dug, and undisturbed soil samples were collected using soil cores down to a depth of 90 cm at 0.2 m intervals. Following the methods described by Kobusinge *et al*. (2023), soil bulk density was determined using the positive head core method of Black (1965), while soil organic carbon was measured using the wet oxidation method (Walkley & Black, 1934). Hydraulic conductivity was assessed using the positive head method (McKenzie & Cresswell, 2002), and particle size distribution was analyzed through the hydrometer method (Okalebo *et al.,* 2002). Only soil physical properties that significantly influence water retention were selected for analysis (Gwak & Kim, 2017)

5.3.3.2 Relative humidity and temperature per systems

One I-button for temperature and relative humidity of the air was installed at 1.3 m above the ground (as described by a Sarmiento-Soler *et al.,* 2019), fixed to the coffee plant with silicon sealant, and shielded from precipitation with aluminum foil. Every hour, the relative humidity and temperature were automatically recorded. Every two months, data were obtained from the I-buttons using an I-button reader, and the I-button was refreshed before being put back into the field.

5.3.3.3 Leaf area index

From February 2022 to April 2023, the leaf area index (LAI) was measured every two weeks between 11:00 a.m. and 1:00 p.m., East African Time (EAT), using a ceptometer LP-80 (PAR/LAI Ceptometer, Decagon Devices, Pullman, Washington, USA) as described by Castro-Pacheco *et al.* (2024). This particular time was chosen since the sun is overhead the coffee and is in full sunlight. Ceptometer consists of an integrated microprocessor-driven data logger and probe. The probe contains 80 independent sensors, spaced 1 cm apart. The photosensors measure PAR (Photosynthetically Active Radiation) in the 400 to 700 nm waveband (Decagon Devices, 2013). Two measurements were made for coffee, shade trees, and cover crops: one above and one below the canopy. The ceptometer was initially positioned above the coffee canopy to measure the photosynthetic active radiation (PAR) above canopy. It was then positioned at random under the coffee canopy at four sites (East, West, South, and North direction), with the device automatically calculating the average. The PAR for each plant above and below the canopy was measured under identical solar intensity. If the amount of sunshine changed after the above canopy PAR was measured, the measurement was done again at the new amount of sunshine. It was visually seen that the intensity of the sun had changed. The ceptometer LP-80 determined LAI based on light intercepted by the plant. Within a plot, LAI data were measured on each of the four coffee plants.

5.3.3.4 Soil moisture content

In each SMCP, the soil moisture content was measured at a depth of 1.5 m between February 2022 and April 2023 using a Sentek Diviner 2000 at NaCORI (Sentek, 2000). While at KCPL it was measured up to 1.4 m, but in certain plots, because the soils were shallow. The soil moisture measurements were from June 2023 to June 2024. In every plot, three access tubes were drilled with a soil auger and positioned randomly diagonally. PVC pipes with a diameter of 3.5 cm and a thickness of 0.5 cm were used to make the access tubes. The Diviner 2000 is a handheld, movable soil monitoring system that uses a cable to link a portable display/logger unit and an independent depth-sensing probe. The probe is easy to use because it takes readings automatically at intervals of 10 cm deep. It is also less hazardous to the environment because it uses electromagnetic waves rather than gamma rays (da Silva *et al.,* 2007). The Diviner 2000 was used to manually measure the volumetric soil moisture twice a week at 10:00 a.m. The measurements were automatically recorded by the instrument. Device data were translated into volumetric soil moisture content using the Sentek default calibration equation (Scaled Frequency=0.2746 * (volumetric water content ^0.3314) + 0) (Sentek, 2000).

5.3.3.5 Measurement of runoff

Since the measured slope at NaCORI was 4%, no runoff was measured as suggested by Zizinga *et al.* (2022). However, because the slope at KCPL was more than 4%, runoff traps were constructed in each study plot (Figure 34). Runoff traps were placed along the slope and in the middle of the plot. In each plot one runoff trap was constructed. These were constructed using bricks, concrete and iron sheets. The iron sheets were cut in small pieces with width measuring 10cm and put in an area of 15 m by 2 m connecting to a constructed channel leading the water into the 5 litre jerrican. Runoff was manually collected daily and measured using a measuring cylinder (calibrated in litres) and the measured water was converted to mm by dividing it with the area of the runoff trap.

Figure 33: Construction of the runoff trap at Kaweri Coffee Plantation Limited (KCPL), Mubende, Uganda (Source: Author)

5.3.3.6 Rainfall, coffee water requirements, root zone actual evapotranspiration (ET_a), water balances and soil water deficits

A weather station within NaCORI, roughly 0.5 km from the study site, provided the daily meteorological data, which included wind speed (m s^{-1}), relative humidity (%), maximum and minimum temperatures (°C), solar radiation (MJ m^{-2}), and rainfall (mm). However, only rainfall data were obtained from KCPL. Temperature data were obtained from satellite data downloaded from NASA (https://power.larc.nasa.gov/data-access-viewer/). Rainfall and coffee water requirement (CWR) during respective periods were derived from meteorological data collected from this weather data using equation 4

$$CWR = Reference\ Evapotranspiration\ (ET_0) * \ Crop\ coefficient\ (Kc) \text{………...Equation 4}$$

Kc=0.95 -Crop coefficient for well weeded mature coffee (Allen *et al.,* 1998).

Penman-Monteith equation 5 was used to determine ET0 (Allen *et al.,* 1998). According to Fries *et al.* (2020), a month is defined as dry if reference evapotranspiration (ET0) is higher than precipitation (P), and as wet if precipitation (P) is more than reference evapotranspiration (ET0).

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \text{………………………………………………………Equation 5}$$

where ET_o reference evapotranspiration (mm day^{-1}), R_n net radiation at the crop surface (MJ m^{-2} day^{-1}), G soil heat flux density (MJ m^{-2} day^{-1}), T mean daily air temperature at 2 m height (°C), u_2 wind speed at 2 m height (m s^{-1}), e_s saturation vapour pressure (kPa), e_a actual vapour pressure (kPa), e_s - e_a saturation vapour pressure deficit (kPa), Δ slope vapour pressure curve (kPa $°C^{-1}$), g psychrometric constant (kPa $°C^{-1}$).

Deep percolation and runoff of water in the field plots were ignored because the experimental field at NaCORI was level (with a slope of 4%) and the groundwater table was deep (>7 m). Based on the soil water budget, Equation 6 was used to determine the actual crop evapotranspiration (ETa, mm) for each SMCP on a monthly basis.

$$ETa = (MCB - MCE) + P - R \text{………………………………………………………Equation 6}$$

Where, MCB = moisture content in the soil profile at the beginning of the month, MCE = moisture content in the soil profile at the end of the month and P =

Accumulated rainfall for soil moisture content measurement period, R=runoff (Padovan *et al.,* 2015; Zizinga *et al.,* 2022) where, runoff was not collected it was equal to zero. For this investigation, ETa were computed down to a depth of 0.4 meters since coffee plants typically absorb water in this zone (Sarmiento-Soler *et al.,* 2019) and because evapotranspiration processes are linked to the root system and higher soil horizons. The calculation of mean monthly soil moisture balances involved subtracting the moisture content at the end of the month (MCE) from the moisture content in the soil profile at the beginning of the month (MCB). The difference between soil moisture at field capacity and soil moisture in the soil each month was used to compute root zone water deficits (Andales, 2019). By using cores to gather undisturbed soil up to 0.4 meters, the soil field capacity per SMCP was ascertained. The pressure plate method (30 kPa suction) was then used for analysis.

5.3.3.7 Efficiency of soil moisture conservation practices in conserving root zone soil moisture

The efficiency of SMCP was determined by dividing the difference in soil moisture between SMCPs and the control system by the control system's value, as stated in equation (7)

$$\Delta M_{SMCP} = (M_{SMCP} - M_{Control}) / M_{Control}, \quad \text{...Equation 7}$$

Where, M=soil moisture and SMCP= soil moisture conservation practice

5.3.3.8 Coffee growth parameters

Four coffee plants per treatment per replicate were used to measure the coffee growth parameters in each plot. Coffee plants in the middle of the plots were used.

Stem girth, plant height, number of stem internodes, number of primary internodes, length of the longest primary, total number of primaries (lateral primary branches), canopy height, and canopy diameter are among the parameters that were measured. The measurements were taken with reference to Bote (2016) and Ferrao *et al.* (2019).

5.3.3.9 Coffee yield per tree

Coffee yield data were only gathered at NaCORI. This is because the study period at KCPL was relatively short and insufficient to capture a full coffee production cycle, yield data were collected only at NaCORI, where the experimental timeline allowed for complete and reliable measurement of coffee productivity. During the course of a year, red cherries were harvested every two weeks from four coffee trees per system per replicate. A digital SF-400A weighing scale was used to determine the fresh weight of the cherries, which were then dried in a solar drier until they reached a moisture level of 13–14% (UCDA, 2019a Handbook). The coffee was then weighed again to determine its dry weight. This dried coffee was hullied and the green bean used for both physical parameters and screen sizes. The physical quality parameters of coffee were determined following the ISO 10,470 procedures (ISO, 2011). The colour and smell were determined by experienced tester using methods by Wale Mengistu *et al.* (2020). Three replicates of a 350g sample were used for analysis as recommended by UCDA (2019a Handbook) for screen size. The coffee physical parameters and screen sizes were analyzed at NaCORI.

5.3.4 Data Analysis

Using the aov() , analysis of variance (ANOVA) was performed to ascertain the effect of SMCPs on selected soil physical characteristics, soil moisture content, crop evapotranspiration (ETa), LAI, microclimate, and yield. In addition, ANCOVA was conducted to determine the effect of location on soil moisture content. Using the car package, means were separated for significant differences using the LSD.test function at a 5% significance level (Fox & Weisberg, 2023). The ggplot2 package was used to draw the graphs. Version 4.2.1 of the R program (R Foundation for Statistical Computing, Vienna, Austria) was used for all analyses.

5.4 Results

5.4.1 Soil physical characteristics under different soil moisture conservation practices (SMCPs) at the National Coffee Research Institute (NaCORI)

Results showed that all the selected soil physical properties at 0.0-0.4 m depth varied significantly ($p \leq 0.05$) across the soil moisture conservation practices (SMCPs) (Table 11). The highest bulk density (1.71 g/cc) was recorded under ACS and the least under CCS (1.41 g/cc) whereas, soil porosity was highest under CCS (46.78%) and lowest under ACS (35.38%). The amounts of organic carbon content, Ksat and sand were highest under CMS (2.36%, 13.09 mm/hr and 57.92, respectively) and lowest under ACS (2.05%, 3.96 mm/hr and 49%, respectively). For clay, the highest content (38.69%) was recorded under COSS and the lowest (32.39%) under CCS while the highest content of silt (14.08%) was under COSS and least (9.56%) under CMS. On the other hand, all the soil physical properties at 0.5-0.9 m depth apart from Ksat varied significantly ($p \leq 0.05$) across the SMCPs

(Table 12). The highest bulk density (1.96 g/cc) was recorded under ACS and the least under CCS (1.63 g/cc) whereas, soil porosity was highest under CCS (38.61%) and lowest under ACS (26.13%). The highest organic carbon content was recorded under CMS (1.85%) and least under COSS (1.54%). Additionally, the highest sand content (38.39%) was observed under CMS and lowest (30.17%) under CCS. For clay, the highest content (53.83%) was recorded under CCS and the lowest under CMS (50.56%) while, the highest silt content was recorded under ACS (16.17%) and lowest under CMS (11.09%).

Table 11: Influence of soil moisture conservation practices on selected soil physical properties under at 0.0-0.4m at the National Coffee Research Institute, Mukono, Uganda

	Soil Physical properties						
SMCPs	BD (g/cc)	Porosity (%)	Organic carbon	Ksat (mm/hr)	Sand (%)	Clay (%)	Silt (%)
ACS	1.71±0.04 a	35.38± 1.21 c	2.05 ±0.08b	3.96± 1.07 b	49.00± 1.96c	37.38± 1.57a	13.63 ±1.33a
COSS	1.60±0.03b	43.25±0.97b	2.09 ±0.07b	4.19 ± 0.05b	50.93±1.56bc	38.69± 1.25a	14.08 ± 1.06a
CMS	1.45± 0.03c	45.27± 0.97ab	2.36±0.07a	13.09 ± 0.85a	57.92± 1.56 a	32.53± 1.25b	9.56 ± 1.06b
CCS	1.41± 0.03c	46.78± 0.96a	2.31± 0.07a	10.83± 0.85a	55.36± 1.56ab	32.39±1.24b	12.25± 1.06ab
p value	1.966e-06 ***	2.22e-07 ***	0.006161 **	2.904e-08 ***	0.004183 **	0.0013658 **	0.03848 *
cv	5.95	6.64	8.96	30.28	8.65	10.62	25.81

Ksat, saturated hydraulic conductivity; BD, bulk density; COSS, open sun coffee system; CCS, coffee cover crop system; CMS, coffee mulch system; ACS, coffee Albizia coriaria system; ns, non-significant. Within each variable column, mean values sharing the same letter are not significantly different.

Table 12: Influence of soil moisture conservation practices on selected soil physical properties under at 0.5-0.9m at the National Coffee Research Institute, Mukono, Uganda

	Soil Physical properties						
SMCPs	BD (g/cc)	Porosity (%)	Organic carbon (%)	Ksat (mm/hr)	Sand (%)	Clay (%)	Silt (%)
ACS	1.96±0.02a	26.13± 0.91c	1.67±00.07ab	0.62 ±0.09a	32.17± 2.02b	51.67±1.36a	16.17± 1.14a
CCS	1.63±0.02c	38.61±0.72a	1.62±0.06b	0.64±0.07a	30.17 ±1.61b	53.83 ± 1.08a	16.00± 0.91a
CMS	1.65±0.02c	37.62±0.72a	1.85 ±0.06a	0.46±0.07a	38.39±1.61a	50.56±1.08a	11.06±0.91b
COSS	1.77± 0.02b	33.20±0.72b	1.54±0.06b	0.59±0.07a	32.33±1.61b	53.00±1.08a	14.67±0.91a
p value	1.894e-11 ***	1.894e-11 ***	0.005176 **	0.27896	0.008099 **	0.1823	0.001519 **
cv	3.3	6.24	10.55	36.55	14.41	6.17	18.98

Ksat, saturated hydraulic conductivity; BD, bulk density; COSS, open sun coffee system; CCS, coffee cover crop system; CMS, coffee mulch system; ACS, coffee Albizia coriaria system; ns, non-significant. Within each variable column, mean values sharing the same letter are not significantly different.

5.4.2 Microclimate created by the different soil moisture conservation practices at the National Coffee Research Institute

Micro air temperature was significantly different ($p < 0.001$) across the SMCPs and between wet season (21.88 ºC) and dry season (22.42 ºC). In both dry and wet seasons, the lowest micro air temperature was recorded under ACS (22.02 and 21.47 ºC, respectively) whereas, the highest was under CCS (22.56 ºC) during the dry season and CMS (22.04 ºC) during the wet season. During the dry season, air temperature was not significantly different ($p \geq 0.05$) among CCS, CMS and COSS. Also, the interaction between SMCPs and season was not significant ($p=0.1997$) (Table 13). Results further showed that the air relative humidity varied significantly ($p < 0.001$) across SMCPs and seasons. In both dry and wet seasons, the highest air relative humidity was recorded under ACS (84.99 and 84.99%, respectively) and lowest under CMS (81.58 and 85.89%, respectively) and COSS (81.58% and 86.28% respectively). However, the interaction between SMCPs and season was not significant ($p=0.3939$) (Table 14).

Table 13: Micro air temperature under different soil moisture conservation practices in Robusta coffee at the National Coffee Research Institute, Mukono, Uganda

SMCPs	Dry Season Mean±sem (ºC)	Max (ºC)	Min (ºC)	Wet season Mean±sem (ºC)	Max (ºC)	Min (ºC)
ACS	22.02± 0.06b	36.82	15.5	21.47± 0.05c	32.74	15.43
CCS	22.56±0.05a	38.38	14.89	21.93±0.04b	39.01	15.08
CMS	22.49±0.05a	36.56	14.87	22.04±0.04a	41.62	15.2
COSS	22.49±0.05a	37.36	15.06	21.96±0.04ab	38.5	15.2
p value: SMCPs	2.368e-11 ***			<2e-16 ***		
Season: Dry	22.42±0.03a	38.38	14.87			
Wet	21.88±0.02b	41.62	15.06			
p value: Season (Wet & Dry)	$5.037e^{-13}$ ***					
p value: SMCPs*Season	0.1997					
c.v (%)	20.19			19.59		

ACS, coffee Albizia coriaria system; CCS, coffee cover crop system; CMS, coffee mulch system; COSS, coffee open sun system; SMCPs, soil moisture conservation practices; values followed by the same letters are non-significant.

Table 14: Micro air relative humidity created by the soil moisture conservation practices (SMCPs) at the National Coffee Research Institute (NaCORI), Mukono, Uganda

SMCPs	Dry season			Wet season		
	Mean±sem (%)	Max	Min	Mean±sem (%)	Max	Min
ACS	84.99±0.25a	100	30.88	89.68±0.18a	100	35.80
CCS	82.31±0.20b	100	27.79	87.10±0.15b	100	29.89
CMS	81.63±0.20c	100	26.47	85.89±0.15c	100	25.12
COSS	81.58±0.20c	100	24.91	86.28±0.15c	100	28.28
p value: SMCPs	< 2.2e-16 ***			< 2.2e-16 ***		
Season Wet	87.01±0.07a	100	25.12			
Dry	82.41±0.13b	100	24.91			
p value: season	<2e^{-16} ***					
p value: SMCPs*season	0.3939					
cv	21.8			18.85		

ACS, coffee Albizia coriaria system; CCS, coffee cover crop system; CMS, coffee mulch system; COSS, coffee open sun system; SMCPs, soil moisture conservation practices; values followed by the same letters are non-significant.

5.4.3 Influence of soil moisture conservation practices (SMCPs) on coffee leaf area index (LAI)

Results further showed that coffee leaf area index (LAI) was significantly different (p<0.001) across the SMCPs (Figure 35). The highest LAI in both dry (2.09) and wet (2.51) season was recorded under ACS and the lowest (1.44 and 1.53, respectively) was under CCS. Coffee LAI was significantly (p<0.001) higher during the wet season across the different SMCPs though LAI among seasons was not significantly (p=0.686) different within SMCPs.

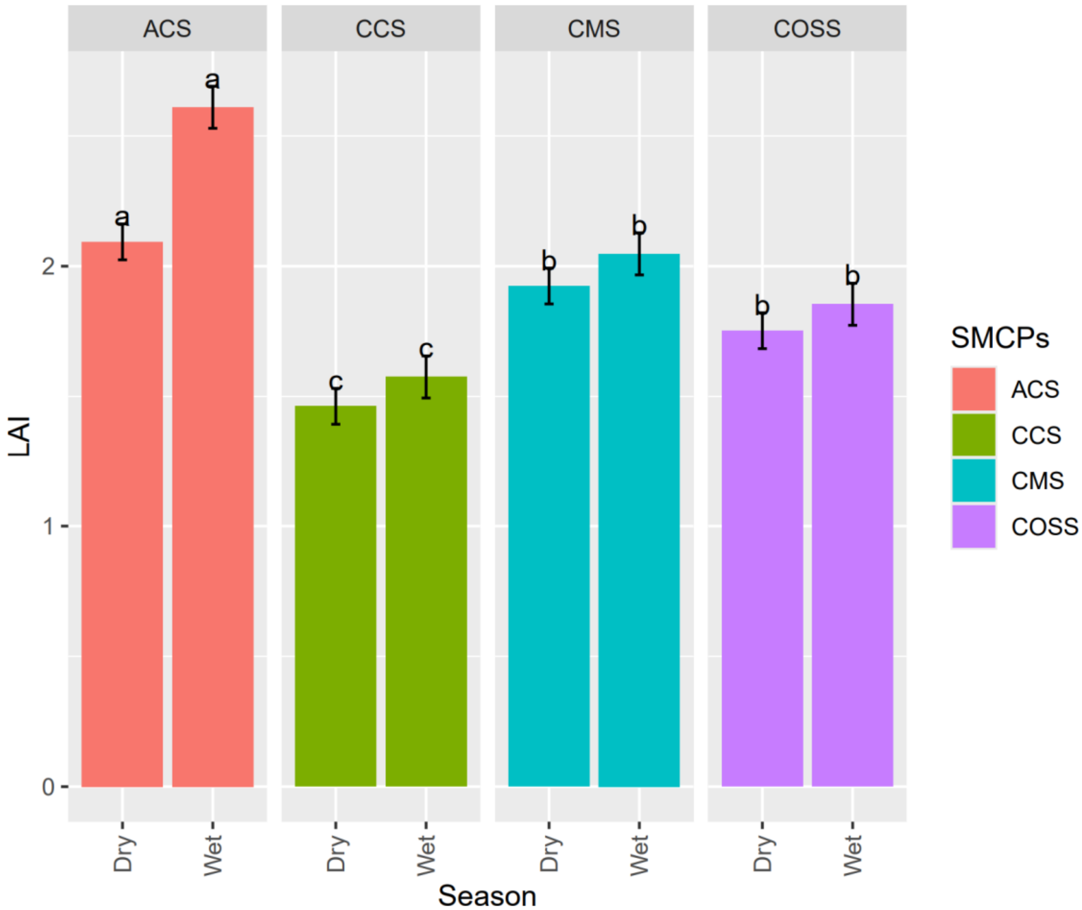


Figure 34: Coffee Leaf Area Index under the different soil moisture conservation practices per season at the National Coffee Research Institute, Mukono, Uganda

SMCPs and seasons with the same letters are not significant; SMCPs; soil moisture conservation practices; LAI, leaf area index; ACS, coffee Albizia coriaria system; CCS, coffee cover crop system; CMS, coffee mulch system; COSS, open sun coffee system.

5.4.4 Influence of soil moisture conservation practices on Actual crop Evapotranspiration (ETa) at the National Coffee Research Institute

Table 15 below shows that there was no significant difference ($p \geq 0.05$) in ETa across the SMCPs but significant differences ($p < 0.001$) were observed between dry and wet season. However, the highest ETa was recorded under CMS (6.34 mm) and the lowest under ACS (6.19 mm) in the wet season while in the dry season, the highest ETa (1.87 mm) was observed under CCS and the lowest under CMS (1.73 mm). Furthermore, there were significant differences ($p < 0.001$) in ETa across the different months but no significant difference ($p = 0.841$) across the SMCPs within a month (Figure 36b). The month of April 2023 had the highest ETa (COSS=13.63 mm, CMS=13.64 mm, ACS=13.74 mm and CCS=13.75 mm) while the lowest was recorded in the month of June 2022 for ACS (0.78 mm), COSS (0.82 mm), July for CMS (0.98 mm) and CCS (0.8 mm). On the other hand, Crop Water Requirements (CWR) was highest in January (114.86 mm) while the lowest was in February (95.49 mm) (Figure 36a).

Table 15: Daily actual crop evapotranspiration per season at the National Coffee Research Institute, Mukono, Uganda

SMCPs	Wet season Mean±sem (mm)	Max	Min	Dry season Mean±sem (mm)	Max	Min
ACS	6.19±0.42a	13.88	2.66	1.74±0.13a	2.92	0.51
CCS	6.22±0.34a	14.09	2.78	1.87±0.11a	3.65	0.52
CMS	6.34±0.32a	13.75	2.64	1.73±0.10a	2.81	0.28
COSS	6.33±0.31a	13.82	2.86	1.78±0.09a	3.11	0.57
p value: SMCPs	0.9887			0.777		
Season Wet	6.30± 0.13a					
Dry	1.78±0.16b					
p value: season	$<2.2e^{-16}$ ***					
p value: SMCPs*season	0.972					
cv	45.89			41.36		

ACS, coffee Albizia coriaria system; CCS, coffee cover crop system; CMS, coffee mulch system; COSS, open sun coffee system; values followed by the same letters are non-significant.

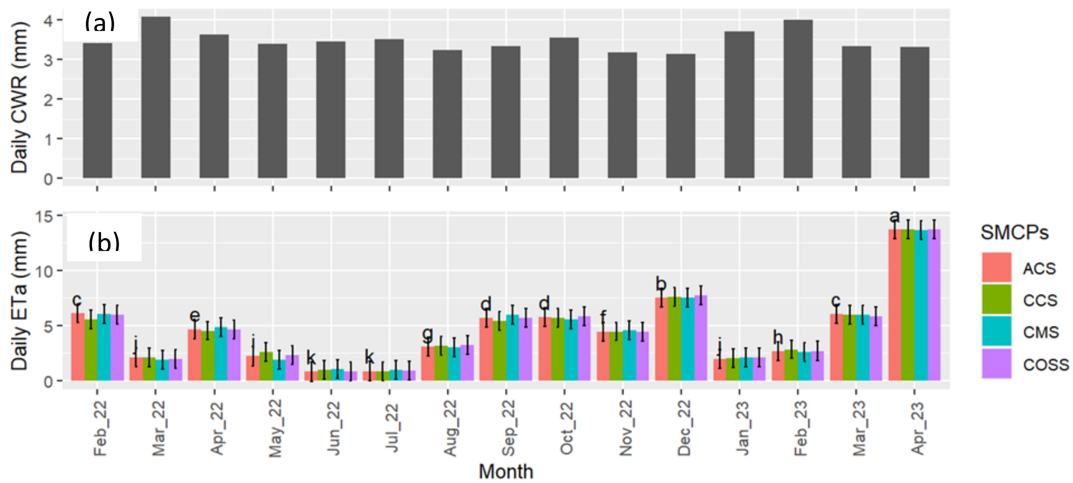


Figure 35: Daily CWR per month (a) and Daily actual crop evapotranspiration (ETa) (b) during rainfed conditions at the National Coffee Research Institute, Mukono, Uganda

Months with the same letters are not significant; ETa, actual evapotranspiration; CWR, coffee water requirements; CMS, coffee mulch system; ACS, coffee Albizia coriaria system; CCS, coffee cover crop system; COSS, open sun coffee system; Feb, February; Mar, March; Apr, April; Jun, June; Jul, July; Aug, August; Sep, September; Oct, October; Nov, November; Dec, December, Jan, January

5.4.5 Effect of soil moisture conservation practices on Actual crop Evapotranspiration at Kaweri Coffee Plantation Limited

Table 16 shows the effects of SMCPs on ETa at KCPL. Results showed that there was a significant difference ($p<0.001$) in ETa between the dry (1.27 mm) and the wet season (7.17 mm). However, there were no significant differences ($p\geq0.05$) in ETa among SMCPs in both dry and wet season. CMS had a high ETa during the wet season (7.27 mm) while in the dry season, ETa was highest under ACS (1.34 mm). Furthermore, there was a significant difference ($p<0.01$) in ETa among the months, with November having the highest (COSS=9.21 mm, CMS=9.44 mm, ACS=9.29 mm and CCS=9.38 mm) while July had the lowest (COSS=13.63 mm, CMS=13.64 mm, ACS=13.74 mm and CCS=13.75 mm) (Figure 37b). Crop Water Requirements (CWR) was only met by ETa in the months of September, October, November and December (Figure 37a). There was no significant ($p=0.9583174$) difference in ETa among SMCPs of the same month.

Table 16: Daily actual evapotranspiration among the different soil moisture conservation practices (SMCPs) at Kaweri Coffee Plantation Limited (KCPL), Mubende, Uganda

SMCPs	Wet season			Dry season		
	Mean±sem (mm)	Max	Min	Mean±sem (mm)	Max	Min
ACS	6.99±0.35	9.50	4.04	1.34±0.10	2.90	0.15
CCS	7.20±0.35	9.74	4.56	1.24±0.10	2.65	0.18
CMS	7.27±0.35	9.75	4.20	1.30±0.10	2.60	0.07
COSS	7.15±0.35	9.50	4.66	1.21±0.11	3.14	0.23
p value	0.9502			0.7964		
Season						
Wet	7.17±0.12	9.75	4.04			
Dry	1.27±0.13	3.14	0.07			
p value season	< 2.2e-16 ***					
p value season*SMCPs	0.988					
cv	25.57			58.84		

ACS, coffee Albizia coriaria system; CCS, coffee cover crop system; CMS, coffee mulch system; COSS, open sun coffee system; values followed by the same letters are non-significant.

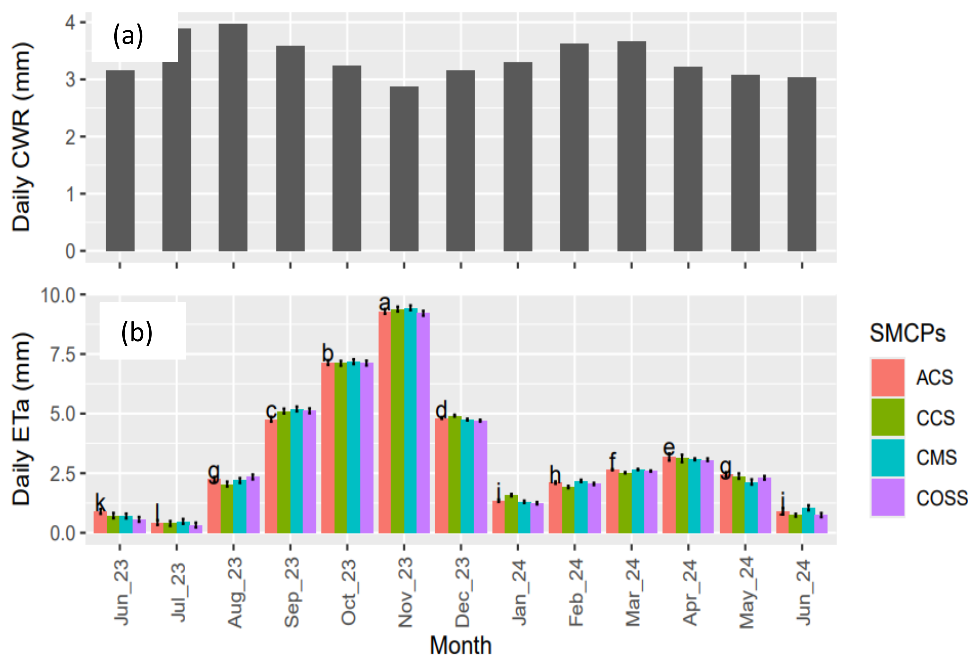


Figure 36: Daily Crop Water Requirements (CWR) (a) and Daily actual crop evapotranspiration (ETa) (b) per month during rain fed conditions at Kaweri Coffee Plantation Limited (KCPL), Mubende, Uganda

Months with the same letters are not significant; ETa, actual evapotranspiration; CWR, coffee water requirements; CMS, coffee mulch system; ACS, coffee Albizia coriaria system; CCS, coffee cover crop system; COSS, open sun coffee system; Feb, February; Mar, March; Apr, April; Jun, June; Jul, July; Aug, August; Sep, September; Oct, October; Nov, November; Dec, December, Jan, January

5.4.6 Influence of Location on Actual Evapotranspiration during the wet and dry season

During the Wet season ETa was significantly ($p \leq 0.05$) higher at Mubende (7.15 mm) as compared to Mukono (6.30 mm) (Table 17). In contrast, during the dry season ETa was significantly ($p<0.001$) higher at Mukono (1.78 mm) as compared to Mubende (1.11 mm)

Table 17: Influence of Location on Actual Evapotranspiration (ETa) during the wet and dry season

Season	Location	ETa (mm) Mean±sem
Wet	NaCORI	6.30±0.15
	KCPL	7.15±0.26
	p value	0.01374 *
		40.2
Dry	NaCORI	1.78±0.06
	KCPL	1.11±0.07
	p value	5.685e-09 ***
		49.8

NaCORI, National Coffee Research Institute; KCPL, Kaweri Coffee Plantation Limited

5.4.7 Soil moisture content per soil moisture conservation practices per depth at the National Coffee Research Institute

Results further showed that soil moisture content (SMC) varied significantly ($p<0.001$) across SMCPs at all depths in both seasons (Tables 18 and 19). In both seasons and for all the soil depths, the highest SMC was recorded under CMS – 76.04 mm (0.0-0.4 m), 126.52 mm (0.5-0.9 m) and 160.43 mm (1.0-1.5 m) for dry season and 81.68 mm (0.0-0.4 m), 126.83 mm (0.5-0.9 m) and 162.09 mm (1.0-1.5

m) for wet season. In addition, for 0-0.4 and 0.5-0.9 m depths, the lowest SMC was recorded under ACS in both dry and wet seasons - 46.37 mm (0.0-0.4 m) and 96.06 mm (0.5-0.9 m) for dry season and 56.02 mm (0.0-0.4 m) and 97.22 mm (0.5-0.9 m) for wet season. For the 1.0-1.5 m depth, the lowest soil moisture content was observed under CCS - 114.55 mm for dry season and 118.19 mm for wet season. Results further showed that there was a significant difference ($p<0.001$) in soil moisture across the months (Figure 38). In all SMCPs, SMC reduced in the months of March, June, July 2022, January and February 2023. The month of April, 2023 had the highest soil moisture. However, the interaction between SMCPs and month was not significant ($p=0.9856$).

Table 18: Soil moisture content under different soil moisture conservation practices during the dry season at the National Coffee Research Institute, Mukono, Uganda

	Soil depth (m)		
SMCPs	0.0-0.4	0.5-0.9	1.0-1.5
ACS	46.37±2.82c	96.06±3.87b	142.67±4.48b
CCS	55.58±2.35b	97.18±3.22b	114.55±3.73c
CMS	76.04±2.20a	126.52±3.02a	160.43±3.50a
COSS	51.35±2.23bc	104.42±3.06b	142.62±3.55b
p value	$< 2e^{-16}$ ***	$1.646e^{-11}$ ***	$3.561e^{-14}$ ***
cv	27.66	20.67	18.27

CMS, coffee mulch system; ACS, coffee Albizia coriaria system; CCS, coffee cover crop system; COSS, open sun coffee system; mm, milliliters

Table 19: Soil moisture content under different soil moisture conservation practices during the wet season at the National Coffee Research Institute, Mukono, Uganda

	Soil depth (m)		
SMCPs	0.0-0.4	0.5-0.9	1.0-1.5
ACS	56.02±2.29c	97.22± 3.37b	137.58±4.22b
CCS	67.58±1.90b	103.47±2.80b	118.19±3.51c
CMS	81.68±1.78a	126.83±2.63a	162.09±3.30a
COSS	61.47±1.81c	104.82±2.66b	135.38±3.35b
p value	$< 2.2e^{-16}$ ***	$3.651e^{-12}$ ***	$2.748e^{-15}$ ***
cv	19.36	17.65	17.41

CMS, coffee mulch system; ACS, coffee Albizia coriaria system; CCS, coffee cover crop system; COSS, open coffee sun system; mm, milliliters.

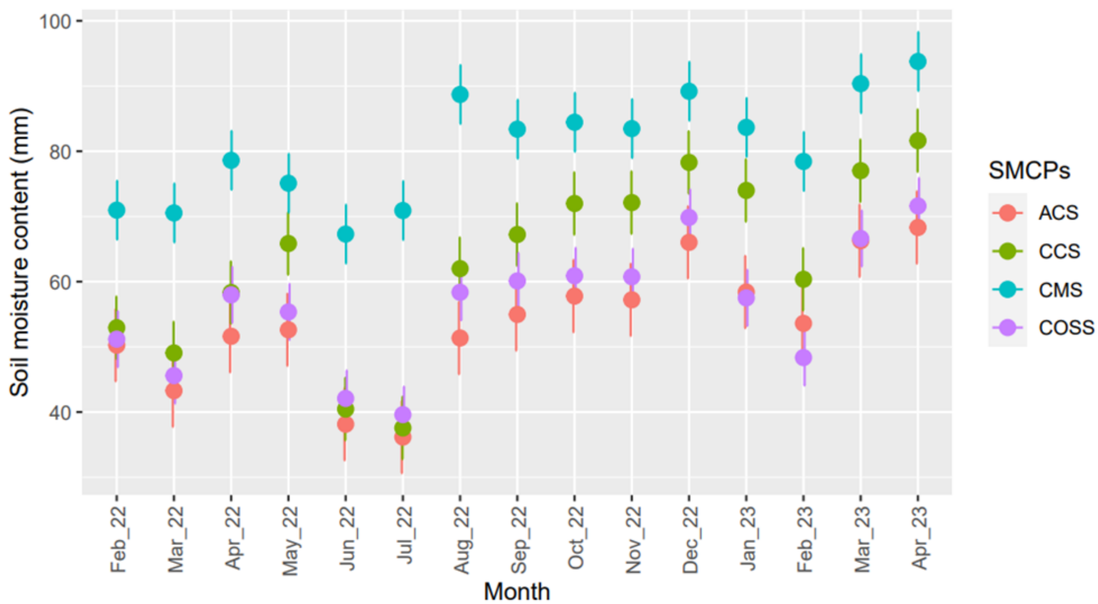


Figure 37: Soil moisture content per month per soil moisture conservation practice at 0.4m at the National Coffee Research Institute, Mukono, Uganda

CMS, coffee mulch system; ACS, coffee Albizia coriaria system; CCS, coffee cover crop system; COSS, open coffee sun system; mm, milliliters; Feb, February; Mar, March; Apr, April; Jun, June; Jul, July; Aug, August; Sep, September; Oct, October; Nov, November; Dec, December, Jan, January.

5.4.8 Soil moisture content per soil moisture conservation practices (SMCPs) per depth at Kaweri Coffee Plantation Limited (KCPL)

In the dry season, soil moisture content varied significantly ($p \leq 0.05$) across the SMCPs for all depth (Table 20). The highest soil moisture content was recorded under ACS at 0.0-0.4 m (60.28 mm) and 0.5-0.9 m, it was highest under CCS (62.11 mm) whereas, the lowest was observed under COSS for both 0.0-0.4 m (49.35 mm) and 0.5-0.9 m (40.94 mm). For 1.0-1.4 m depth, the highest soil moisture content (52.67 mm) was recorded under CMS and the lowest (38.25 mm) was under COSS. Similarly, in the wet season, soil moisture content varied significantly ($p \leq 0.01$) across the SMCPs for both soil depths (Table 21). For soil depths of 0.0-0.4 m soil moisture was highest under ACS (81.01 mm) and at 0.5-0.9 m, the highest soil moisture content was recorded under CCS (72.92 mm) while at 1.0-1.4 m, CMS had the highest soil moisture content (62.69 mm). On the other hand, the lowest soil moisture content for soil depth, 0.0-0.4 m and 0.5-0.9 m was recorded under COSS (69.32 mm, 47.13 mm respectively) while at 1.0-1.4 m, lowest was recorded under CCS (40.35 mm). Soil moisture content was more under CCS and ACS throughout the year and least under COSS (Figure 39) while in 2024, CMS had the highest soil moisture in February, March and June 2024. KCPL and NaCORI had similar trends of soil moisture with reduction happening in January, February, March, June and July (Figure 38 and 39).

Table 20: Soil moisture content (mm) under selected soil moisture conservation practices during the dry season at Kaweri Coffee Plantation Limited, Mubende, Uganda

	Soil depth (m)		
SMCPs	0.0-0.4	0.5-0.9	1.0-1.4
ACS	60.28±234a	50.72±6.22ab	45.61±6.13a
CMS	59.58±2.07a	50.25±4.57ab	52.67± 3.88ab
CCS	58.04±1.91a	62.11±4.86a	38.38±4.67b
COSS	49.35±2.21b	40.94±4.98b	38.25±6.87b
p value	0.0007796 ***	0.032263 *	0.003475 **
cv	26.91	65.18	61.15

CMS, coffee mulch system; ACS, coffee Albizia coriaria system; CCS, coffee cover crop system; COSS, open coffee sun system; mm, milliliters

Table 21: Soil moisture content (mm) under selected soil moisture conservation practices during the wet season at Kaweri Coffee Plantation Limited, Mubende, Uganda

	Soil depth (m)		
SMCPs	0.0-0.4	0.5-0.9	1.0-1.4
ACS	81.01±1.97a	57.82±6.09b	55.52±5.80ab
CMS	80.52±1.58a	59.12±4.60b	62.69±3.81a
CCS	80.27±1.87a	72.92±5.13a	40.35±4.34c
COSS	69.32±2.29b	47.13±4.94b	40.76±6.68bc
p value	2.093e-05 ***	0.0052426 **	0.005342 **
cv	19.25	63.49	58.27

CMS, coffee mulch system; ACS, coffee Albizia coriaria system; CCS, coffee cover crop system; COSS, open coffee sun system; mm, milliliters

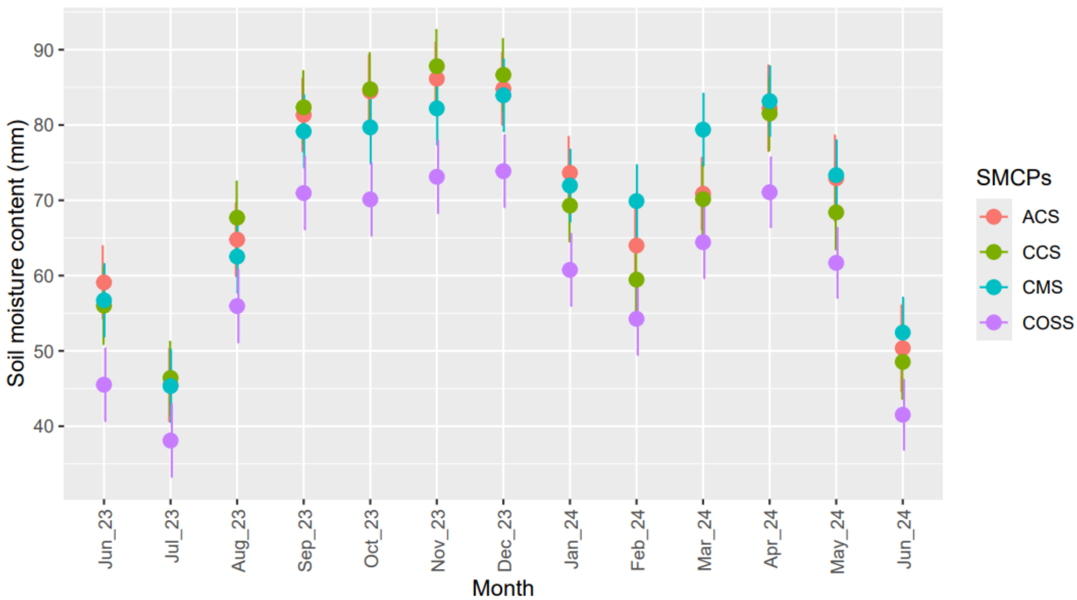


Figure 38: Soil moisture per month per soil moisture conservation practice (SMCP) within the coffee rootzone at Kaweri Coffee Plantation Limited (KCPL), Mubende district

CMS, coffee mulch system; ACS, coffee Albizia coriaria system; CCS, coffee cover crop system; COSS, open coffee sun system; mm, milliliters; Feb, February; Mar, March; Apr, April; Jun, June; Jul, July; Aug, August; Sep, September; Oct, October; Nov, November; Dec, December, Jan, January.

5.4.9 Influence of Location on Soil Moisture Content during the wet and dry season

During the wet season, soil moisture within the 0.0-0.4 m depth was significantly higher ($p<0.001$) at Mubende (77.68 mm) compared to Mukono (67.92 mm) (Table 22). At deeper depths (0.5-0.9 m and 1.0-1.4 m), however, soil moisture was significantly higher ($p<0.001$) at Mukono (109.51 mm and 139.92 mm, respectively) than at Mubende (59.16 mm and 51.92 mm, respectively).

In the dry season, soil moisture was generally higher at Mukono across all soil depths, although the difference at 0.0-0.4 m was not significant. At 0.5-0.9 m and 1.0-1.4 m, Mukono had significantly higher soil moisture ($p<0.001$), with 107.26 mm and 140.61 mm, respectively, compared to Mubende with 50.40 mm and 48.94 mm.

Table 22: Influence of Location on Soil Moisture Content during the wet and dry season

		Soil depth		
Season	Location	0.0-0.4 m	0.5-0.9 m	1.0-1.4 m
Wet	NaCORI	67.92±1.11	109.51±2.15	139.92±2.04
	KCPL	77.68±0.98	59.16±2.33	51.92±2.23
	p value	6.950e-11 ***	< 2.2e-16 ***	< 2.2e-16 ***
		21.8	38.9	30.8
Dry	NaCORI	58.42±1.21	107.26±2.19	140.61±2.01
	KCPL	56.59±1.16	50.40±2.20	48.94±2.49
	p value	0.3539	< 2.2e-16 ***	< 2.2e-16 ***
		31.0	38.8	30.4

NaCORI, National Coffee Research Institute; KCPL, Kaweri Coffee Plantation Limited

5.4.10 Effects of soil moisture conservation practices on runoff at Kaweri Coffee Plantation Limited

The amount of runoff under different soil moisture conservation practices (SMCPs) in both dry and wet season is shown in table 23 below. Results show that there was difference significant difference ($p \leq 0.01$) in the runoff across the SMCPs in both wet and dry season. In both the dry and the wet season, runoff was highest under COSS (0.40 mm, 2.28 mm respectively) and lowest under CMS (0.04 mm, 0.65 mm respectively). In addition, there was a significant (p=0.04601) interaction between SMCPs and seasons.

Table 23: Influence of soil moisture conservation practices on monthly runoff at Kaweri Coffee Plantation Limited, Mubende, Uganda

SMCPs	Dry Season			Wet season		
	Mean±sem (mm)	Max (mm)	Min (mm)	Mean±sem (mm)	Max (mm)	Min (mm)
ACS	0.05±0.02b	0.42	0	1.78±0.33ab	8.07	0
CCS	0.06±0.02b	0.63	0	1.19±0.21bc	5.44	0
CMS	0.04±0.01b	0.29	0	0.65±0.15c	3.77	0
COSS	0.40±0.10a	2.33	0	2.28±0.50a	13.58	0
p value: SMCPs	4.401e-07 ***			0.003031 **		
Season: Dry	0.14±0.12	2.33	0			
Wet	1.47±0.13	13.58	0			
p value: Season (Wet & Dry)	3.282e-06 ***					
p value: SMCPs*Season	0.04601 *					
cv	272.59			174.43		

CMS, coffee mulch system; ACS, coffee Albizia coriaria system; CCS, coffee cover crop system; COSS, open coffee sun system; mm, milliliters

5.4.11 Change in soil moisture content and Soil moisture deficits in the different soil moisture conservation practices at the National Coffee Research Institute

Table 24 below shows the change in soil moisture content at 0.4 m depth for the different soil moisture conservation practices (SMCPs) at National Coffee Research Institute (NaCORI), Kituza, Mukono. There was no significant difference in change in soil moisture content (SMC) during the dry season across the SMCPs. CMS had the least change in SMC (-6.20 mm) and the highest was under CCS (-9.42 mm). While in the wet season, there was a significant difference ($p<0.001$) in change in SMC within SMCPs. The highest change was in CCS (10.09 mm) and least under CMS (6.26mm) (Table 5.12). Results further showed that in both dry and wet seasons, soil moisture deficit (SMD) varied significantly ($p \leq 0.05$) across the SMCPs (Table 25) and months (Figure 40). In both dry and wet seasons, the highest SMD was recorded under ACS (104.29 and 94.63 mm, respectively) whereas, the lowest was registered under CMS (65.38 and 58.84 mm, respectively). However, there was no significant ($p=0.6632309$) between SMCPs and seasons. Furthermore, SMD was more in the month of June 2022 (range: from 72.04-110.38 mm) and July 2022 (range: 68.43-112 mm) across all the SMCPs. Lowest SMD were observed in April 2023 (range: 45.57-80.22 mm) across all SMCPs.

Table 24: Change in soil moisture content at 0.4 m depth for the different soil moisture conservation practices at National Coffee Research Institute, Mukono, Uganda

SMCPs	Dry season Mean±sem (mm)	Wet Mean±sem (mm)
ACS	-6.98±1.26	7.99±0.99ab
CCS	-9.42 ±1.04	10.09±0.82a
CMS	-6.20 ±0.98	6.26±0.77b
COSS	-7.78 ±0.95	9.08±0.75a
P value SMCPs	0.175974	0.005697 **
Season		
Wet	8.36±0.50a	
Dry	-7.60 ± 0.41 b	
p value Season	< 2.2e-16 ***	
p value Season*SMCPs	0.001153 **	
cv	94.28	82.83

CMS, coffee mulch system; ACS, coffee Albizia coriaria system; CCS, coffee cover crop system; COSS, open coffee sun system; mm, milliliters

Table 25: Soil moisture deficits for the different soil moisture conservation practices at National Coffee Research Institute, Mukono, Uganda

SMCPs	Dry season			Wet season		
	Mean±sem (mm)	Max	Min	Mean±sem (mm)	Max	Min
ACS	104.29±4.47a	131.38	67.89	94.63±2.04a	133.11	60.66
CCS	89.03b±3.70b	113.76	54.59	75.50±1.69b	108.9	53.9
CMS	65.38±3.47c	92.64	8.09	58.84±1.59c	90.47	35.58
COSS	102.56±3.37b	130.98	69.07	91.17±1.54a	133.62	60.49
P value: SMCPs	6.152e-12 ***			< 2.2e-16 ***		
Season Wet	74.80± 1.24b	133.62	35.58			
Dry	89.39±1.52a	131.38	8.09			
P value: season	0.0005805 ***					
P value: SMCPs*season	0.6632309					
cv	20.16			18.01		

CMS, coffee mulch system; ACS, coffee Albizia coriaria system; CCS, coffee cover crop system; COSS, open coffee sun system.

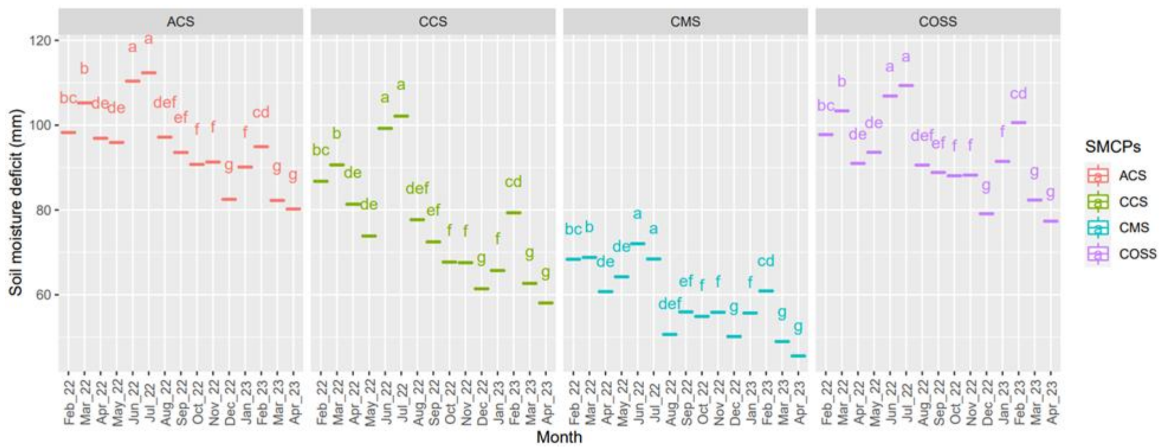


Figure 39: Soil moisture deficit levels of different soil moisture conservation practices per month at the National Coffee Research Institute, Mukono, Uganda

Within a SMCP, months followed by the same letter are not significant; CMS, coffee mulch system; ACS, coffee Albizia coriaria system; CCS, coffee cover crop system; COSS, coffee open sun system; mm, milliliters; Feb, Feburary; Mar, March; Apr, April; Jun, June; Jul, July; Aug, August; Sep, September; Oct, October; Nov, November; Dec, December, Jan, January.

5.4.12 Change in soil moisture content in the different soil moisture conservation practices at Kaweri Coffee Plantation Limited

Table 26 shows that there was no significant difference in change in soil moisture among SMCPs for both dry and wet seasons. KCPL experienced negative change in soil moisture in both dry and wet season. During the dry season, ACS (-4.82 mm) experienced the highest negative change in soil moisture whereas, the least was observed under COSS (-2.42 mm). However, in the wet season, the highest negative change in soil moisture was under CCS (-17.75 mm) while the lowest was under ACS (-10.54 mm).

Table 26:Change in soil moisture content at 0.4m per soil moisture conservation practices at Kaweri Coffee Plantation Limited, Mubende, Uganda

SMCPs	Dry season Mean±sem (mm)	Wet Mean±sem (mm)
ACS	-4.82±7.61	-10.54±3.25
CCS	-3.27 ±9.04	-17.75±5.10
CMS	-2.72 ±7.10	-12.95±4.74
COSS	-2.42 ±6.38	-12.09±4.67
P value SMCPs	0.9961	0.985
Season		
Wet	-11.83±3.93a	
Dry	-3.31± 3.21b	
p value Season	< 2.2e-16 ***	
p value Season*SMCPs	0.8890	
cv	-563.24	-75.98

CMS, coffee mulch system; ACS, coffee Albizia coriaria system; CCS, coffee cover crop system; COSS, open coffee sun system; mm, milliliters.

5.4.13 Influence of Location on change in soil moisture content

There was a significant difference ($p<0.001$) in soil moisture change between Mukono and Mubende (Table 27). During the wet season, Mukono recorded an increase of 8.36 mm, while Mubende showed a decrease of -11.83 mm. In the dry season, significant differences were still observed between the two locations (p ≤

0.05), with Mukono having a larger negative change (-7.60 mm) compared to Mubende (-3.31 mm).

Table 27: Influence of Location on change in soil moisture content

Season	Location	Change in soil moisture
	NaCORI	8.36±0.41
	KCPL	-11.83±1.75
Wet	p value	< 2.2e-16 ***
		97.0
	NaCORI	-7.60±0.63
	KCPL	-3.31±1.81
Dry	p value	0.02614 *
		124.7

NaCORI, National Coffee Research Institute; KCPL, Kaweri Coffee Plantation Limited

5.4.14 Efficiency of soil moisture conservation practices in conserving soil moisture relative to the coffee open sun system

Results showed that the efficiency of SMCPs for conserving soil moisture at NaCORI was significantly ($p<0.05$) increased by CMS (45.32%) and CCS (13.68%) but, decreased by ACS by 29.32% within the coffee root zone (Figure 41). On the other hand, all the SMCPs increased the efficiency for conserving soil moisture at KCPL but not significantly ($p=0.9796$) (Figure 42). However, the highest increment (19.45%) was registered under CMS, followed by ACS (18.73%) and least was under CCS (17.38%).

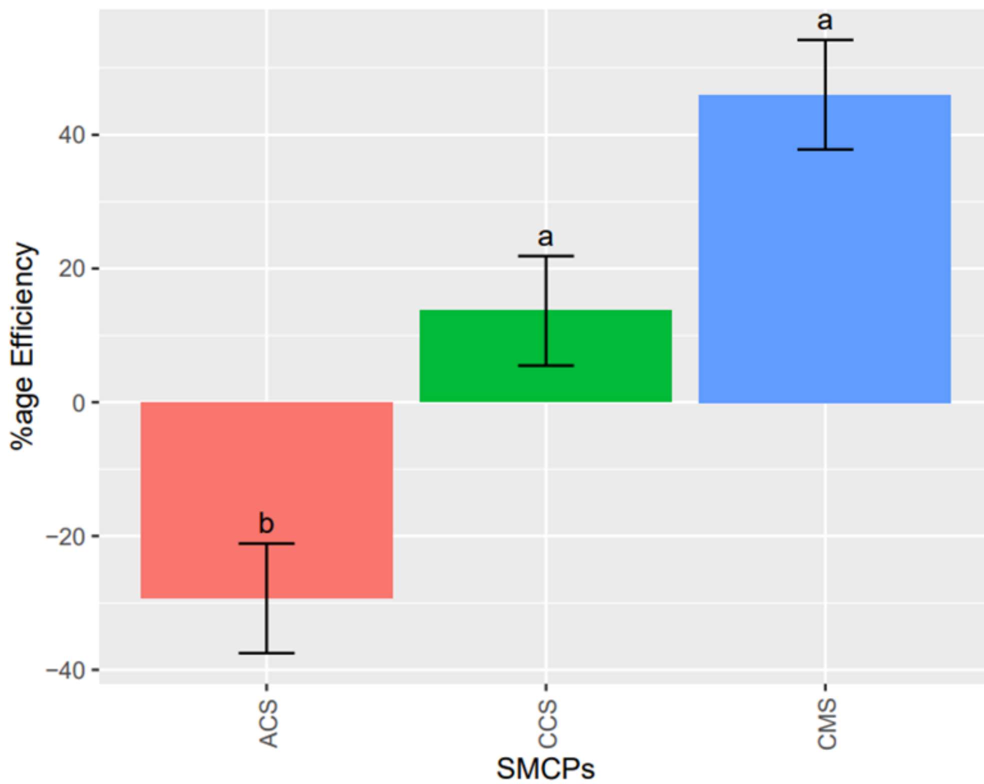


Figure 40: Percentage efficiency of different soil moisture conservation practices in conserving soil moisture at the National Coffee Research Institute, Mukono, Uganda

SMCP followed by the same letters are not significant; CMS, coffee mulch system; ACS, coffee A. coriaria system; CCS, coffee cover crop system; %age, Percentage.

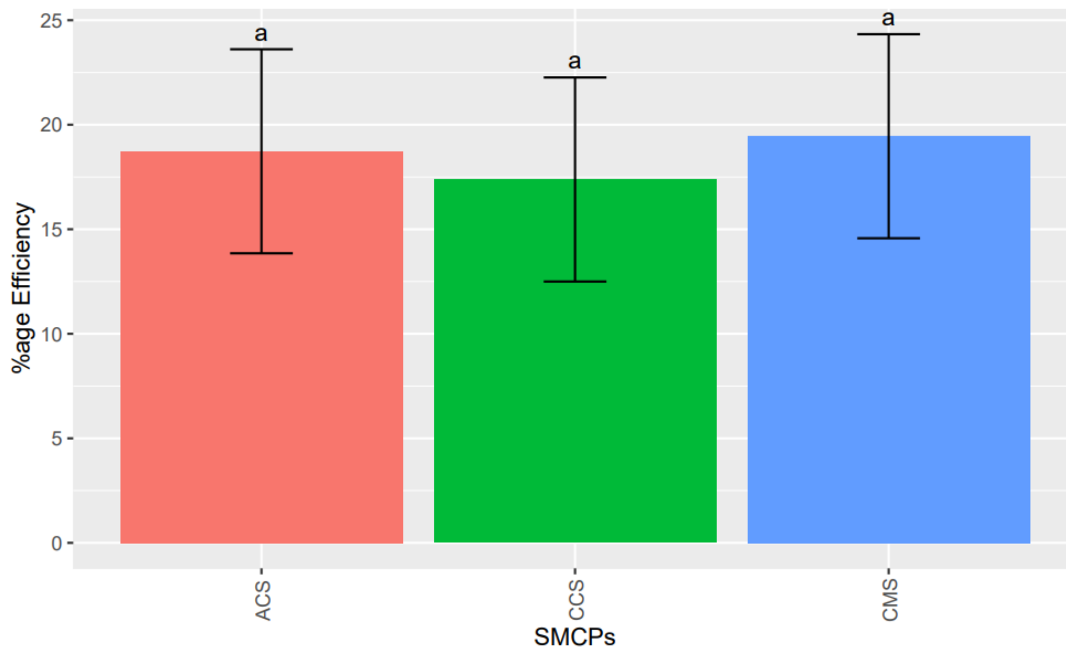


Figure 41: Percentage efficiency of different soil moisture conservation practices in conserving soil moisture at Kaweri Coffee Plantation Limited, Mubende Uganda. *SMCP followed by the same letters are not significant; CMS, coffee mulch system; ACS, coffee A. coriaria system; CCS, coffee cover crop system; %age, Percentage.*

5.4.15 Comparison of efficiency between NaCORI and KCPL

No significant differences were observed in the efficiency of soil moisture conservation practices between the two locations, with NaCORI showing 15.05% efficiency and KCPL 18.52%. (Table 28).

Table 28: Percentage soil moisture conservation efficiency between NaCORI and KCPL

Location	Efficiency (%)
NaCORI	15.05±9.02
KCPL	18.52±8.51
p value	0.6623
	164.5

NaCORI, National Coffee Research Institute; KCPL, Kaweri Coffee Plantation Limited

5.4.16 Influence of soil moisture conservation practices on coffee growth parameters at the National Coffee Research Institute

There was no significant difference ($p \geq 0.05$) in coffee growth parameters across the SMCPs in both seasons (Table 29 and 30). However, in the dry season, CMS had the highest stem girth (5.24 cm), number of stem internodes (52.28), length of the longest primary (110.8 cm) and number of primary internodes (26.3) while ACS had the highest canopy diameter (298.3 cm) and canopy height (144.2 cm). On the other hand, the lowest stem girth (4.99 cm), canopy diameter (283.4 cm), stem length (253.6 cm) were recorded under CCS while the lowest number of primaries (42.15), number of stem internodes (48.98), length of the longest primary (92.7 cm) and number of primary internodes (18.38) were observed under ACS and COSS had the lowest canopy height (130.7 cm). In the wet season, CMS had the highest number of primaries (41.98), canopy diameter (361.3 cm), length of the longest primary (136 cm) and number of primary internodes (31.27) while ACS had the highest stem girth (5.84). On the other hand, CCS had the lowest stem girth (5.52 cm), number of primaries (33.82), canopy diameter (326.1 cm), number of primaries

(25.02), stem length (289.4), canopy height and length of the lowest primary (104.4) whereas, ACS had the lowest number of stem internodes (55.68).

Table 29: Influence of the different soil moisture conservation practices on Robusta coffee growth parameter in the dry season at the National Coffee Research Institute, Mukono, Uganda

SMCPs	SG (cm)	NP	CD	NSI	LLP	NPI	SL	CH
ACS	5.14±0.29	42.15±4.45	298.3±18.82	48.98±2.20	92.7±8.129	18.38±2.70	260.9±14.27	144.2±16.95
CCS	4.99±0.23	43.77±3.51	283.4±14.86	50.45±1.73	101.4±6.42	24.94±2.13	253.6±11.27	134.2±13.39
CMS	5.24±0.23	45.52±3.51	287.4±14.86	52.28±1.73	110.8±6.42	26.03±2.13	264.3±11.27	136.4±13.39
COSS	5.07±0.23	45.52±3.51	283.6±14.86	51.45±1.74	102.6±6.42	25.03±2.13	266.1±11.27	130.7±13.39
p value	0.887	0.922	0.927	0.677	0.392	0.157	0.868	0.94
cv	15.47	27.32	17.88	11.77	21.6	30.62	14.91	34.08

ACS, coffee Albizia coriaria system; CCS, coffee cover crop system; CMS, coffee mulch system; COSS coffee open sun system; SG stem girth; NP, number of primaries; CD, canopy diameter; NSI, number of stem internodes; LLP, length of longest primary; NPI, number of primary internodes; SL, stem length; CH, canopy height.

Table 30: Influence of the different soil moisture conservation practices on Robusta coffee growth parameters in the wet season at the National Coffee Research Institute, Mukono, Uganda

SMCPs	SG (cm)	NP	CD (cm)	NSI	LLP (cm)	NPI	SL	CH (cm)
ACS	5.84±0.31	39.08±4.29	351.4±26.63	55.68±2.89	112.1±12.49	25.77±3.28	305.1±12.02	136.6±19.66
CCS	5.52±0.24	33.82±3.39	326.1±21.03	59.18±2.28	104.4±9.87	25.02±2.59	289.4±9.5	99.4±15.53
CMS	5.80±0.243	41.98±3.39	361.3±21.03	62.68±2.28	136±9.87	31.27±2.59	305.9±9.5	136.3±15.53
COSS	5.58±0.24	35.07±3.39	332.4±21.03	62.93±2.28	119.3±9.87	27.02±2.59	304.1±9.5	135.5±15.53
p value	0.771	0.325	0.63	0.185	0.161	0.353	0.581	0.271
cv	14.83	31.37	21.24	13.02	28.78	32.61	10.91	42.54

ACS, coffee Albizia coriaria system; CCS, coffee cover crop system; CMS, coffee mulch system; COSS coffee open sun system; SG stem girth; NP, number of primaries; CD, canopy diameter; NSI, number of stem internodes; LLP, length of longest primary; NPI, number of primary internodes; SL, stem length; CH, canopy height.

5.4.17 Influence of soil moisture conservation practices on coffee growth parameters at Kaweri Coffee Plantation Limited

Table 31 below shows the effect of the different SMCPs on Robusta coffee growth parameters in the wet season at KCPL. Results showed that only the number of stem internodes and canopy height varied significantly ($p \leq 0.05$) across the SMCPs. The highest number of internodes was recorded under CCS (72.56) whereas, the lowest was observed under ACS (50.0). On the other hand, the highest canopy height was recorded under ACS (198.1 m) and the lowest under COSS (121.3 m). Though the other growth parameters were not significantly different ($p \geq 0.05$) across the SMCPs, CCS had the biggest (5.62 cm) and tallest stems (323.0 cm) whereas, CMS had the biggest canopy (59.11 cm) and highest number of primary internodes (28.44). ACS had the longest primary branches (128.5 cm) while, COSS had the highest number of primary branches. On the other hand, ACS had the lowest number of primaries (48.0) and shortest stems (308.1 cm) whereas, COSS had smallest stems (4.77 cm) and canopy (204.5 cm) as well as the shortest primaries (107.3 cm) and lowest number of primary internodes (23.89).

Table 31: Influence of soil moisture conservation practices on Robusta coffee growth parameters in the wet season at Kaweri Coffee Plantation, Uganda

SMCPs	SG (cm)	NP	CD (cm)	NSI	LLP (cm)	NPI	SL	CH (cm)
ACS	5.22±0.24	48.0±4.84	216.5±15.66	50.0±4.48b	128.5±8.81	25.67±1.86	308.1±18.84	198.1±22.74a
CCS	5.62±0.14	56.0±5.90	208.6±15.72	72.56±3.57a	116.2±6.18	27.44±1.75	323.0±7.70	183.3±22.33ab
CMS	5.16±0.28	48.11±5.57	227.1±21.34	63.89±3.35a	115.1±7.89	28.44±2.36	316.0±12.26	133.7±18.31bc
COSS	4.77±0.24	59.11±5.39	204.5±17.58	66.56±2.58a	107.3±6.45	23.89±1.67	308.6±3.43	121.3±12.52c
p value	0.078	0.381	0.816	**0.0009238 *** **	0.268	0.387	0.796	**0.02827***
cv	12.78	31.07	24.87	16.94	19.2	22.36	11.56	37.8

ACS, coffee Albizia coriaria system; CCS, coffee cover crop system; CMS, coffee mulch system; COSS coffee open sun system; SG stem girth; NP, number of primaries; CD, canopy diameter; NSI, number of stem internodes; LLP, length of longest primary; NPI, number of primary internodes; SL, stem length; CH, canopy height.

5.4.18 Influence of Location on coffee growth parameters

NaCORI had a significantly ($p < 0.01$) had higher stem girth (5.38 cm) compared to KCPL (4.97 cm) (Table 32). The number of primaries was significantly ($p < 0.001$) higher at KCPL (53.11) than at NaCORI (40.88). Canopy diameter and number of stem internodes was significantly ($p < 0.001$) higher at NaCORI (314.64 cm and 55.74 respectively) compared to KCPL (230.49 cm and 48.01 respectively). The length of the longest primary and stem length differed significantly ($p < 0.001$) with KCPL recording the highest values (127.39 cm, and 308.59 respectively) compared to NaCORI (110.59 cm and 280.99 cm, respectively)

Table 32: Influence of Location on change on coffee growth parameters

Location	Coffee growth parameters							
	SG (cm)	NP	CD (cm)	NSI	LLP (cm)	NPI	SL	CH (cm)
NaCORI	5.38±0.09	40.88±1.64	314.64±6.61	55.74±1.48	110.59±2.95	25.74±0.79	280.99±4.01	130.88±5.79
KCPL	4.97±0.09	53.11±1.47	230.49±7.34	48.01±1.65	127.39±3.28	27.08±0.88	308.59±4.47	145.77±6.44
p value	0.002211 **	7.555e-08 ***	1.983e-14 ***	0.0009083 ***	0.0001711 ***	0.225992	3.291e-06 ***	0.07462
	15.4	29.7	22.4	26.6	23.4	28.0	12.8	39.5

SG stem girth; NP, number of primaries; CD, canopy diameter; NSI, number of stem internodes; LLP, length of longest primary; NPI, number of primary internodes; SL, stem length; CH, canopy height. NaCORI, National Coffee Research Institute; KCPL, Kaweri Coffee Plantation Limited

5.4.19 Influence of soil moisture conservation practices on coffee bean quality at the National Coffee Research Institute, Mukono, Uganda

Table 33 shows that there was no significant difference ($p \leq 0.05$) in any of the coffee bean defects among the SMCPs. ACS had the lowest percentage (1.2%) of blacks while CMS had the highest (3.9%). ACS had the lowest floats (0.3%), COSS and CCS with the highest (1.0%). It was also found that ACS had the greatest percentage of bean damage (0.1%), while CMS had the lowest percentage (0.0%). Nipped beans were more under CMS (13.3%) and least under CCS (11.3%). Additionally, Table 34 shows that all of the coffee beans analyzed in ACS, CCS, and COSS were clean, however 8.3% of the coffee samples from CMS were earthly. Furthermore, a majority of the coffee beans across all SMCPs (more than 50%) had a brownish green color, with CCS having the highest percentage (85.7%) and ACS having the lowest (57.1%). Furthermore Table 35, showed that there was no significant difference in coffee screen sizes among SMCPs. Screen size 19 was least under ACS (2.7%), although CMS had the highest (9.4%). When it came to screen 18, ACS had the lowest percentage (6.9%) and CMS had the highest (17.0%). Screen 17 was least under ACS (15.9%) and most under COSS (25.5%), while screen 16 was most under ACS (27.9%) and least under CMS (20.5%). Contrarily, CCS had the highest screen 14 (14.8%) and the lowest was under COSS (9.0%), while ACS had the highest screen 15 (21.6%) and the lowest was under COSS (13.1%). Screen 13 was highest in CCS (9.3%), and lowest in CMS (5.4%); on the other hand, screen 12 was highest in CCS (8.4%) and lowest in CMS (4.9%). In general, CCS dominated screen 14-12, ACS in screen 15-16, CMS in screen 18-19, and COSS in screen 17.

Table 33: Percentage of coffee beans with defects under selected soil moisture conservation practices on Robusta coffee at the National Coffee Research Institute, Mukono, Uganda.

System	% Blacks	% Floats	%Insect	% Nipped	% Partly black	% Hole	% Sound beans	% Defects beans
ACS	1.2±1.0	0.6±0.5	0.1±0.1	12.8±2.0	3.2±3.5	0.0±0.02	82.3±4.4	17.7±4.3
CCS	3.2±1.0	1.0±0.5	0.0±0.1	11.3±1.9	9.6±3.4	0.01±0.02	74.7±4.2	25.3±4.2
CMS	3.9±0.8	0.6±0.4	0.0±0.0	13.3±1.5	10.2±2.6	0.02±0.01	72.5±3.3	27.5±3.3
COSS	3.0±0.8	1.0±0.4	0.0±0.0	12.5±1.6	8.4±2.8	0.02±0.01	75.1±3.5	24.9±3.5
p value	0.279	0.526	0.1386	0.864	0.458	0.839	0.383	0.383
cv	88.44	157.28	454.33	39.75	108.23	207.7	14.72	45.47

ACS, coffee Albizia coriaria; CCS, coffee cover crop; CMS, coffee mulch system and COSS, Open sun coffee.

Table 34: Percentage of coffee beans with different levels of smell and colour under selected soil moisture conservation practices on Robusta coffee at the National Coffee Research Institute, Mukono, Uganda

Levels of variable	ACS (%)	CCS (%)	CMS (%)	COSS (%)
Smell of the coffee beans				
Clean	100.0	100.0	91.7	100.0
Earthly	0.0	0.0	8.3	0.0
Colour of the coffee beans				
Blue green	14.3	0.0	0.0	0.0
Greenish Brown	28.6	0.0	16.7	20.0
Brownish green	57.1	85.7	83.3	80.0
Pale	0.0	14.3	0.0	0.0

ACS, coffee Albizia coriaria; CCS, coffee cover crop; CMS, coffee mulch system and COSS, Open sun coffee.

Table 35: Influence of selected Soil Moisture Conservation Practices on coffee bean size at the National Coffee Research Institute, Mukono, Uganda.

	Screen size							
System	12	13	14	15	16	17	18	19
ACS	7.0±1.6	6.3±1.5	12.1±2.1	21.6±2.6	27.9±2.5	15.9±3.2	6.9±3.6	2.7±2.5
CCS	8.4±1.6	9.3±1.4	14.8±2.0	15.6±2.5	19.3±2.4	19.3±3.1	9.2±3.5	4.2±2.4
CMS	4.8±1.2	5.4±1.1	10.3±1.6	15.5±1.9	20.5±1.9	18.1±2.4	17.0±2.7	9.4±1.9
COSS	7.1±1.3	5.9±1.2	9.0±1.7	13.1±2.1	20.7±2.0	25.5±2.6	14.1±2.9	5.0±2.0
p value	0.341	0.19	0.183	0.108	0.079	0.097	0.14	0.144
cv	62.04	57.33	48.19	40.93	29.42	40.92	72.71	107

ACS, coffee Albizia coriaria; CCS, coffee cover crop; CMS, coffee mulch system and COSS, Open sun coffee.

5.4.20 Influence of soil moisture conservation practices on coffee yield, Actual Crop Evapotranspiration and Water Use Efficiency at the National Coffee Research Institute

Study results showed that there was no significant ($p \leq 0.05$) difference in dry coffee yield, ETa and WUE per hectare per year across the different SMCPs (Table 36). However, coffee under CMS had the highest coffee yield (2,025.35 Kg $Ha^{-1}year^{-1}$) while CCS had the lowest yield (1,935.07 Kg $Ha^{-1}year^{-1}$) whereas, Annual ETa was highest under COSS (1,690.57 mm) and least under ACS (1,664.80 mm). In addition, WUE was highest under CMS (1.22 kg $Ha^{-1}mm^{-1}$) and least under CCS (0.62 kg $Ha^{-1}mm^{-1}$).

Table 36: Influence of the different soil moisture conservation practices on the dry coffee yields, Actual Crop Evapotranspiration and water use efficiency at the National Coffee Research Institute

SMCPs	Dry Coffee yield (Kg $Ha^{-1}year^{-1}$)	ETa (mm $year^{-1}$)	WUE (Kg $Ha^{-1}mm^{-1}$)
ACS	1935.07±748.5	1664.80±9.18	1.16±0.44
CCS	1028.82±591.3	1664.96±7.25	0.62±0.35
CMS	2025.35±591.3	1667.90±7.25	1.22±0.35
COSS	1964.09±591.3	1690.57±7.25	1.15±0.35
p value	0.67394	0.4298	0.64241
cv	59.36	0.75	58.90

CMS, coffee mulch system; ACS, coffee Albizia coriaria system; CCS, coffee cover crop system; Kg, kilogram; Ha, hectare, ETa, actual crop evapotranspiration; WUE, water use efficiency; mm, millimeters.

5.5 Discussion

5.5.1 Influence of soil moisture conservation practices on Soil physical properties

Based on the study findings, the soil moisture conservation practices (SMCPs) varied significantly ($p \leq 0.05$) for all the studied soil physical parameters based on depth. Bulk density (BD) was highest under ACS followed by COSS in the 0-0.4 m and this result is consistent with Kobusinge *et al.* (2023). Similarly, higher bulk densities under unconserved plots than under conserved plots were found by Challa *et al.* (2016) and Jiru and Wegari (2022). This study's observation that organic carbon decreases with depth as also reported by Sakin (2012), explains why BD increased with depth (Tsui *et al.,* 2013; Nath, 2014; Hosea *et al.,* 2018). The average BD for all SMCPs exceeded the recommended values for agricultural soil (Bohn *et al.,* 2001; Kobusinge *et al.,* 2023). According to Tracy *et al.* (2013), this high BD compacts the soil, preventing water from moving through the soil and dispersing evenly. Additionally, the highest porosity was observed in CCS; this could be because of low BD, which creates macropores under this system (Edim Udom & Ehilegbu, 2018). Increasing macroporosity and pore connectivity positively influences the root densities and yields of crops (Williams & Weil, 2004; Chen & Weil, 2010). In both soil depths, organic carbon (OC) was highest under CMS. Mulching has been shown to greatly increase the amount of OC in the soils (Shumba *et al.,* 2024). However, OC was notably low under COSS in the 0.0-0.4m and CCS in the 0.5-0.9m and decreased with depth, as also noted by several earlier studies (e.g. Alemayehu, 2003; Gebresilase *et al.*, 2009; Hailu *et al.*, 2012; Tumwebaze & Byakagaba, 2016). Since organic matter is the main source of nutrients in low input farming systems (Kaizzi *et al.,* 2007), a further decline in the soil's organic matter content is predicted to have an effect on the soil's sustainability and productivity (Page *et al.,* 2020). A previous study by Madigan *et al.* (2022) similarly reported increased OC in the 0-0.4 m. They explained this occurrence by pointing to higher decomposition rates caused by higher faunal activity in the top layers. Holding nutrients, reducing soil erosion, and improving water infiltration all depend on the soil organic carbon (OC) (Page *et al.,* 2020). Since the OC affects the properties of the soil that make it hydrophobic, or resistant to water, and absorbs moisture, it not only determines the amount of moisture present but also the wettability of the soil (Igwe, 2005). Results further showed that under CMS and CCS, Ksat was significantly high in the 0-0.4m range. This finding agrees with several research studies that observed that mulching improves the physical characteristics of soil, including Ksat (e.g. Kakaire *et al.,* 2015; Nzeyimana *et al.,* 2017; Onwuka & Uzoma, 2018; Zhao *et al.,* 2021). On the other hand, Lal (2000), reported that mulch had no significant effect on Ksat for any of the soil layers (0 to 50 cm depth). Furthermore, Ksat was highest under ACS and CCS in the 0.5-0.9 m depth, though not significantly different from the other SMCPs. Igwe (2005) suggests that there may be a link between BD and macropores and consequently, soils may absorb more water more quickly (Easton, 2016). Additionally, the amount of clay rose and peaked under CCS in the 0.5-0.9 m depth and under COSS in the 0-0.4 m depth. While some authors such as Jiru and Wegari, (2022) and Kobusinge *et al.* (2023) have observed low clay content under conserved plots, others (Belayneh *et al.,* 2019; Dagnachew *et al.,* 2020) have reported higher clay content under conserved plots. However, high clay concentration can lead to reduced water infiltration (Adhikary *et al.,* 2008; Cleophas *et al.,* 2022). Study results also showed that CMS had the lowest silt level, and the ACS had the highest silt content. Our findings are in line with earlier studies (Moges *et al.,* 2013; Zebene, 2016; Dori *et al.,* 2022) that reported that agroforestry systems had a higher silt concentration than other agro-systems.

5.5.2 Microclimate created by the different soil moisture conservation practices

In both seasons, the lowest micro temperature was recorded under ACS and highest under CMS at NaCORI. Our findings are in line with earlier studies which have reported lower micro temperatures in coffee agroforestry compared to other coffee systems (de Carvalho *et al.,* 2020; Colombo *et al.,* 2023). These results are reinforced by predictions from the bioclimatic MaxEnt model, which indicated that implementing agroforestry systems with 50% shade cover could lower mean temperatures and preserve approximately 75% of land suitable for coffee cultivation by 2050, particularly at altitudes between 600 and 800 m (Gomes *et al.,* 2020). In comparison to the ambient temperature at the nearby weather station at NaCORI, the temperature in ACS was 0.49 ºC lower while in CMS it was 0.04 ºC higher for all seasons. Application of mulch is also known to lower the soil temperature in coffee agrosystems (Gurnah & Mutea, 1981; Zhao *et al.,* 2024). It should be noted that lowering the temperature when it is outside the ideal range of 22 ºC to 28 ºC for Robusta coffee is very crucial for its production and productivity (Coste, 1992; UCDA, 2019a Handbook). Noteworthy, a temperature decrease within the optimal range encourages higher soil microbial activity, decreased evaporation, and thus, improving crop establishment (Gutierrez, 2007). According to a number of studies (e.g., Craparo, 2020; DaMatta & Ramalho, 2006; Vaast *et al.,* 2006), plants that experience temperatures continuously above 30 ºC may experience reduced and/or abnormal growth. On the other hand, Dayal *et al.* (1991) and Wang *et al.* (2016) revealed that CMS had the greatest temperature when compared to other systems. This is because, according to Stigger *et al.* (2018), mulch creates an insulating layer that keeps heat and moisture from the air from reaching the soil's surface. High temperatures increase evapotranspiration rates, which accelerates soil moisture depletion and intensifies drought stress. This limits water availability for key physiological processes such as photosynthesis, nutrient uptake, and berry filling. Heat stress also disrupts stomatal regulation, leading to reduced carbon assimilation, while simultaneously causing oxidative stress and damage to cellular structures. These in turn negatively impact yield and quality. Throughout the dry and wet seasons, relative humidity was 3.7% higher under ACS and 0.14% lower under CMS. Several authors have reported that coffee grown beneath trees has higher relative humidity than coffee grown in an unshaded system (Ehrenbergerová *et al.,* 2018; Pezzopane *et al.,* 2010). When shade lowers air temperature and light intensity, the relative humidity in the air around coffee plants rises (Assefa & Gobena, 2019). The increased transpiration rates of canopy trees, which pull moisture from deeper soil layers and increase the creation of water vapor, contributing to the high relative humidity in the shade (Assefa & Gobena, 2019). Robusta can grow in conditions with low air humidity or high air humidity that is almost saturated as long as the dry season is short (DaMatta & Ramalho, 2006). High humidity is bad for coffee plants during the rainy season because it increases the chance of fungi that cause diseases like *Hemileia vastatrix*, which causes coffee leaf rust, and pests like coffee berry borer, *Hypothenemus hampei* (Mendesil & Tesfaye, 2009). High air temperature under CMS could have caused its low relative humidity. However, Wang *et al.* (2016) discovered that mulching had no effect on the air's relative humidity when compared to no-mulch.

5.5.3 Influence of soil moisture conservation practices on coffee leaf area index

Additionally, the study results showed that the Robusta coffee LAI varied significantly between the SMCPs, with the highest values under ACS and the lowest values under CCS. Bote and Struik (2011) reported increased LAI with shade; plants use increased leaf area as a coping mechanism to adapt to shading and capture more intense light (Taiz & Zeiger, 2010). The observed LAI drop in COSS, CMS, and CCS was jointly caused by high irradiance and Vapour Pressure Deficit (VPD), which may have increased leaf damage and impeded leaf growth (DaMatta & Ramalho, 2006; Sarmiento-Soler, 2020). Similarly, Robakowski *et al.* (2003) observed that increased light intensity leads to a reduction in leaf area. Numerous studies have demonstrated that leaf area is a key factor in light interception and, consequently, indirectly affects vegetative growth, development rates, photosynthetic efficiency, evapotranspiration, and the utilization of nutrients and water (Williams & Martinson, 2003; Blanco & Folegatti, 2005; Unigarro *et al.,* 2015). On the other hand, it has been noted that cover crops deplete the soil of light, nutrients, and water (Yang *et al.,* 2019), which can have an impact on the development of cash crops. Study results showed that higher LAI values were recorded in coffee plants grown under *A. coriaria*, indicating that these plants were more capable of absorbing CO_2 and generating dry matter than plants grown in sunlight (Bote & Struik, 2011). In ACS and CCS, less water reaches the ground because of the high LAI of *A. coriaria* and the cover crop, which intercepts rainfall (Duan, 2017; Yang *et al.,* 2019). This could have contributed to the low soil moisture content under these systems (Wang *et al.,* 2007).

5.5.4 Influence of soil moisture conservation practices on Actual crop Evapotranspiration

During the wet season, the highest Actual crop evapotranspiration (ETa) was observed under CMS at both sites. Mulch has been shown to boost transpiration by 78%, which explains this finding (Odokonyero *et al.,* 2022). These results, however, were in opposition to research by Eberbach and Pala (2005), which found that ETa under CMS was higher during the dry season. As was discovered at NaCORI, the high temperature of the air and low atmospheric relative humidity under CMS may have contributed to the high ETa (Kosa, 2009). Mulching has been shown to increase transpiration in other crops, such wheat, by 14–15% when compared to unmulched soils (Balwinder-Singh *et al.,* 2011). Zhang *et al.* (2009) reported that elevated ETa improves photosynthesis, which in turn supports crop growth and yield. CCS had the highest ETa at NaCORI during the dry season, whereas ACS had the highest ETa at KCPL. It is possible that SMCPs have a site-specific impact on ETa. Additionally, DeVincentis *et al.* (2022) observed that during the dry season, the cover crop's ETa was higher than the control's. High ETa under coffee agroforestry systems were reported by Siles *et al.* (2010a) and Cannavo *et al*. (2011). Coffee and cover crops and coffee and *A. coriaria* may compete with one another for water due to the high ETa during the dry season, which could result in yield losses (Schmidhuber & Tubiello, 2007; Blanco-Canqui *et al.,* 2015). ETa was low under ACS at both sites during the wet season. ETa was significantly different

($p>0.001$) across the months but SMCPs at both sites did not differ within a month. The water stress experienced in these months caused the available water to fall short of the crop's water requirements, resulting in low ETa in June and July 2022 at NaCORI and June, July 2023 and June 2024 at KCPL (Stoyanova *et al.,* 2023). In comparison to the rainy season, the dry season's ETa was lower. The reduced ETa rate during the dry season could be due to low soil moisture (Stoyanova *et al.,* 2023). The ETa across the SMCPs at NaCORI did not meet CWR in the months of March, April, May, June, July, August 2022, January, and February 2023. At KCPL, in the months of June, July, August of 2023, January, February, March, May and June 2024, CWR was still not met by ET. This impacts coffee growth and yields (Castanheira *et al.,* 2022). Low rainfall during those months caused the low ETa (Stoyanova *et al.,* 2023). Both soil water availability and atmospheric demand have an impact on ETa. De Lannoy *et al.* (2006) also noted that a drop in the rate of evapotranspiration is caused by a decrease in the moisture content. Saraswati *et al.* (2002) similarly recorded high ETa during the rainy season. When the soil is moist, water has a high potential energy and is usually free to flow, which facilitates evaporation (O'Geen, 2013). Water stress occurs when ETa during the dry season is less than CWR; this slows crop growth and reduces yields. Carr (2001) and Ronchi and Mirandi (2020) noted that while water stress is essential for floral induction, water availability is not expected to be a limiting factor in areas where fruit growth and rainfall occur at the same time. NaCORI had a high ETa during the dry season and the least during the wet season and the reverse is true for KCPL. The low ETa during the dry season at KCPL could be due to low soil moisture content during the dry season but when the soil moisture within the first 0.4 m increased ETa increased and surpassed the one of NaCORI. Coffee plants absorb soil moisture within the first 0.4 m (Sarmiento-Soler *et al.,* 2019)

5.5.5 Soil moisture content per soil moisture conservation practices

Due to uneven distribution of rainfall, farming can only be done with water-saving techniques (Chimdessa *et al.,* 2019). In all the SMCPs, the soil moisture content was higher during the rainy than in the dry season as reported by Das *et al.* (2018). Over the course of the study, CMS had the highest soil moisture at NaCORI, while ACS, CCS and CMS had the highest soil moisture at KCPL. The observed variation in soil moisture content trends between NaCORI and KCPL reflects site-specific differences in environmental conditions and soil characteristics. It also shows that the performance of soil moisture conservation practices is context-dependent. High soil moisture content under CMS is in line with other studies that showed highest soil moisture under mulched (Oladohun, 1980;; Ye *et al.,* 2024) and cover crops (Alele *et al*., 2023) systems compared to other SMCPs. Mulching increases soil moisture (Balwinder-Singh *et al*.., 2011). Mulching materials usually give shade over the soil surface to help with improved soil moisture conservation (Lamptey, 2022). The months of March, June, July 2022, January, and February 2023 at

NaCORI saw a decrease in soil moisture in all SMCPs. Soil moisture was low in June, July of 2023 and June 2024 at KCPL and increased as the rainy season began in September 2023 and March 2024. This is probably because the study sites were rainfed, meaning that during the rainy seasons, soil moisture is added but during dry periods, no new soil moisture is provided, and evapotranspiration continues to remove soil moisture (Bayer *et al,* 2015). KCPL had least soil moisture content compared to NaCORI across all depth and season except for 0.0-0.4 m during the wet season. At NaCORI, soil moisture rose with depth in all SMCPs and during both seasons as also observed by Balwinder-Singh *et al.* (2011). The high clay content that firmly binds the soil water explains the high soil moisture in deep soil layers (Satyanaga *et al.,* 2013; Huntley, 2023). At KCPL, soil moisture dropped with depth as also observed by Fang *et al.* (2016) and Meng Sun (2023). Also, in both the dry and wet seasons at NaCORI, the soil moisture content in the range of 0.0-0.4 m and 0.5-0.9 m was significantly ($p<0.001$) higher in CMS and lower in ACS, as also reported by Ye *et al.* (2024). This could be in part due to the fact that the research site has low density, high porosity, and rich organic carbon, and all these have an impact on the high soil moisture content (Kobusinge *et al.,* 2023). However, soil moisture was least under CCS in the 1.0-1.5 m depth, agreeing with Bodner *et al.* (2007) and Kahimba *et al*. (2007). At KCPL, soil moisture was high under CMS, ACS and CCS in the 0.0-0.4 m, this is due to the shading effect on the soil surface. The cover crop often reduces evapotranspiration from the soil's surface and shadows the soil, which could have accounted for CCS's increased moisture content (Alele *et al.,* 2023). Water infiltration is further enhanced by cover crops (Kobusinge *et al.,* 2023). The low bulk density, high porosity, and high organic carbon under CCS at NaCORI further explain this (Kobusinge *et al.,* 2023). Lower soil moisture under ACS at NaCORI than it was under COSS as also observed by Sarmiento-Soler *et al.* (2019), Siles *et al.* (2010b), and Harmand *et al.* (2007) could be because the roots of shade trees used quite a lot more soil water. Also the high bulk density under ACS may have reduced water infiltration (Kobusinge *et al.,* 2023). However, this was contrary at KCPL, where ACS had high soil moisture within the 0-0.4m. The significantly low soil moisture in cover crop in the 1.0-1.5 m at both sites could indicate that the cover crop roots are concentrated within this layer (DeVincenties *et al.,* 2022). The high soil moisture at both sites indicates a stronger capability for water retention of CMS, even though it had high ETa of CMS during the wet season (McMillen, 2013). The soil data at NaCORI explain this, which is caused by the high organic carbon content of CMS relative to other SMCPs across the depths. Mulches decrease evaporation during the dry season, extending the amount of time that plants must absorb water (McMillen, 2013).

5.5.6 influence of soil moisture conservation practices on runoff

Study results further showed that runoff was more during both season under COSS and least under CMS at KCPL. CMS, CCS and ACS had the least amount of runoff during dry season. This finding is in agreement with a number of earlier studies that have reported less runoff occurring in mulched plots compared to other SMCPs (e.g. Nzeyimana, 2018; Tay & Ratnam, 2020; Bombino *et al.,* 2021; Fan *et al.,* 2023). The protective role of mulch against water erosion is evident through the reduction in the impact of raindrops, while organic residue also diminishes surface runoff and heightens infiltration (Mulumba & Lal, 2008). The least runoff under CCS in both seasons could be because the cover crop above-ground biomass, protects soil particles from direct rain (Blanco-Canqui *et al.,* 2015). Also, cover crops have been shown to increase infiltration by 2.8 and 2.2 times as compared to control (Mitchell *et al.,* 2017). Moreso, the low runoff under ACS also during the dry season agrees with earlier studies which have reported reduced runoff under agroforestry systems (e.g. Naharuddin *et al.,* 2018; de Carvalho *et al.*, 2021). Beer (1995) attributed this reduction to the fact that shade trees reduces rain-splash erosion due to reduced impact of rainfall on the ground. In addition, *A. coriaria* sheds off leaves during the dry season which cover the ground and thus reduce the runoff (Li *et al.,* 2014; Liu *et al.,* 2017). Consistent with this, Blanco-Sepúlveda *et al.* (2024) reported that shade litter cover was the dominant factor, explaining 90% of the variability in erosion compared to overall shade cover. Similarly, Blanco and Aguilar (2015) analyzed both types of vegetation cover and found that the litter layer was the key factor influencing erodibility, estimating that effective erosion control occurs when the litter layer covers 60-65% of the soil surface

5.5.7 Change in soil moisture content and Soil moisture deficits in the different soil moisture conservation practices

Furthermore, KCPL experienced negative change in soil moisture in both dry and wet season while NaCORI experienced negative change in soil moisture only during the dry season. At NaCORI, the highest change in soil moisture content was recorded under CCS and lowest under CMS throughout both the wet and dry seasons. Similarly, Mendis *et al.* (2022) reported high reduction in soil moisture under cover crops whereas, several studies have shown an increase in soil moisture under mulch (e.g. Fan *et al.,* 2023; Ye *et al.,* 2024). However at KCPL, during the dry season, ACS experienced the highest negative change in soil moisture and least was observed under COSS. In the wet season, high negative change in soil moisture was under CCS and least under ACS. The system's high ETa experienced may be the cause of the high change in soil moisture during the dry under CCS at NaCORI and ACS at KCPL (Wang *et al.,* 2021). Low ETa under CMS in NaCORI and COSS in KCPL during the dry season is another reason for the minimal change in soil moisture since ETa is strongly correlated with soil moisture (Wilson *et al.,* 2020). Negative change at KCPL during the wet season could be because it had high ETa, low soil moisture, and received low rainfall as compared to NaCORI. This means that soils were still dry at the end of the rainy season leading to water stress affecting coffee growth and yields. The mean rainfall received per month during the wet season at KCPL was 172.5mm and 188.5mm at NaCORI. Also KCPL soil moisture is more near the soil surface in that it can easily evaporate as compared to NaCORI with more soil moisture in the lower layers. Kurc and Small (2007) reported that actual evapotranspiration (ETa) is closely linked to the soil moisture within the top 5 cm of soil. When soil moisture increases, a larger portion of rainfall is directed toward surface runoff or groundwater recharge compared to periods of low soil moisture (Brandes & Wilcox, 2000). This means the negative change in soil moisture contributed to the low soil moisture in the deep soil layers at KCPL. Despite CMS having the greatest ETa at NaCORI during the wet season, the season's rains made up for this loss (Zhang *et al.,* 2010).

The soil water deficit varied with the seasons and SMCPs at NaCORI. Results of this study showed that CMS conserved more moisture than the other SMCPs, agreeing with Stelli *et al.* (2018) and Ibrahim *et al*. (2020). This in part explains why there was a low water deficit under it (Choudhury, 2023). Reduced rainfall, especially in the months of June and July in all SMCPs, made the water deficit in coffee plants at 0.4 m of root depth worse (Afolabi & Omonijo, 2009). Then, as water constraints worsened, crop evapotranspiration actually dropped as also reported by Ramirez-Builes and Kusters (2021). Low soil moisture affects plant water status, nutrient uptake, vegetative development, yield, fruit size, and quality, as observed by Kutywayo *et al.* (2010). A period of water deprivation stress followed by an abundance of water in the root zone may cause the root mortality, leaf loss, degradation of chlorophyll, and significant decrease in photosynthetic assimilates (Hee-Myong, 2001). However, Kutywayo *et al.* (2010) and Lima *et al.* (2021) stated that a regulated water deficit stress is necessary to overcome the floral bud dormancy in coffee.

5.5.7 Efficiency of soil moisture conservation practices in conserving soil moisture relative to the coffee open sun system

In the coffee root zone at NaCORI, CMS and CCS increased soil moisture whereas, ACS decreased soil moisture but at KCPL, CCS, ACS, and CMS enhanced the soil moisture content. These results are consistent with research by Stelli *et al.* (2018), which showed that over the period of around six weeks without irrigation, plants covered with mulch conserved an average of 35% more soil water content than plants without mulch. Mulching is a helpful technique for lowering soil water loss and improving the efficiency of water consumption (Amitav, 2019) and this may be attributed to the improved infiltration capacity and soil transmission qualities (Cairns *et al.,* 2012; Kobusinge *et al.,* 2023). In addition, the finding that CCS increased soil moisture in this study is supported by studies by Liebig *et al.* (2015) and Júnior *et al.* (2022). Recent research has shown that even in regions with variable rainfall, long-term use of cover crops improves soil water relations (Basche *et al.,* 2016). Schmidhuber *et al.* (2009), noted that cover crops compete with related crops for nutrients and water, harbor pests and diseases, lowering yields, and sometimes climbing related crops. Furthermore, the finding from this study show that ACS decreased soil moisture at NaCORI is supported by earlier studies by Ehrenbergerová *et al.* (2018) which observed that locations with shade were drier than those without. In contrast, results at KCPL showed that ACS increased soil moisture, agreeing with the findings of Etafa (2022) and Morais *et al.* (2006), who found that soil moisture was higher beneath the canopies of shade trees. This shows that effect of shade tree on soil moisture conservation could be site specific explaining the differences in effect of ACS at the two sites. Though the efficiency of soil moisture conservation among the two sites was not significant. KCPL had a higher efficiency compared to NaCORI and this is due to the fact that the shade tree at KCPL also increased soil moisture conservation while at NaCORI, it decreased soil moisture

5.5.8 Effect of soil moisture conservation practices on coffee growth parameters

Though there was no significant ($p \geq 0.05$) difference in coffee growth parameters across the SMCPs in both seasons, the highest values of most of the growth parameters were recorded under CMS and ACS (Table 15 and 16). This finding is in line with earlier studies by Amin *et al.* (2018) and Djoah *et al.* (2022) which have reported that mulching enhances the growth and yield of coffee. Similarly, studies by Piato *et al.* (2020) demonstrated that shade trees had a positive impact on coffee growth. This could have been in part due to the fact that the mulching and agroforestry systems enhance conservation of soil water by decreasing evaporation and managing the soil's temperature (Lil, 2010; Padovan *et al.,* 2018; El-Beltagi *et al.,* 2022; Hailu & Asefa, 2024). In addition, higher values of growth parameters under mulch and agroforestry systems could also be attributed to higher nutrients (N, P and K) added through decomposition of the organic matter from the mulching material and litter fall from the *A. coriaria* since coffee strongly responds to these nutrients (Nzeyimana *et al.,* 2020; Kobusinge *et al.,* 2023). On the other hand, the number of stem internodes (NSI) and canopy height (CH) varied significantly ($p \leq 0.05$) across the SMCPs) with the highest value of NSI being recorded under CCS while the highest CH was observed under ACS. Yimyam *et al.* (1998) reported that coffee intercropped with black bean or lablab increased coffee height, number of primary branches, and canopy diameter as compared to no cover treatment. Similarly, Carvalho *et al.* (2024), observed that using soybean as a cover crop in coffee plantation increased NSI but in this case, not significantly. Beyond enhancing productivity, incorporating cover crops in coffee plantations fosters greater plant diversity, which in turn boosts the population of natural enemies that target key Arabica coffee pests (Rosado *et al.,* 2021). Likewise, previous studies have shown that shade promotes taller canopy growth (Yuliasmara *et al.,* 2022; Sembiring *et al.,* 2023). Plant height tends to increase under low light conditions because auxin, a growth hormone, is more stable and effective in such environments, whereas it is prone to damage or degradation under high light intensity (Korobova *et al.,* 2023). This increase in height under shade serves as an adaptive strategy, allowing coffee plants to optimize light capture by individual leaves (Ayalew, 2018).

5.5.9 Effect of soil moisture conservation practices on coffee bean quality

This study's findings demonstrated that there was no significant ($p \geq 0.05$) difference across the SMCPs among all coffee bean defects. These results concur with those of Silva Neto *et al.* (2018), who found no difference on the impact of various management practices on defects in coffee beans. Even though there are no significant differences in coffee bean defects among treatments, a small variation may have a detrimental effect on the coffee's final cup quality (Franca & Oliveira, 2008). In general, ACS had the largest percentage of sound beans and the lowest percentage of blacks, floats, and partially beans. The present findings corroborate those of Odeney *et al.* (2015), who discovered that shade reduces the proportion of rejects, which includes berries that are diseased, mummified, or desiccated. Similarly, Muschler (1998) found that coffee cultivated in Costa Rica under shade had a drop in rejects from 10% to less than 1%. Shade delays ripening and influences uniform ripening, which may contribute to a lower frequency of physical damages (Muschler, 2001; Vaast *et al.,* 2006). Shade also produces a microclimate that reduces heat stresses in plants, increases the leaf to fruit ratio and net photosynthetic rate, and prolongs the berry maturity time (DaMatta & Ramalho, 2006). It has been observed, nonetheless, that shade boosts the production of large coffee beans (Muschler 2001). According to Kathurima *et al.* (2012), Kenya's shade contributed significantly to the rise in premium grades, AA and AB, which are highly valued in the world market for coffee. Larger beans are often preferred in the commercial market because they are associated with uniform roasting, better appearance, and higher market prices. Berries grow and develop more slowly at lower temperatures in shaded places because this gives them more time to fill and gather more sugar and phenolic chemicals, which are associated to scent. A higher overall sensory quality of coffee is the outcome of this (Muschler, 2001). As Silva Neto *et al.* (2018) also revealed, all systems had insect damaged beans percentages that were extremely close to zero; however, the results in this investigation showed that the highest number of beans damaged by insects was reported under ACS. Coffee berry borer (CBB), *Hypothenemus hampei* (Ferrari), coffee berry moth, *Prophantis smaragdina* (Butler), and coffee bean weevil, *Araecerus fasciculatus* (De Geer) are the main insects that cause damage to coffee beans, though a variety of other insect species may also attack coffee berries (Abedeta *et al.,* 2011; Gaitán *et al.,* 2015; Barrera, 2017). Shade is a preferred habitat for the coffee berry borer infestation as shown by the higher infection rates in shaded coffee plants compared to coffee in the sun (Mariño *et al.,* 2016). The current data further showed that there was no significant difference in coffee bean size among SMCPs, as Silva Neto *et al.* (2018) also disclosed. CMS had more of screens 18 and 19, COSS had screen 17, ACS had screens 15 and 16, while CCS had more of screens 14, 13, and 12. CMS dominated the upper screen sizes since bean size distribution has been shown to be influenced by soil properties, specifically pH, organic matter, texture, and manganese (Mn) (Yadessa *et al.,* 2020a, b). Application of mulches in coffee agro-systems increases soil organic carbon and plant nutrients (Nzeyimana *et al.,* 2017, 2019). The larger beans in CMS may have resulted from mulching, which also improves moisture retention in coffee agro-systems (Mohammedsani *et al.,* 2018) as observed in this chapter. Soil moisture is one of the primary factors influencing bean size, according to Wrigley (1988). This is because the amount of integument inside each ovule before the parchment lignifies and creates an embryonic sac that is eventually filled with endosperm affects the size of the final bean. The flexibility of the parchment, which is the ovule's outer layer, also plays a role in this. The integument volume is determined by the moisture content of the soil during the expansion phase of berry growth (Worku *et al.,* 2022). On the other hand, the small bean sizes under ACS might have been caused by low soil moisture content. However, due to fewer blossoms and fewer fruits per plant than coffee cultivated in the open, Bote and Struik (2011) discovered that coffee grown in shade generated larger beans than coffee grown in the sun (Damatta, 2004).

5.5.10 Effect of soil moisture conservation practices on coffee yield, Actual Crop Evapotranspiration and Water Use Efficiency

Study results further showed that coffee yields increased by 3.11 under CMS but, decreased by 47.62% and 1.48% under CCS and ACS respectively at NaCORI. This finding agree with studies by Bucagu *et al.* (2013) and Nzeyimana *et al.* (2018) that reported higher yields of coffee under mulched plots and research by Kimemia (2003) and Giller (2001) who reported reduced coffee yield under cover crops. WUE was highest under CMS and lowest under CCS, agreeing with Zhang *et al.* (2024) who reported higher WUE under mulch compared to other coffee systems. The high yield under CMS, or 1.22 kg of coffee produced per mm of water, may be the cause of the system's high WUE. According to Ngangom *et al.* (2020), the increase in yield further illustrates how well mulch improves soil moisture retention and WUE. In a similar vein, Zizinga *et al.* (2022) showed that mulch in maize increased WUE. Furthermore, the finding that coffee yield decreased under ACS is supported by studies Campanha (2004) and Vaast *et al.* (2006). However, some authors have reported that agroforestry systems positively affect coffee (Lui, 2018; Vaast *et al.* 2008) whereas, others have reported no difference (Meylan *et al.,* 2017; Rigal *et al.,* 2020). According to Vaast *et al.* (2008), an increase in bean size and weight was due to decreased fruit load in the shade which caused less competition for nutrients and carbohydrates. The age of the coffee plant may also have an impact on the outcome. For example, a meta-analysis by Piato *et al*. (2020) revealed that shade had beneficial effects on older shrubs of the Robusta coffee plant (mean age, 16 years), but minimal or negative impacts on younger bushes. Therefore, it is imperative to utilize management strategies that are suited for the local environment, such as selecting the species and degree of shade (Koutouleas *et al.,* 2022). On the other hand, noted that limited water resources cause cover crops to lower yields. Coffee and cover crops may compete with one another for water and nutrients in the soil, which could explain the reduced yields under CCS (Giller, 2001; Gardarin *et al.,* 2022). Another reason for lower yields of coffee under cover crops could have been the lower potassium as observed by Kobusinge *et al*. (2019). Potassium is essential for coffee fruit set, dry weight, and volume (Kobusinge *et al.,* 2023). However, Carvalho *et al.* (2010) demonstrated that the use of cover crops increased coffee productivity.

CHAPTER SIX: CONCLUSION, RECOMMENDATION AND SUGGESTIONS FOR FUTURE RESEARCH

6.1 Conclusion

Climate change poses a significant threat to global coffee production, as farmers may face not only decreased yields but also a decline in areas suitable for coffee cultivation (Jaramillo *et al.,* 2011; Haggar & Schepp, 2012; Bracken *et al.,* 2023). This shift is likely adversely affect the ecosystem (Bilen *et al.,* 2023). More so, Feng (2015) stated that variations in the climate could make variations in soil moisture more unclear. In Uganda, most farmers rely on rainfall as a source of water for production. To be able to maintain productivity amidst water stress, farmers will need to adopt soil moisture conservation practices. This study therefore aimed at determining the effect of climate change on soil moisture in Uganda, estimating water use efficiency of Robusta coffee under different phenological stages under coffee *Albizia coriaria* and open sun systems and also determining the effect of soil moisture conservation practices on water relations in Robusta coffee agro-systems.

Despite the increase in erratic rains and temperature as previously reported by a number of scholars (e.g. Endris *et al.,* 2019 & Olaka *et al.,* 2019), soil moisture will increase as a result of climate change. This will increase coffee suitability in Uganda by 10% in the years 2025-2050, with areas in central, western and eastern reminding suitable while Karamonja sub-region will increase in suitability. The increase in suitability will be due to increase in rainfall in this area. However, there will be a reduction in soil moisture suitability West Nile and Mid Northern Uganda. This therefore calls for the need to adopt soil moisture conservation practice in less suitable areas.

Water availability is crucial for successful coffee cultivation, as it affects the plant's phenology, which in turn impacts its yield, quality, and marketability (Silva *et al.,* 2019). Estimation of water use efficiency (WUE) in Chapter 4 showed that ACS had a high WUE per phenological stages compared to COSS. Under ACS, Yellow berries and 60-90% phenological stages had the highest WUE while under COSS, 10-50% and 100-ripening had the highest WUE. ACS took longer time to complete its fruit phenological stages as compared to COSS. There was system and varietal effect on coffee water use, this could mean there is competition for water between coffee and *A. coriaria.* Similarly, there was a varietal and system effect on coffee bean weight and coffee growth response. Bean weight was higher under COSS than ACS. The COSS had a high bean weight with clone 203/32/2 while ACS had a high bean weight with clone MFCT1. The choice and placement of varieties relative to shade trees is therefore a key consideration for improved water use, coffee growth response and bean weight that ultimately influence yield.

Adoption of suitable soil water conservation practices (SMCPs) is proving to be an effective means in mitigation of water stress induced by climate change (Kumar & Bhople, 2017). However, Chapter 5, shows that effect of SMCPs on soil water relations is site specific. CMS influenced the soil water relations better compared to other SMCPs at NaCORI even though it had a high ETa during the wet season. At KCPL, CCS, ACS and CMS improved soil moisture content compared to COSS.

6.2 Recommendations

1) Near future unstable areas of West Nile and Mid Northern Uganda should adopt soil moisture conservation practices such as CMS to reduce on water stress likely to come due to climate change.
2) Policy makers should encourage the adoption of these soil moisture conservation practices such as mulch, cover crop and *Albizia coriaria* through incentives and subsides.
3) *A. coriaria* should be optimally used as a way for improving water use efficiency of fruit development without compromising on bean weight and yield. For example, clone MFCT1 can be adopted under *A. coriaria*
4) This study also highlighted that the effect of SMCPs on soil water relations is site specific. Therefore, the need for site specific studies when

recommending SMCPs that farmers can adopt as they adapt to the effects of climate change.

5) Extension services should train farmers on the appropriate soil moisture conservation practices for their areas particularly where coffee suitability is expected to decline.

6.3 Suggestions for future research

1) There is also need to determine how the changes in soil moisture suitability in the near future will translate to changes in coffee production.
2) There is also need to do cost:benefit analysis of soil moisture conservation practices
3) There is need to determine which genotypes perform well under shade in terms of increased yields and reduced water use so as to strategically place those genotypes under shade in an agroforestry system.
4) There is a need to investigate the vertical distribution of fine roots in both coffee and shade trees within coffee agroforestry systems
5) This study focused on central region, therefore future studies should extend the analysis to regions with distinct rainfall regimes, such as eastern and northern Uganda, in order to assess the transferability and robustness of the findings across broader agro-ecological zones

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Dimensions on Maize (Zea mays L.) Production in a Sub-Humid Climate. *Water*, 14, 79. https://doi.org/10.3390/w14010079

APPENDICES

Appendix 1: Approval from Research Ethics Committee

UG-REC-026 Exemption Letter Version 1.0 29th May, 2021

UGANDA CHRISTIAN UNIVERSITY
A Centre of Excellence in the Heart of Africa

29th May, 2021

Judith Kobusinge
P. O. Box 1, Kyambogo
Kampala, Uganda.
+256(0) 779218566
judithkobusinge24@yahoo.com

UG-REC-026 EXEMPTION NOTICE

To: Ms. Judith Kobusinge, Principal Investigator
Re: UCUREC Application titled ***"Effect of Selected Soil Moisture Conservation Practices on Water Budgeting in Robusta Coffee in Uganda"***

Application Number: **UCUREC-2021-104-01**

Version: 1.0

Type: [ ] Initial Review
[ ] Protocol Amendment
[ ] Letter of Amendment (LOA)
[ ] Continuing Review
[ ] Material Transfer Agreement
[*] Other, Specify: **Exemption Request**

I am pleased to inform you that the **UG-REC-026; UCUREC** exempted the above referenced application.

Exemption of the research is for the period from 29th May, 2021, to 29th May, 2022.

This research is considered minimal risk category.
As Principal Investigator of the research, you are responsible for fulfilling the following requirements of approval:

1. All co-investigators must be kept informed of the status of the research.
2. Changes, amendments, and additions to the protocol must be submitted to the REC for re-review and approval prior to the activation of the changes. The REC exemption number assigned to the research should be cited in any correspondence.

1 of 2

A Complete Education for A Complete Person

P.O. Box 4, Mukono, Uganda (East Africa), Plot 67-173, Bishop Tucker Road, Mukono Hill,
Tel: +256 (0) 31 235 0800, Web: www.ucu.ac.ug UgandaChristianUniversity @UCUniversity
Founded by the Province of the Church of Uganda. Chartered by the Government of Uganda

UGANDA CHRISTIAN UNIVERSITY
A Centre of Excellence in the Heart of Africa

3. Reports of unanticipated problems during study or other must be submitted to the UCUREC for notification. New information that becomes available which could change the status of the study; i.e. involving participants, must be communicated to UCUREC.

4. Regulations require review of an exempted study not less than once per 12-month period. Therefore, a continuing review application must be submitted to the REC eight weeks prior to the above expiration date of 29th April, 2022 in order to continue the study beyond the approved period. Failure to submit a continuing review application in a timely fashion may result in suspension or termination of the study, at which point any change in approach to data collection must be communicated.

5. You are required to register the research protocol with the Uganda National Council for Science and Technology (UNCST) for final clearance to undertake the study in Uganda.

The following is the list of all documents approved in this application by UG-REC _026:

	Document Title	Language	Version	Version Date
1.	Research Proposal	English	1.0	7th May, 2021
2.	Request for REC exemption	English	1.0	7th May, 2021
3.	Risk Management Plan	English	1.0	4th May, 2021
4.	Administrative Clearance National Coffee Research Institute	English	1.0	17th May, 2021
5.	Data Collection Tools	English	1.0	7th May, 2021
6.	Kobusinge Judith Admission Letter	English	1.0	10th September, 2019

Signed and Stamped

Prof. Peter Waiswa
UCUREC Chairperson,
pwaiswa@musph.ac.ug

2 of 2

A Complete Education for A Complete Person

P.O. Box 4, Mukono, Uganda (East Africa), Plot 67-173, Bishop Tucker Road, Mukono Hill,
Tel: +256 (0) 31 235 0800, Web: www.ucu.ac.ug UgandaChristianUniversity @UCUniversity
Founded by the Province of the Church of Uganda. Chartered by the Government of Uganda

Appendix 2: Approval from Uganda National Council of Science and Technology

Uganda National Council for Science and Technology

(Established by Act of Parliament of the Republic of Uganda)

UNCST

Our Ref: A117ES **19 August 2021**

Judith Kobusinge
Kyambogo University
Kampala

Re: Research Approval: **Effect of selected soil moisture conservation practices on water budgeting in Robusta coffee in Uganda**

I am pleased to inform you that on **19/08/2021**, the Uganda National Council for Science and Technology (UNCST) approved the above referenced research project. The Approval of the research project is for the period of **19/08/2021** to **19/08/2024**.

Your research registration number with the UNCST is **A117ES**. Please, cite this number in all your future correspondences with UNCST in respect of the above research project. As the Principal Investigator of the research project, you are responsible for fulfilling the following requirements of approval:

1. Keeping all co-investigators informed of the status of the research.
2. Submitting all changes, amendments, and addenda to the research protocol or the consent form (where applicable) to the designated Research Ethics Committee (REC) or Lead Agency for re-review and approval **prior** to the activation of the changes. UNCST must be notified of the approved changes within five working days.
3. For clinical trials, all serious adverse events must be reported promptly to the designated local REC for review with copies to the National Drug Authority and a notification to the UNCST.
4. Unanticipated problems involving risks to research participants or other must be reported promptly to the UNCST. New information that becomes available which could change the risk/benefit ratio must be submitted promptly for UNCST notification after review by the REC.
5. Only approved study procedures are to be implemented. The UNCST may conduct impromptu audits of all study records.
6. An annual progress report and approval letter of continuation from the REC must be submitted electronically to UNCST. Failure to do so may result in termination of the research project.

Please note that this approval includes all study related tools submitted as part of the application as shown below:

No.	Document Title	Language	Version Number	Version Date
1	Data collection tool	English	1	07 May 2021
2	Project Proposal	English	1.0	
3	Approval Letter	English	1.0	2021-05-07
4	Administrative Clearance	English	1.0	2021-05-07
4	Response to comments (Addressed to Executive Secretary	English	1	18 August 2021

Yours sincerely,

Hellen Opolot
For: Executive Secretary
UGANDA NATIONAL COUNCIL FOR SCIENCE AND TECHNOLOGY

LOCATION/CORRESPONDENCE

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Appendix 3: Introductory letter to study sites

KYAMBOGO UNIVERSITY

P. O. BOX 1 KYAMBOGO
Tel: 041 - 4286792 Fax: 256-41-220464
Website :www.kyu.ac.ug, Email: drgt@kyu.ac.ug

Directorate of Research and Graduate Training

Office of the Director

Date: 24/5/23

TO WHOM IT MAY CONCERN

RE: Kobusinge Judith

Dear Sir/Madam,

This is to introduce to you the above named student Reg: No 19/U/GDSB/18977/PD pursuing PhD in Biological sciences Department of Biological sciences, Kyambogo University.

She/he intends to carry out research on Effect of selected soil moisture conservation practices on water budgeting in Robusta coffee in Uganda in partial fulfillment of the requirements for the award of PhD in biological science.

The purpose of this letter therefore is to request you to grant him/her permission to carry out his/her study in your institution.

Any assistance rendered to him/her will be highly appreciated.

Yours sincerely,

Prof. Bosco Bua
AG. DIRECTOR

KYAMBOGO UNIVERSITY
01 JUN 2023
DIRECTOR
DIRECTORATE OF RESEARCH AND GRADUATE TRAINING