Sokoine University of Agriculture

PhD Thesis

Adapting Coffee (*Coffea Arabica,* L.) Production to Climate Change through Types of Seedlings and Soil Fertility Management Practices in Tanzania

Suzana Gasper Mbwambo

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ADAPTING COFFEE (*Coffea arabica,* L.) PRODUCTION TO CLIMATE CHANGE THROUGH TYPES OF SEEDLINGS AND SOIL FERTILITY MANAGEMENT PRACTICES IN TANZANIA

Thesis submitted to Sokoine University of Agriculture in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

By

SUZANA GASPER MBWAMBO

Principal Supervisor: Dr. Sixbert K. Mourice
Co-supervisor: Prof. Akwilin J. P. Tarimo

***Department of* Crop science and Horticulture**
***College of* Agriculture**
Sokoine University of Agriculture, Morogoro, Tanzania

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EXTENDED ABSTRACT

In Tanzania, coffee is the second largest traditional export commodity after tobacco, accounting for 24 % of the country's total foreign exchange earnings. Average annual production has stagnated at about 50,000 metric tons over the past 35 years. One of the widely held reasons is climate change, manifested by high rainfall variability and decline as well as increase in temperature. Elsewhere different adaptation strategies like use of shade trees, drought tolerant coffee varieties and organic fertilizer have been proposed to deal with the effect of climate change on coffee production. However, climate change adaptation studies for coffee production in Tanzania are largely missing. An overall objective of this work was to develop agronomic techniques for adapting *Coffea arabica,* L. production to climate change. Specifically, the study aimed to: 1) asses coffee growers' perceptions on climate change; 2) asses the relationship between scientific climate change record and production records; 3) evaluate field performance of compact coffee variety under selected propagation methods and soil fertility amendment practices and 4) determine the role of type of seedling and fertilizer management practices in increasing resilient of coffee species to the changing climate.

The study was undertaken in the Northern Highland zone (Kilimanjaro and Arusha regions) and Southern Highland zone (Songwe, Mbeya and Ruvuma regions), purposively selected based on the level of Arabica coffee production. First a survey was conducted to examine smallholder farmers' perceptions of climate change. The findings indicate that, 163 (67 %) farmers perceived climate change has been taking place in their areas (increase in temperature and decrease in rainfall); the most influential factors in their perception being level of education, farming experience and access to climatic information. Farmers' perceptions were also consistent with meteorological data both pointing to significant decline in rainfall and increase in temperature. Smallholder farmers have been responding to climate change through planting shade trees, use of disease-tolerant varieties, soil fertility management, and irrigation practices. A follow-up study was conducted to assess the impact of current climate

change on Tanzania's Arabica coffee production. The findings reveal minimum temperature has been increasing at a higher rate than the maximum temperature in both zones. Increase in minimum temperature by 1°C during short rains and annual mean temperature resulted in a significant coffee production decrease in Kilimanjaro and Arusha regions by -6,041 and -4,450 tons respectively. Field experiments were also established to evaluate performance of cutting, grafting and seed propagules when combined with 75 g N. P. K tree^{-1}, 37.5 g N. P. K +10 Kg Farmyard manure (FYM) tree^{-1} and 37.5 g N. P. K +20 Kg FYM tree^{-1}. Two split plot experiments laid out in a Randomized Complete Block Design with three replications were established at the two locations (Lyamungu-Hai district and Burka - Arusha district) based on the existing climatic gradient; cutting-propagated plants resulted into highest yield ranging between 1800-3600 Kg green coffee ha^{-1} while grafted-propagated plants had the lowest green coffee yield (600-1700 Kg ha$^{-1.}$). The fourth study utilized climatic data from Coordinated Regional Climate Downscaling Experiment under Representative Concentration Pathway 4.5 to evaluate the potential of cutting, seed and grafted seedlings in attenuating the effects of climatic conditions using Dynamic Agroforestry Coffee model.

During the Near-term period (2026-2056) rainfall will increase in Kilimanjaro region at the range of 0.2-13 % while in Arusha region the increase will be 6.05-13 %. Minimum temperature is expected to increase at higher rate than maximum temperature at the range of 1.4-1.48 °C in Kilimanjaro region and in Arusha region at the range of 1.36-1.64 ºC. The use of cutting, seed and grafted propagated coffee plants when combined with FYM will result into 40% 35 % and 10% yield reduction respectively. Specific Leaf Area (SLA) among the three types of seedlings also varied; 28 (cutting), 19 (Seed) and 9 (grafted). Higher SLA observed in cutting-propagated plants may affect coffee production since it is linked to high loss of water in plants. Future higher yield loss was observed with the use of inorganic fertilizer (38%) than FYM (18%) in all the three types of seedlings.

Based on the above results, it can be concluded that during the last 40 years, coffee farmers from the Northern and Southern Highlands zone of Tanzania have experienced increase in temperature and decrease in rainfall. Rise in minimum temperature and decline in long rains has significantly affected coffee production in the Northern Highlands zone. Similar to the historical period, minimum temperature is expected to increase at the higher rate than maximum temperature in the Northern Highlands zone during the Near-term period. Integrated nutrients sources are able to provide sufficient nutrients to the three types of seedlings as the recommended rates of inorganic fertilizer. Yield of cutting propagated plants under the age of four years if established at the same time with seeds and grafted propagated plants is significantly higher than that of its counterpart. However, grafted propagated plants are more resilient to climate change. It is therefore recommended that, integrated soil fertility management (37.5 g N.P.K +10 Kg FYM) $tree^{-1}$ to be used as one of the adaptation strategies because apart from providing nutrients to the coffee plants the package also helps in improving water retention properties of the soil. In addition, seedling distribution should be location specific, with cuttings-propagated plants being distributed in areas with rainfall above 1200 mm $year^{-1}$.

The findings hold significant policy implications for enhancing coffee production in regions affected by climate change. Policymakers should enhance timely and accurate weather information delivery along with developing institutions responsible for education and extension services provision. Multiplication and adoption of improved coffee varieties has to be enhanced and promoted by the policymaker. By promoting adoption of improved coffee varieties policymakers can enhance farmers' adaptive capacity and reduce the vulnerability of coffee production to climate-related risks. Future studies will focus on monitoring the response of three types of seedlings above the age of four years assuming that at a later age coffee tree will have reached its maximum production and so more nutrients and water will be required.

IKISIRI KUU

Nchini Tanzania, kahawa ni bidhaa ya pili kwa ukubwa inayouzwa nje ya nchi baada ya tumbaku, ikichangia asilimia 24 ya mapato yote ya fedha za kigeni. Uzalishaji umekuwa wastani wa tani 50,000 kwa mwaka katika kipindi cha miaka 35 iliyopita; mojawapo ya sababu ikiwa ni kushuka kwa kiwango cha mvua na ongezeko la joto. Ingawa baadhi ya taarifa zipo sehemu zingine kuhusu jinsi ya kushughulikia athari za mabadiliko ya tabianchi, tafiti za kukabiliana na mabadiliko hayo kwa kahawa nchini Tanzania hazipo. Madhumuni makuu ya kazi hii ni kutengeneza mbinu za kilimo cha kahawa ya Arabika hapa nchini, zinazozingatia mabadiliko ya tabianchi. Utafiti huu ulilenga hasa: 1) kubaini mitazamo ya wakulima wa kahawa juu ya mabadiliko ya tabianchi; 2) kubaini uhusiano kati ya takwimu za kisayansi za mabadiliko ya tabianchi na rekodi za uzalishaji wa kahawa; 3) kutathmini utendaji wa miche ya kahawa itokanayo na vikonyo, kupachikiza pamoja na mbegu na urutubishaji shirikishi wa udongo na 4) Kubainisha miche ya kahawa pamoja na mbinu za urutubishaji shirikishi wa udongo zenye uwezo wa kukabiliana na mabadiliko ya tabianchi.

Utafiti huu ulifanyika katika Nyanda za Juu Kaskazini (mikoa ya Kilimanjaro na Arusha) na Nyanda za Juu Kusini (mikoa ya Songwe, Mbeya na Ruvuma) kulingana na kiwango cha uzalishaji wa kahawa ya Arabika. Uchunguzi wa mitazamo ya wakulima kuhusu mabadiliko ya tabianchi ulifanyika na wakulima 163 (67 %) walibaini ongezeko la joto na upungufu wa mvua kwa miaka 40 iliyopita. Kiwango cha elimu, uzoefu wa kilimo na upatikanaji wa taarifa za hali ya hewa viliathiri mitazamo yao. Maoni ya wakulima na takwimu za hali ya hewa vyote vinaashiria kupungua kwa mvua na ongezeko la joto. Wakulima wanakabiliana na mabadiliko ya tabianchi kwa kupanda miti ya vivuli, matumizi ya aina zinazostahimili magonjwa, na umwagiliaji. Tathimini kuhusu uhusiano kati ya mabadiliko ya tabianchi na takwimu za uzalishaji wa kahawa ya Arabika pia ilifanyika. Kiwango cha chini cha joto kimeongezeka kwa kasi zaidi kuliko kiwango cha juu cha joto katika ukanda wa Kaskazini na Nyanda za Juu Kusini. Ongezeko la 1°C katika kiwango cha chini cha joto wakati wa mvua fupi na wastani wa joto la mwaka lilipunguza

uzalishaji wa kahawa (tani -6,041 na -4,450) katika mikoa ya Kilimanjaro na Arusha mtawalia. Kupanda kwa kiwango cha chini cha joto na kupungua kwa mvua kumeathiri kwa kiasi kikubwa uzalishaji wa kahawa katika Nyanda za Juu Kaskazini. Utendaji wa miche itokanayo na vikonyo, mbegu na upachikizaji pamoja na matumizi ya mbolea kwa viwango vya g 75 za N. P. K na g 37.5 za N. P. K + kg 10 na Kg 20 za samadi kwa mti ulitathiminiwa pia. Tathimini hii ilifanyika Lyamungu- Wilaya ya Hai na Burka- Wlaya ya Arusha kulingana na mwelekeo wa hali ya hewa uliopo. Mimea itokanayo na vikonyo ilitoa mavuno mengi zaidi (1800 -3600 Kg ha^{-1} kahawa safi) wakati mimea iliyopachikizwa ilikuwa na mavuno ya chini zaidi (600-1700 Kg ha^{-1}). Takwimu za hali ya hewa kutoka CORDEX-Africa katika kipindi cha 2025-2056 zilitumika kubaini uwezo wa miche ya vikonyo, mbegu katika kupunguza athari za mabadiliko ya tabianchi katika Nyanda za Juu Kaskazini kwa kutumia modeli ya Kahawa ya *Dynamic Agroforestry Coffee.* Katika kipindi hicho mvua itaongezeka katika mkoa wa Kilimanjaro na Arusha kwa kiwango cha 0.2-13% na 6.05-13 % mtawalia. Kiwango cha chini cha joto kinatarajiwa kuongezeka kwa kasi kuliko kiwango cha juu cha joto katika mkoa wa Kilimanjaro (1.4-1.48 °C) na Arusha (1.36-1.64 °C). Katika kipindi kijacho matumizi ya vikonyo yatasababisha upotevu wa mavuno kwa 40%, mbegu (35%) na Kupachikiza (10%). Mavuno kutokana na matumizi ya mchanganyiko wa samadi na mbolea ya viwandani yalikuwa makubwa kuliko yale ya mbolea ya viwandani. Eneo la majani (SLA) kwenye mti wa kahawa lilitofautina katika aina tatu za miche; 28 (vikonyo), 19 (Mbegu) na 9 (kupachikizwa). Kupungua kwa mavuno kwenye mimea itokanayo na vikonyo katika kipindi kijacho kunaweza kusababishwa na wingi wa majani unaoweza kusababisha upotevu mkubwa wa maji. Upotevu wa mavuno katika siku zijazo unachangiwa na matumizi ya mbolea za viwandani (38%) kuliko mbolea ya samadi (18%) katika aina tatu za miche. Mimea iliyopachikizwa ikionyesha ustahimilivu zaidi katika kukabiliana na mabadiliko ya tabianchi.

Kwa ujumla utafiti huu unaonyesha wakulima wa kahawa kutoka kanda zote mbili kutambua ongezeko la joto na kupungua kwa mvua katika miaka 40 iliyopita. Kupanda kwa kiwango cha chini cha joto na kupungua kwa mvua kumeathiri kwa kiasi kikubwa uzalishaji wa

kahawa katika Nyanda za Juu Kaskazini. Kama ilivyo kwa miaka iliyopita kiwango cha chini cha halijoto kinatarajiwa pia kuongezeka kwa kiwango cha juu zaidi kuliko kiwango cha juu cha halijoto katika Nyanda za Juu Kaskazini katika kipindi cha 2026-2055. Urutubishaji shirikishi unauwezo wa kutoa virutubisho vya kutosha kama viwango pendekezwa vya mbolea ya viwandaani. Mimea ya vikonyo ilipata mavuno zaidi ikilinganishwa na mimea ya mbegu na kupachikizwa. Hata hivyo, mimea iliyopachikizwa inastahimili mabadiliko ya tabianchi.

Inashauriwa kutumia g 37.5 za N.P.K + Kg 10 Kg za samadi kwa mti kama njia ya kukabiliana na mabadiliko ya tabianchi kwani mbali na kurutubisha udongo husaidia uhifadhi wa maji ardhini. Usambazaji wa miche unapaswa kuwa mahususi kwa eneo, mimea itokanayo na vikonyo itumike katika maeneo yenye mvua zaidi ya 1200 mm kwa mwaka. Matokeo haya yana athari kubwa za kisera katika kuimarisha uzalishaji wa kahawa katika maeneo yaliyoathiriwa na mabadiliko ya tabianchi. Watunga sera wanapaswa kuimarisha utoaji wa taarifa za hali ya hewa pamoja na kuzijengea uwezo taasisi zinazohusika na utoaji wa elimu na huduma za ugani. Uzalishaji na uhamasishaji wa aina bora za kahawa ufanyike na watunga sera. Kwa kuhimiza utumiaji wa aina bora za kahawa watunga sera wanaweza kuongeza uwezo wa wakulima kuhimili mabadiliko ya tabianchi na kupunguza athari zinazohusiana na hali ya hewa katika kilimo cha kahawa. Hatua zinazopendekezwa zinatarajiwa kuchangia juhudi za Malengo endelevu katika kukabiliana na athari za mabadiliko ya tabianchi hapa Tanzania.Tafiti za siku zijazo zitazingatia ufuatiliaji wa mwitikio wa miche ya kahawa itokanayo na vikonyo, mbegu na upachikazaji yenye zaidi ya umri wa miaka minne ikizingatiwa kuwa katika umri huo mti wa kahawa utakuwa umefikia uzalishaji wake wa juu na hivyo virutubisho na maji zaidi yatahitajika.

DECLARATION

I, **SUZANA GASPER MBWAMBO,** do hereby declare to the Senate of Sokoine University of Agriculture that this dissertation is my own original work done within the period of registration and that it has neither been submitted nor being concurrently submitted in any other institution.

_____ _____

SUZANAG.MBWAMBO **Date**
(PhD Crop Science Candidate)

The above declaration is confirmed

_____ _____

Dr Sixbert K. Mourice **Date**
(Supervisor)

_____ _____

Prof Akwilin J. P. Tarimo **Date**
(Supervisor)

LIST OF PAPERS

The current dissertation is based on the following published/submitted papers

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DEDICATION

This dissertation is dedicated to the memory of my beloved late father who always inspired me to study hard and aim higher, but the Almighty God needed him earlier than he could see this success. May his soul rest in peace, Amen.

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LIST OF SYMBOLS AND ACRONYMS

g	Gram
Kg	Kilogram
ANOVA	Analysis of variance
CBD	Coffee berry disease
CLR	Coffee leaf rust
CV	Coefficient of variability
FC	Field capacity (of a soil)
FYM	Farmyard manure (in the context of this work: cattle manure)
GDP	Gross domestic product
ICO	International Coffee Organization
IPM	Integrated pest management
ISFM	Integrated soil fertility management
ITC	International Trade Centre
K	Potassium
KNCU	Kilimanjaro Native Cooperative Union
N	Nitrogen
NGO	Non-governmental organization
(S)OC	(Soil) organic carbon
P	Phosphorus
pH	Negative logarithm of hydrogen ion concentration
SPSS	Statistical package for social sciences
TaCRI	Tanzania Coffee Research Institute
TCB	Tanzania Coffee Board
BOT	Bank of Tanzania
IPCC	Intergorvemental Pannell of Climate Change
IUSS	International Unions Soil Sciences
Tmax	Daily Maximum Temperature
Tmin	Daily Minimum temperature
Co_2	Carbon dioxide
NPK	Nitrogen: Phosphorus: Potassium
CAN	Calcium Ammonium Nitrate
TSP	Triple Super Phosphate
DAP	Diammonium Phosphate
SSP	Single Super Phosphate
FYM	Farmyard Manure

UNDP	United Nation Development Plan
mm	Millimetre
RCBD	Randomized Complete Block design
CWD	Coffee Wilt Disease
CLR	Coffee Leaf Rust
BCD	Beery Coffee Disease
MAM	March, April and May
OND	October, November and December
ITCZ	Intertropical Convergence Zone
ENSO	El-Nino Southern Oscillation
WI	Weight of fresh sample
W2	Weight of oven dried sample
SMC	Soil Moisture Content
SAFERNAC	Soil Analysis for Fertility Evaluation and Recommendation on Nutrient Application to Coffee
DynACof	Dynamic Agroforestry Coffee crop model
CORDEX	Coordinated Regional Climate Downscaling Experiment
RCM	Regional Climate Model
PBIA	Percent bias
RMSE	Root Mean Squared Error
MAE	Mean Absolute Error
SS	Skill Score
CAF2014	Coffee Agroforestry Model
ARIMA	Autoregressive Integrated Moving Average
RCP	Representative Concentration Pathway
TMA	Tanzania Metrological Agency
APARDifi	Apparent Photosynthetic Active Radiation -Diffuse
APARDir	Apparent Photosynthetic Active Radiation -Direct
GPP	Gross Primary Productivity
LUE	Light Use Efficiency
KDif	Light extinction coefficient of the layer for the diffuse light
KDir	Light extinction coefficient of the layer for the direct light
LAI	Leaf Area Index
GCB	Gross Carbohydrate Budget
CM_{RE}	Carbon Mass of the reserves from the previous

	day
RM	Maintenance respiration
pa	Living fraction of the organ
CM	Carbon Mass
NC	Nitrogen Content
MRN	Respiration Rate per nitrogen unit
Q10	Response of organ respiration to temperature

CHAPTER ONE

1.0 GENERAL INTRODUCTION

1.1 Global Importance of Coffee

Coffee (*Coffea arabica,* L) is one of the most widely consumed hot beverages all over the world (ICO, 2018). The demand for this commodity has increased by 50 % since 1990s due to increase in domestic coffee consumption from exporting countries and from new emerging markets such as China, South Korea and Turkey (Sänger, 2018). It accounts for trade worth approximately USD 100 billion (Goldschein, 2011), making it the second most traded commodity after petroleum oil. Every day, about 1.5 billion cups of coffee are consumed globally, of which one-fifth are drunk in the United States (Luttinger and Dicum, 2006). The average coffee production from all exporting countries for the crop year 2017/18 was 159.7 million 60 kg bags of green coffee whereby Brazil contributed 35 % followed by Vietnam (13 %), Colombia (10 %), and Indonesia (7 %), Tanzania ranks 15th in the world and 3rd in Africa after Ethiopia and Uganda; contributing about 1 % of global output (TCB, 2020).

1.2 Importance of Coffee to the Tanzanian Economy

Coffee is Tanzania's second largest traditional export commodity, accounting for 24 % of the country's total foreign exchange earnings after Tobacco (NBS, 2019). The crop contributes about 4 % to gross domestic product (GDP), generating an average of US$ 100 million annually (BOT, 2017). Overall, the coffee industry in Tanzania directly employs some 450,000 families, of which some 120,000 are in the Robusta growing areas. An additional estimated 2.4 million people are indirectly engaged in the industry locally (TCB, 2020).

1.3 Coffee Arabica Cultivation

1.3.1 Its origin

Coffee (*Coffea arabica,* L), originates in Ethiopia. Legend has it that an Ethiopian goat herder, Kaldi, discovered coffee after noticing that his goats became a little extra energized after eating certain berries found on his land (Gebeyehu *et al.,* 2020). It was first produced commercially in Yemen, Arabian Peninsula, hence its name *Coffea arabica* coined by the famous Swedish taxonomist, Carolus Linneaus

(1707-1778). It was later smuggled to Indonesia (Java), the Martinique Islands (West Indies) and India.

1.3.2 History of coffee cultivation in Tanzania

Early study by Semoka *et al*.(2005) reported that Arabica coffee was introduced to Tanzania in 1893 from the Reunion Island by the French Roman Catholic missionaries, and was first planted at the missionary stations of Morogoro and Kilema in Tanzania. In 1898, German missionaries, and settlers had established coffee as a commercial crop along the foot of Mount Kilimanjaro (Wrigley, 1988). In the 1920s and 1930s, local small-scale production of Arabica coffee had taken the commercial dimension, through encouragement by Sir Charles Dundas (TCB, 2012) and was linked to the cooperative movement. The Kilimanjaro Native Cooperative Union (KNCU) was established in 1932 based on several primary societies at the village or inter-village level, with the aim of promoting coffee as cash crop (Mhando *et al.,* 2013). Introduction of Arabica coffee in the Southern Highlands is said to be related to Bourbon and Kent seed smuggling by labourers coming from estates in the north, and the introduction of Blue Mountains through Malawi (TCB, 2012). Throughout the country, coffee is produced under three main production systems; Pure stand practiced by smallholders (mainly in the South), Coffee:Bananas intercropping, practiced by smallholder (mainly in the North and the West). Estate sector, usually pure stand with or without shade trees (less than 10 % of total production (TCB, 2017).

1.3.3 Agro-ecological requirements for *Coffea arabica* L.

Coffea arabica L. is a woody perennial evergreen dicotyledonous tree or shrub of variable size growing up to 8-10 m high (Wrigley, 1988). According to Wrigley (1988), Arabica coffee thrives well between altitudes of 1000 and 2200 metres above mean sea level. The crop requires 1200 mm of rainfall spread over duration of eight months and a dry season of no longer than 3 months. The ideal temperature for *C. arabica* ranges from 15-25 ^{o}C. Coffee productivity and quality are highly dependent on temperature and rainfall conditions (Haggar & Schepp, 2012). This is because the blossoming and fructification of Arabica coffee, in particular, requires a specific series of dry and wet spells alternations (Wrigley, 1988). Therefore, statistically significant

variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer) (IPCC, 2007), can impact on the production cycles and negatively affect coffee production (Rahn *et al.,* 2018). The crop also prefers very deep (usually more than 1.5 m), well drained friable loamy and clay soils. Soils with high available water holding capacities and a pH in the range of 5-7, the ideal range being 5.8-6.2 (Smith *et al.*, 2011) with high nutrient retention capacities are suitable for coffee production. Such soils may be in the soil groups Luvisol, Nitisol, Andosol and Vertisol (IUSS Working Group, 2006).

1.4 Statement of the Problem and Justification

1.4.1 Trend of coffee production in Tanzania

World production is currently estimated to reach over 130 million 60 kg bags. Brazil and Vietnam lead production and together represent slightly less than half of world volume. Africa produces about 12 % of world volume; the Tanzanian share is less than one percent of the world production (0.6 % in 2011) (Ruben *et al*., 2018). According to TCB, (2020), Tanzania's average annual coffee production has stagnated at a level of about 50,000 metric tons over the past 35 years. At the same time, yields have fluctuated significantly. Smallholder coffee productivity per tree also range between 250 and 300 g of parchment, which is very low compared to the potential yield of over 1 kg per tree (Baffes, 2003). In the northern zone of Tanzania, for instance, annual coffee production trend indicates a decline over years whereby Kilimanjaro, once a giant coffee producer, appears to have suffered most, with annual production decreasing from about 20 000 tons in 1981/82 to less than 5000 tons by 2005/06 (Maro *et al.,* 2010). Expansion of Arabica coffee in the Southern highlands of Mbinga and Mbeya is enhanced by growing land scarcity in the Northern region, relatively older trees and increasing temperatures that affect Arabica coffee yield (Craparo *et al*., 2015). Factors that contribute to the decline in productivity include, unreliable marketing and low prices (TCB, 2020), high production costs, especially due to the high prices of the fungicides for CBD and rust control (Teri *et al.*, 2004) and decline in soil fertility (TCB, 2020). Currently, however, some of these limitations have been addressed through breeding for disease-resistant varieties (Kilambo *et al.*, 2015), adoption of

integrated pest management (IPM) practices (Magina, 2011) and the decline of soil fertility has also been addressed through integrated soil fertility management (ISFM) (Maro *et al.,* 2014). Climate change is one of the latest, and perhaps the most serious, challenges facing coffee production in Tanzania (TCB, 2017). Despite the fact that, the general feeling is that the climate has been changing over the years and may be responsible for current low production and productivity (Craparo *et al*., 2015; TCB, 2017; Wagner *et al*., 2021), there have been limited assessment covering the whole country's coffee-growing areas.

1.4.2 Evidence of climate change

The Intergovernmental Panel on Climate Change (IPCC, 2014) reported that each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850. The period from 1983 to 2012 was likely the warmest 30-year period of the last 1400 years in the Northern Hemisphere, where such assessment is possible. Moreover, the condition is likely to worsen in areas lying in low latitudes and low altitudes (Bunn, *et al.*, 2015). Past climate studies in Tanzania have indicated steadily rising temperatures, decreasing rainfall and periodic droughts and excess rainfall associated with El Nino/La Nina cycles (Haggar & Schepp, 2012). The study conducted by Mbwambo and Maro (2016) using a climatic data set for the period between 1965-2014) from Northern zone of Tanzania, showed an increase of temperature with time (a supposedly evidence of warming) in Northern Tanzania, though the annual rate of increase is still less than 0.05 ^{o}C, much lower than the global increase of 0.65-1.06 ^{o}C over the period between 1880-2012 (IPCC, 2013). Similarly, Mbwambo and Maro (2016) observed that, over the half-century, there has been an increase of mean Tmax by 0.9 ^{o}C and mean Tmin by 1.6 ^{o}C. Similar pattern was reported by Craparo *et al.* (2015) who noted that Tmin has been increasing at a higher rate than the other climatic variables. Based on downscaled climate models, Tanzania is projected to experience a mean temperature increase of 2–4 ^{o}C by 2100 (Läderach *et al*., 2012). Recent studies indicate that most areas in Tanzania will experience reduced precipitation and elevated air temperatures (Gulacha &

Mulungu, 2017) as well as increased seasonality of rivers (Kangalawe, 2017).

1.4.3 The impact of climate change in coffee production

There is an increasing body of evidence supporting the view that climate change and variability have significant impact on ecosystem health (Bartzke *et al.,* 2018) and agricultural production (Craparo *et al*., 2015; Lobell *et al.,* 2011; Niles *et al.,* 2015). However, impacts of climatic extremes vary in importance over space and time depending on different farming systems, agro-ecologies and ability of farmers to respond (Niles *et al.,* 2015). Adhikari *et al.* (2015) projected up to 40% yield loss for coffee and tea towards the end of 21st century due to reduction of suitable areas as a result of temperature increase. In their study, Rahn *et al*. (2018) predicted coffee yield losses between 18-32% at elevations less than 1000 m above sea level due to high projected temperature (+2.5 ^{o}C) when atmospheric CO_2 fertilization is not considered. Elevated temperatures affect insect pests, disease pathogens and weed lifecycles, thus accelerating infestation (Ziska *et al.,* 2018). For instance, Jaramillo *et al.* (2011) predicted shrinkage in coffee- growing areas in most of Kenya, Uganda and Rwanda due to the prevalence of the coffee berry borer caused by increases in temperature. Secondly, elevated temperature enhances atmospheric evaporative demand (saturation vapour pressure of air) (Lobell *et al,* 2012).

In addition, most of the oscillations in coffee yield are mainly associated with climatic factors because the crop needs favourable conditions throughout its vegetative and reproductive cycle. According to DaMatta *et al.* (2018), elevated temperatures cause fast crop development and thus shorter crop durations, which is directly associated with low yields and quality. In regions where the average annual temperatures exceed 24 ^{o}C, fruit maturation occurs early, and it generally occurs during the rainy season when harvesting and drying of coffee is difficult due to frequent and unpredictable rainfall. In the case of water deficit, *Coffea arabica* L. can tolerate deficits up to 150 mm per year (Thomaziello *et al.,* 2000). Thus, without adequate adaptation strategies and/or substantial external inputs,

coffee production will be severely reduced in the Tanzanian highlands in the near future (2026-2056) (Craparo *et al.,* 2015).

Smallholder farmers at subsistence level are more likely to be hit by hunger and poverty as destructive impacts of changing climate continue to be realized in the presence of lack of investments and clear policy to overcome the situation at the local and national levels (Rowhani *et al.,* 2011; Schlenker & Lobell, 2010). In Tanzania, the goal to increase coffee production by 100 % (from the 2012 average of 50,000 to at least 100,000 tons/year by the year 2021) (TCB, 2012) may have been over-ambitious, because it might have overlooked the climate change challenges. According to BOT (2022) coffee production for the season 2021/22 was 68 825 tons. This is because the National Coffee Development Strategy does not consider the potential threat of climate change and climate variability to the success of that strategy, despite the known impacts of La Nina droughts on coffee productivity (Haggar & Schepp, 2012). Such a production challenge needs to be aligned to an elaborate climate change adaptation strategy.

1.4.4 Perception and Adaptation Strategies to Climate change

Climate change adaptation issues have become subject of intense global discussions in the past few decades. Although climate change is a global problem, the need for adaptation is higher among developing countries where vulnerability is presumably higher (Adger *et al.,* 2003). Therefore, smallholder farmers need to recognize the changes in climate already taking place in their areas and undertake appropriate investments towards adaptation. According to Arbuckle *et al.* (2015), the coping and adaptation strategies of the farmers are linked to a very large extent with their knowledge and perception on climate change and its impacts. Several farming practices and techniques have been proposed for adapting coffee farming to climate change e.g., shade management, relocate coffee cultivation to different areas and elevations or use of a biotic-stress resilient coffee varieties, integrated pest management (IPM) and water and soil conservation (Rahn *et al.,* 2018). Climate changes also tend to affect production and productivity rate of several crops such as maize, wheat, rice, tea and tobacco which are produced and traded

globally (FAO, 2022; Kitole *et al*., 2023). However, research has demonstrated that an increased yield in these crops is associated with the adoption of drought-resistant varieties, intercropping, minimal tillage, fertilizers, irrigation short-duration crop varieties and crop rotation. For example, intercropping maize/wheat with crops such as groundnuts and beans enables smallholder farmer to improve the nutrients of their soils and as a result the yield of their crops tend to improve. Furthermore, the use of drought tolerant varieties such as drought resistant maize say by one unit may increase maize yield by 0.103 Kg. This is because drought-resistant varieties can sustain elevated temperatures and drought.

In Tanzania coffee farmers have started to use improved coffee varieties which are high yielding and resistant to Coffee Berry Disease (CBD) and Coffee leaf Rust (CLR). The improved coffee varieties are propagated using hybrid seeds, grafting and clones (cuttings) (TaCRI, 2011). Plants derived from hybrid seeds and grafting are characterised by deep and vigorous root systems on one hand while on the other hand plants derived from cuttings lack tap root (Partelli *et al.,* 2014). The observed difference in these types of seedlings may result into different response towards adverse environmental conditions. Therefore, it is important to evaluate coffee seedlings derived from different propagation methods so as to identify the best seedlings for adapting Arabica coffee to adverse conditions caused by climate change. This is significant, considering that future climate projections over the Eastern Africa indicate a declined rainfall (Adhikari *et al.,* 2015).

Soil fertility amendment practices in Tanzania involves application of 75-215 g of N.P.K (20:10:10), 60-175 g of Calcium Ammonium Nitrate (CAN)/Ammonium Sulphate Nitrate (ASN) or 30-100g of urea per tree depending on production level of coffee tree and season of the year (short rain/long rain). Phosphate's fertilizer (Triple Superphosphate (TSP), Di ammonium Phosphate (DAP) or Single Superphosphate (SSP) in combination with 10 kg of farmyard manure (FYM) are used as planting fertilizer. Therefore, it is only at planting time that inorganic fertilizer is integrated with FYM. According to Stockdale *et al*. (2002) the use of inorganic fertilizers has significantly contributed

to increased crop productivity while manure on the other hand, plays an important role in the soil by adding organic carbon and improving water holding capacity. As climate change becomes pervasive and copping options becomes necessary, there is a limited knowledge on the extent to which the current soil fertility management can bring about resilience of coffee cropping systems. Chemura *et al*. (2014) reported that inorganic fertilizers are most active at high water levels while organic manure performs better than inorganic fertilizers under low water levels, possibly due to their ability to increase soil water retention. There is a need therefore to understand the interaction of FYM and inorganic fertilizer management with respect to coffee productivity in the context of changing climate. Therefore, due to climate change, it is desirable to develop tools to define and measure the effect of these changes on coffee production and growth. Modelling reduces the time taken for experiments and the associated cost (Teh, 2006). This is particularly relevant for long-term growing crops such as coffee.

This study is therefore aimed at providing a set of interventions on coffee adaptation to climate change. These interventions are expected to contribute to the efforts of Sustainable Development Goals (SDGs), Country Vision 2025 and Agricultural Sector Development Programme (ASDP II) in adapting climate change impacts in Tanzania. This is the first study in Tanzania which intend to use future climatic data (2026-2056) under the mitigative Representative Concentration Pathway (4.5) scenario, to evaluate the role of types of coffee seedlings used in Tanzania (cuttings, seeds and grafted –propagated plants) in adapting Arabica coffee to climate change alongside with soil fertility amendments. The RCP 4.5 scenario is a stabilization scenario, which means the radiative forcing level stabilizes at 4.5 W/m^2 before 2100 by employment of a range of technologies and strategies for reducing greenhouse gas emissions. The National Climate Change Response Strategy (NCCRS) 2021-2026 prioritize blue economy initiatives and low emissions development pathways. In view of this, this study aligned with the call of the Government of United Republic of Tanzania which called upon all stakeholders and development partners to provide

necessary support and cooperation towards developing climate resilience systems in the country.

1.5 Objectives of the Study

1.5.1 Overall Objective

To Increase coffee production sustainably through improved agronomic practices for adaptation to climate change in the Northern and Southern Highlands of Tanzania.

1.5.2 Specific objectives

i. To assess farmers' perception on climate change in the Northern and Southern Highlands of Tanzania.
ii. To determine relationship between scientific climate change record and production records in the coffee growing area of Tanzania.
iii. To evaluate field performance of compact coffee variety under selected propagation methods and soil fertility amendment practices in the Northern Zone, Tanzania.
iv. To evaluate the ability of type of seedling and fertilizer management practices in adapting Arabica coffee to climate change in Tanzania.

1.5.3 Research hypotheses

Ho: Coffee growers have the correct perception on climate change and use appropriate agronomic practices to cope with it.

Ho: Coffee growers' perception towards climate change is aligned to the past climatic trends.

Ho: Type of seedlings and fertilizer regimes enhance adaptation of coffee production to climate change.

1.6 Conceptual Framework Adopted in the Current Study and organization of the thesis

1.6.1 Understanding climate change in farmers' perspective

According to Niles and Mueller (2016), both the adaptation and mitigation actions require a willingness to change behaviour, and for that, it is necessary to perceive that climate change is happening and action is necessary. Therefore, effective research into an environmental problem facing farmers should start with the farmers

themselves, as D'Emden *et al.* (2005) noted that awareness of a problem is a motivator in devising or adopting problem-solving techniques. This has been addressed in Chapter 2 of this thesis.

1.6.2 Understanding the impact of current climate on coffee production

According to some prediction Coffee productivity will be reduced because of climate change (Craparo *et al*., 2015). This will jeopardize coffee quantity and quality hence endangering coffee producers who occupy 90 percent of the population and their livelihoods mostly rely on coffee. The understanding of the relationship between current climate and coffee production is therefore necessary for the formulation of climate change adaptation strategies for coffee farming in Tanzania, which does not exist yet. This has been addressed in Chapter 3 of this thesis.

1.6.3 Evaluating field performance of compact coffee variety under selected propagation methods and soil fertility amendment practices in the Northern Zone, Tanzania

Three propagation methods are used for mass multiplication of improved coffee varieties in Tanzania, namely, hybrid seeds, grafting and clones (cuttings) (TaCRI, 2011). Cutting propagation is physiologically viable and ensures maximum crop homogeneity, besides other desirable traits, especially grain maturation, fruit yield and size, and plant vigour (Weigel & Jurgens, 2002). The study of Miranda *et al.* (2011) indicated that, this technique has allowed the establishment of Robusta coffee in areas with biotic or abiotic limitations. However, although that, there are gains obtained through the planting of cuttings, problems that arise from the genetic narrowing of the species and shallower radicular systems can be observed in the field. On the other hand, grafting effectively enables a new balancing of the plant's biomass with quick results in Arabian coffee beans contributing to increased productivity (Oliveira *et al*., 2004). Under current climatic conditions where rainfall is not reliable, and temperature has increased it is important that coffee farmers are provided with best coffee seedlings which will be able to adapt to climate change. It is therefore, imperative that field performance of cuttings and grafting propagated compact coffee variety are studied in

details to identify coffee seedlings that will guarantee long term adoption. This has been addressed in Chapter 4 of this thesis.

1.6.4 Crop modeling to determine management practices that adapt Arabica coffee to climate change

Several studies have indicated that the climate is changing and will continoue to do so in the future. Therefore, there is a need to enhance the climate resilience of coffee production. Crop growth model can be used to simulate the relationship between plants and the environment, to predict the expected yield for applications such as crop management and agronomic decision making, as well as to study the potential impacts of climate change on crop productivity (Kasampalis *et al.*, 2018). Crop models can provide insights into the managing of agricultural challenges such as sustainability and how to cope with the possible negative effects of climate changes (Spiertz, 2012).

1.6.4.1 Types of crop models

According to Teh, (2006), models can be categorized as either:

i. *Mechanistic and empirical models; Mechanistic model* represent the cause and effect relationships among the variables under study while empirical model, offers little or no insight to the underlyng cause and effect process of the phenomenon.
ii. *Static and dynamic models;* Static model does not have time as a variable while dynamic model include time as a variable.
iii. *Discrete and continuous model;* Both are dynamic model as they have time as their variables, for continuous model however time is real while for Discrete time is interger value.
iv. *Deterministic and Stochastic model;* Stochastic model contain some element of randomnes or probability disrtibution within the model while the deterministic do not have the randomness element. Most of the agriculture models are deterministic.
v.

Chapter five of this thesis used crop model to determine how cuttings, grafting and seed propagated plants together with soil fertlty management can create more climate resiliance coffee production in the Northen Highlands zone of Tanzania. The general discussion of the results is presented in chapter six and chapter seven provides the general conclusion and recommendations of the study

1.7 Materials and methods

1.7.1 Description of the Study Area

The study area is comprised of two major Arabica coffee growing zones namely, Northern and Southern Highlands zones. In these zones, Arabica coffee production is exclusively rain-fed. A brief description of the selected zones is given below.

1.7.1.1 Northern Highlands zone

The Northern Highland zone involved two regions,Kilimanjaro and Arusha. The Northern Highlands zone is characterized by a bimodal rainfall pattern. The zone grows some of the world's finest mild Arabica coffees. Area under cultivation is estimated to reach 83,000 ha with an average production of about 7,500 to 10,000 tons of parchment per year. The production system is mixed between a majority of smallholders (intercropping with bananas) and a few large estates located mainly in Arusha region (TCB, 2017).

1.7.1.1.1 Kilimanjaro Region

Kilimanjaro region is made up of Hai, Moshi Rural, Siha, and Rombo Districts (Fig. 1.1). The region is located on the slopes of a temporarily inactive volcano of Mount Kilimanjaro, the biggest lone-standing mountain in the world (UNDP, 2014). Annual rainfall in Kilimanjaro region ranges from 1000 to 2000 mm. Soils are deep, well drained brown to red sandy loam to sandy clay loam. The major soil group in the region is the Nitisol, though other groups such as Histosols (upper levels), Luvisols and Cambisols (lower levels) do occur as well. Under objective 3, Lyamungu in Hai district represents areas with optimum conditions for growing coffee in the current time (rainfall above 1 200 mm per year and average temperature range of 20.07 ºC for the past four decade (Table 1.1).

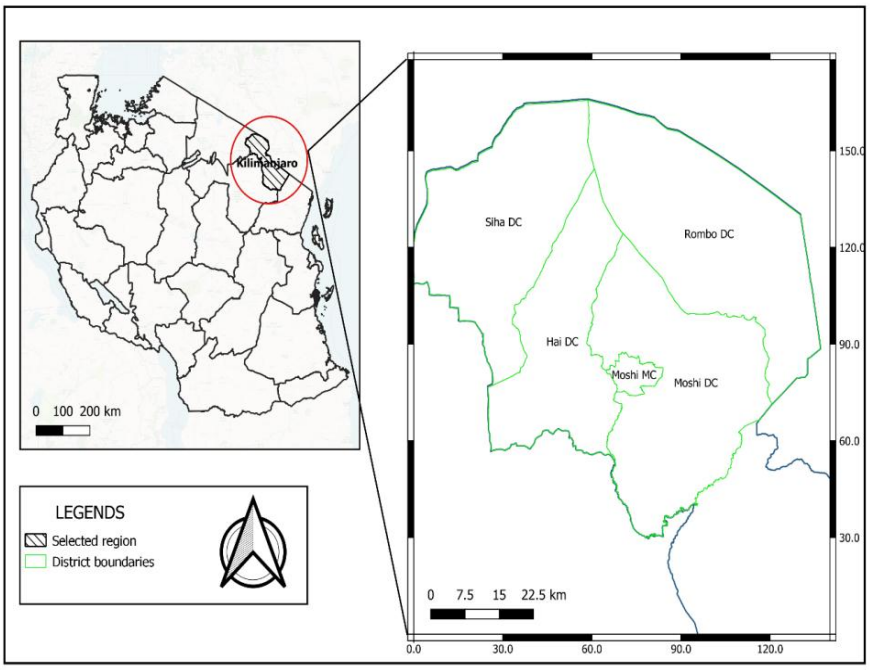

Figure 1.1: Map of Tanzania showing study areas in Kilimanjaro region

1.7.1.1.2 Arusha Region

Arusha region is comprised of Arusha, Arumeru/Meru, Longido, Monduli, and Karatu Districts (Fig. 1.2). Annual rainfall in Arusha region ranges from 800 to 1000 mm. Soils are deep, well drained brown to red sandy loam to sandy clay loam. The major soil group in the study area is the Andosol, though other groups such as Histosols (upper levels) and Cambisols (lower levels) do occur as well. Burka in Arusha district represents a contrasting environment < 618.19 mm drier and 0.31 ^{o}C warmer) compared with Hai district (Table 1.1).

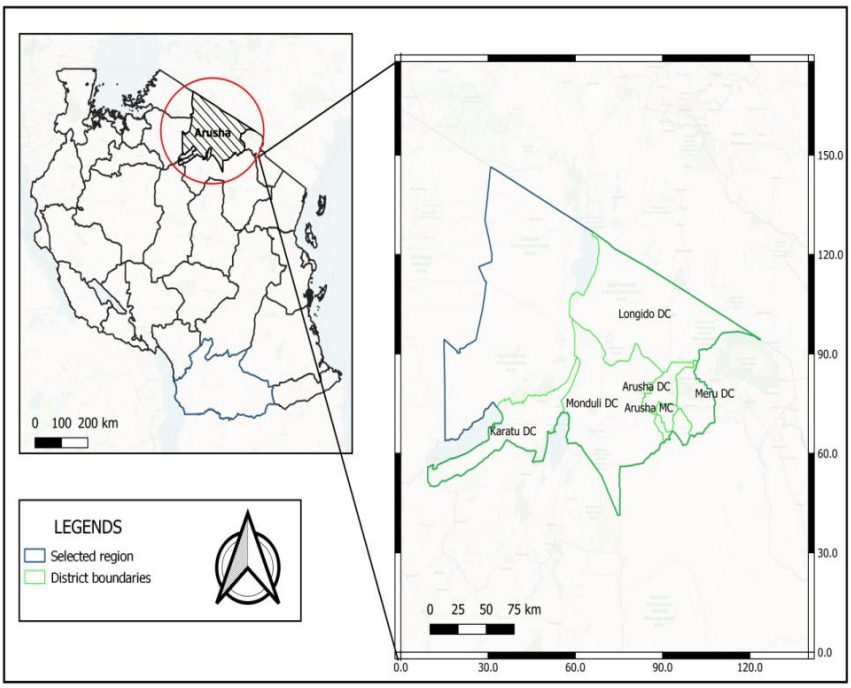

Figure 1.2: Map of Tanzania showing study areas in Arusha region

Table 1.1: Average rainfall (mm) and temperature (^{o}C) for (Lyamungu- Hai district and Burka –Arusha district (1979-2018)

	Location	
	Lyamungu	Burka
Altitude	1 268 m.a.s. l	1 387 m.a.s. l
Latitude	-3.2437	-3.1333
Longitude	37.2464	36.8666
Rainfall	1432.5 mm year^{-1}	814.31 mm year^{-1}
Average temperature	20.07^{o}C	20.38^{o}C

1.7.1.2 Southern Highlands zone

The Southern Highlands zone included three regions; Songwe, Mbeya and Ruvuma regions. Mbeya and Songwe regions were combined to have a 40-year coffee production data since the two regions were one region (Mbeya) before it was split in 2015. The

Tanzania Coffee Development Strategy (2011-21) foresees an increase in coffee area and yield, in the Southern Highland regions (Mbeya, Songwe and Ruvuma) where sufficient land is available for coffee, and climatic conditions are favorable (1000-2000 mm yr^{-1}). Southern Highland zone experiences a unimodal rainfall pattern.

1.7.1.2.1 Mbeya and Songwe region

Mbeya region included Mbeya and Rungwe districts (Fig. 1.3) while Songwe region comprised of Mbozi and Ileje districts (Fig. 1.4).

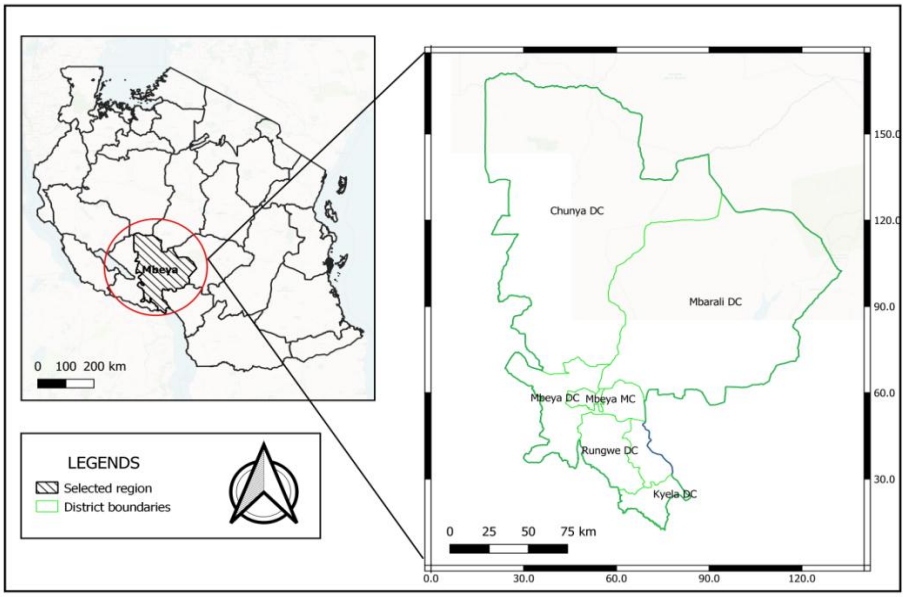

Figure 1.3: Map of Tanzania showing study areas in Mbeya region

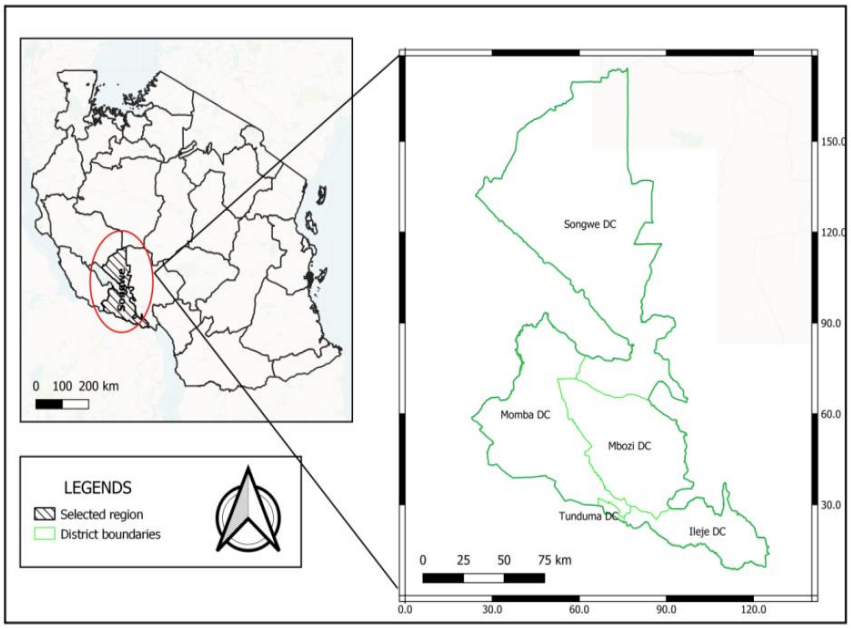

Figure 1 4: Map of Tanzania showing study areas in Songwe region

1.7.1.2.2 Ruvuma region

Ruvuma region comprised of Mbinga, Songea, and Nyasa districts (Fig.1.5)

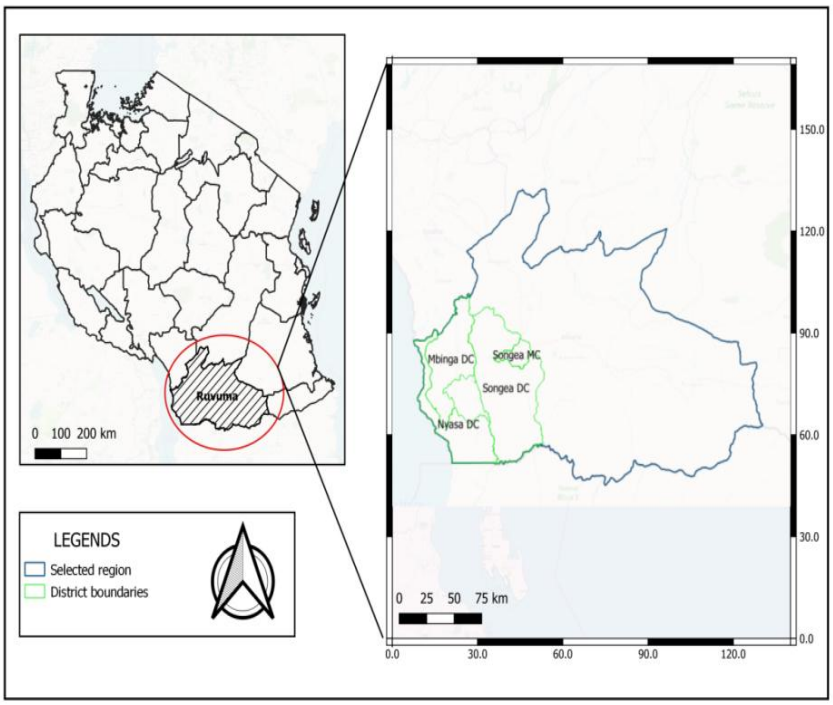

Figure 1.5: Map of Tanzania showing study areas in Ruvuma region

1.7.2 Data collection

Activities that addressed objectives one and two were conducted in the southern and northern highlands zones while the third and fourth objectives were conducted in the northern Highlands zone only. In Objective one data on the perception of farmers with regards to climate change was collected using structured question. Similarly, factors influencing their perceptions and decision to adapt adaptation practices were also assessed. In the second Objective the relationship between the meteorological data and coffee productions was also evaluated and data collected include coffee production (tones/ha) obtained from the Tanzania Coffee Board and climatic data (temperature and rainfall obtained from the Global interpolated climatic database (Worldclim dataset) and official historical coffee production data from Tanzania Coffee Board for a period of 40 years (1970-2018) were used. Under objective three plant characteristics such as plant height, canopy width, berry cluster, stem girth, internodes and number of primary branches together with coffee yield

were collected in order to determine field performance of compact coffee varieties propagated through cuttings, seed and grafting. In the fourth objective historical climatic data was obtained from Tanzania Meteorological agency (TMA) while the future climatic data was obtained from the Coordinated Regional Downscaling Experiment (CORDEX) Africa.

1.7.3 Data analysis

Descriptive and inferential statistics namely frequencies, percentiles, Chi-square contingency test, and t-test were performed in STATA 13.0 (Stata Corp LP, College Station, TX, USA) and SPSS 21.0 (IBM-SPSS Inc, Chicago, IL, USA) software. A binary logistic regression model also was used to assess farmers' perception of climate change as influenced by family, farm, and external variables and to determine factors affecting households' decision to adapt to climate change. Logistic regression is useful for situations in which you want to be able to predict the presence or absence of a characteristic or outcome based on values of a set of predictor variables. It is similar to a linear regression model but is suited to models where the dependent variable is dichotomous. Climatic parameters and coffee production were compared through descriptive statistics, correlation analysis, and multiple regressions. The Mann-Kendall method was used to detect significant trends in climatic data. The minimum temperature has been increasing at a higher rate than the maximum temperature in the Northern and Southern Highlands zones. Chemical and physical properties of soil were analysed at Lyamungu Soil Laboratory according Nunez *et al.,* 2011, Walkley-Black wet digestion method and Bouyoucos Hydrometer method (NSS, 1990). Growth characteristics, yield and yield components data collected were subjected to analysis of variance (ANOVA) using STATISTICA Software version 6.311 using the following statistical model for the spilt plot design as described by Kuehl (2002).

1.7.4 Study limitations

Crop modelling was associated with uncertainties due to lack of observations data such as soil, climate and crop in many points where the study was conducted. During modelling a lot of coffee crop data from vegetative, reproductive and yield were required, yet in the

country only few compact coffee variety data have been documented to date, this caused a lot of data from literature to be used and only a few from field experiments conducted within the area. Observed daily climatic data were also not available in many points that were used for simulation which necessitude simulation climatic data to be used. Nevertheless, despite these limitations, there was good relationship between observed and simulated green coffee indicating that cultivar specific parameters within the model were reasonably adjusted.

CHAPER TWO

2.0 Climate change perceptions by smallholder coffee farmers in the Northern and Southern Highlands of Tanzania.

“The material contained in this chapter has been published in the *Climate Journal* (2021), Vol. 9 (6), 90. https://doi.org/10.3390/cli9060090”

2.1 Abstract

Smallholder farmers are among the most vulnerable groups to climate change. Efforts to enhance farmers' adaptation to climate change are hindered by lack of information on how they are experiencing and responding to climate change. Therefore, this paper examines smallholder farmers' perceptions of climate change, factors influencing their perceptions, and the impacts and adaptation strategies adopted over the past three to four decades. A list of farmers was obtained from the Agricultural Marketing Cooperative Society (AMCOS) and filtered on the basis of age and farming experience. In order to explore factors influencing household perceptions of climate change, a structured questionnaire was administered to the randomly selected household heads. Data on rainfall and temperature were acquired from Lyamungu and Burka Coffee estate (Northern Highlands zone) and Mbimba and Mbinga (Southern Highlands zone) offices of the Tanzania Meteorological Agency (TMA) with the exception of data from Burka Coffee estate, which were acquired from a private operator. Descriptive statistics and logistic regression models were used to analyze the data. Farmers' perceptions were consistent with meteorological data both pointing to significant decline in rainfall and increase in temperature since 1979. Factors such as level of education, farming experience, and access to climate information influenced farmers' perception on climate change aspects. Based on these results, it is recommended to enhance timely and accurate weather information delivery along with developing institutions responsible for education and extension services provision. The focus of education or training should be on attenuating the impacts of climate change through relevant adaptation measures in each coffee-growing region.

Keywords: *Coffea arabica*; climate change; farmers' perceptions; Tanzania

2.2 Introduction

There is substantial evidence that the mean and extremes of climate variables have been changing in recent decades and that rising atmospheric greenhouse gas concentrations could cause such trends to intensify in the near future (IPCC, 2014). According to IPCC (2014) the case in Africa will be more pronounced than the global average, suggesting warming in all seasons. Studies have reported high variability in rainfall and associated adverse effects of rainfall changes in East Africa (Ongoma *et al.*, 2018). A study on climate change in Tanzania by Craparo *et al*. (2015) reported a consistent rise in night-time temperatures (Tmin) (0.31 °C /decade) for over fifty years in the Northern Highlands zone of Tanzania. As temperature increases, its impact on agricultural crops is expected to be remarkably felt with consequences for millions of smallholder farmers, including an increasing burden of agricultural diseases and insect pests. Cash crops such as coffee will be the most affected by climate change (Kajembe *et al*., 22016). As already pointed out by Craparo *et al*. (2015) a 1°C rise in mean minimum (night-time) temperature will cause an annual yield loss of approximately 137 kg of coffee ha^{-1} in northern Tanzania.

Coffee is one of Tanzania's largest export crops (BOT, 2017), contributing 24 % to the annual agricultural foreign exchange earnings and significant tax revenue. The crop contributes about 4 % to gross domestic product (GDP), generating an average of US$100 million annually (BOT, 2017). The coffee sub-sector also supports the livelihoods of over 450,000 farm families in 15 regions directly, and over 2.4 million people employed in its value chain indirectly (TCB, 2012). The average smallholder coffee productivity ranges between 250 and 300 kg/ha, which is very low compared to the potential yield of over 1000 kg/ha. We hypothesize that climate change may be behind the decline of coffee yields in Tanzania, thus putting coffee production and the livelihoods of coffee farmers at risk (TCB, 2012). This is because decrease in rainfall, especially the long rain season and increase in temperature negatively affects the expansion stage, during which rainfall is required to sustain berry development (Craparo *et al*., 2015). Furthermore, drought and increase in temperature results in fruit abortions, increased bean defects,

reduced berry growth, and acceleration of ripening, leading to a reduction in coffee yield and quality (Craparo *et al.,* 2015). Despite the prevailing trend of decreasing productivity, coffee still makes a significant contribution to smallholder livelihoods that produce 95% of coffee in Tanzania (TCB, 2012).

Therefore, a better understanding of climate change and variability by smallholder farmers is necessary for designing adaptation strategies and policies to deal with the impacts of climate change on the Tanzanian coffee sub-sector, where 95% of the produced coffee is grown by smallholder farmers. The understanding largely targets the smallholder farmers who are highly vulnerable to climate change because most depend on rain-fed agriculture, cultivating in marginal areas, and lack access to technical or financial support that could help them invest in more climate-resilient agriculture. Different climatic studies show that sub-Saharan Africa is among the worst impacted region by the climate change and thus, a better understanding of how farmers view climate issues is an imperative step toward improving resilience (Eludoyin *et al*., 2017; Mkonda *et al.,* 2018). Therefore, it can be premised that perceived personal experiences could affect climate change belief and the corresponding adaptation measures taken. It is evident that in areas where farmers lack awareness and knowledge about climate change, their vulnerability has been increasing, causing poor yields, food shortage, and poverty (Komba & Muchapondwa, 2012).

Different studies indicate that smallholder farmers have been responding to climate change impacts through a range of interventions, including agronomic practices such as planting shade trees, pruning, planting drought-tolerant varieties, and application of organic fertilizers (Kajembe *et al.,* 2017; Komba & Muchapondwa, 2012). Some researchers have analyzed how farmer's perceived climate change in Tanzania. Komba and Muchapondwa (2012), investigated whether or not smallholder farmers in Tanzania perceived climate change across four regions: Iringa, Dodoma, Morogoro, and Tanga. Other studies by Kihupi *et al.* (2015) and Mkonda *et al*. (2018) compared smallholders' perception of climate change with meteorological data across different agro-ecological

zones. These studies suggest that farmers have already perceived change in climate conditions. However, these studies were mainly done in arid and semiarid regions of Tanzania where coffee is not the main crop, and when done in Northern and Southern Highland zones, coffee was not taken into account. A study by Temba *et al.* (2017) explored the perceived impacts of climate variability on coffee and banana farming in the highlands of Moshi rural District. The only drawback from this study was that it did not analyze factors influencing perception of climate change. Different scholars have indicated that the adoption of a particular adaptation method by individual households is influenced by several factors; e.g., in Ethiopia Deressa *et al*. (2011) and Uganda, Mugagga (2017) found that farmers' education, access to extension services and credits, climate information, social capital, and agro-ecological settings had a great influence on farmers' choice of adaptation strategies to climate change. In Tanzania, Mkonda *et al*. (2018) indicates that farmers' knowledge on climate change is a good base for undertaking effective adaptations. However, farmers' perceptions of climate change are contextual and location-specific as societies differ in culture, education, demographics, resource endowments, and biophysical and institutional characteristics. This heterogeneity influences the way they perceive changes in their local climate and the way they respond to the change (Maddison, 2006). Therefore, adaptation strategies of the farmers are linked with their perception of climate change and its impacts (Arbuckle *et al*., 2015).

Therefore, the current study contributes to the rapidly advancing climate change and farmers' perception literature by providing practical evidence of the climate trends according to farmers' perceptions and factors affecting perception in the two major Arabica coffee-growing areas of Tanzania. The results will also be used as one step toward the formulation of climate change adaptation strategies specific for coffee in Tanzania and beyond. The research explores the possibility of increasing coffee production sustainably through improved agronomic practices for adaptation to climate change in the Northern and Southern Highlands of Tanzania by assessing farmer's perceptions and determining which factors influence their perceptions.

2.3 Materials and Methods

2.3.1 Description of the study area

The study area was purposively selected based on the level of Arabica coffee production. It comprised of two major Arabica coffee growing zones: the Northern Highland zone (Kilimanjaro and Arusha regions) and Southern Highland zone (Songwe and Ruvuma regions) (Figure 2.1). In these zones, Arabica coffee production is exclusively rain-fed. The Northern Highlands zone is characterized by a bimodal rainfall pattern (Figure 2.2)., while the Southern Highland zone experiences a uni-modal rainfall pattern (Figure 2.3). The bimodal rainfall is characterized by a long rainfall season (March–May) and short rainfall season (October–December), whereas the uni-modal type receives rainfall for seven months (November–May).

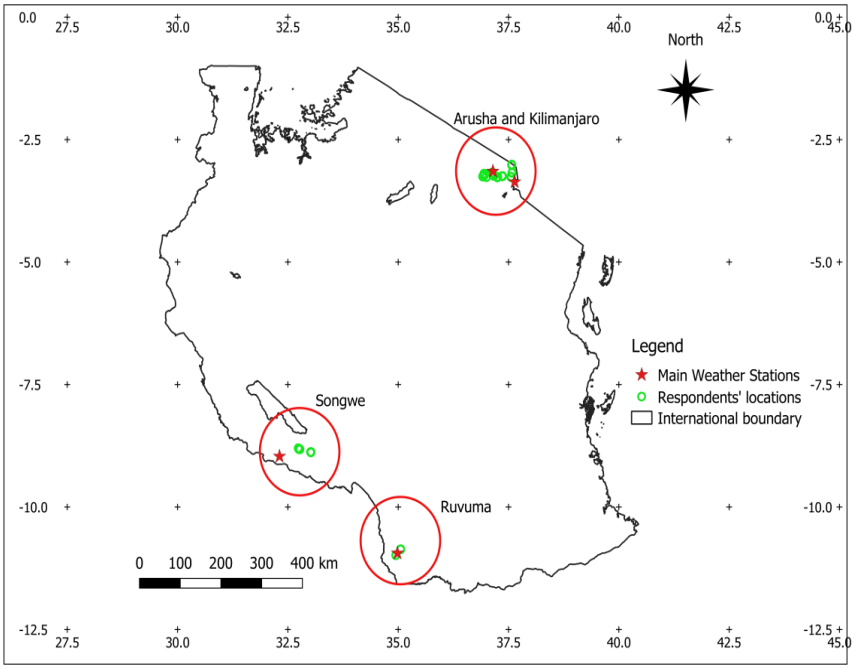

Figure 2.1: Map of Tanzania indicating study locations (red circle)

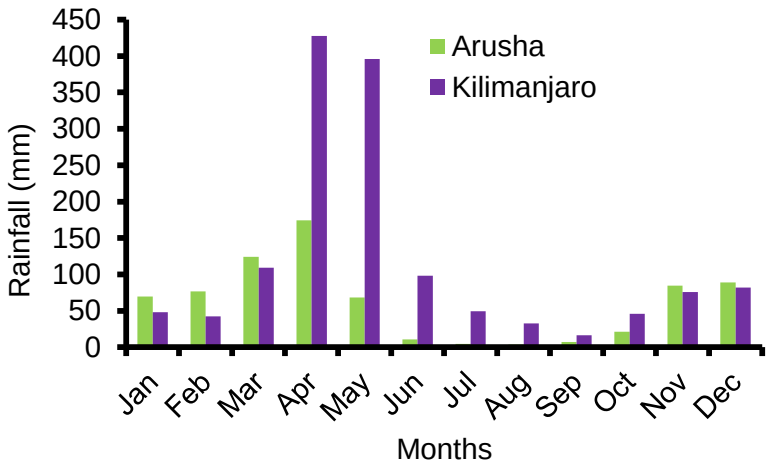

Figure 2.2: Monthly mean rainfall in the Northern Highlands zone

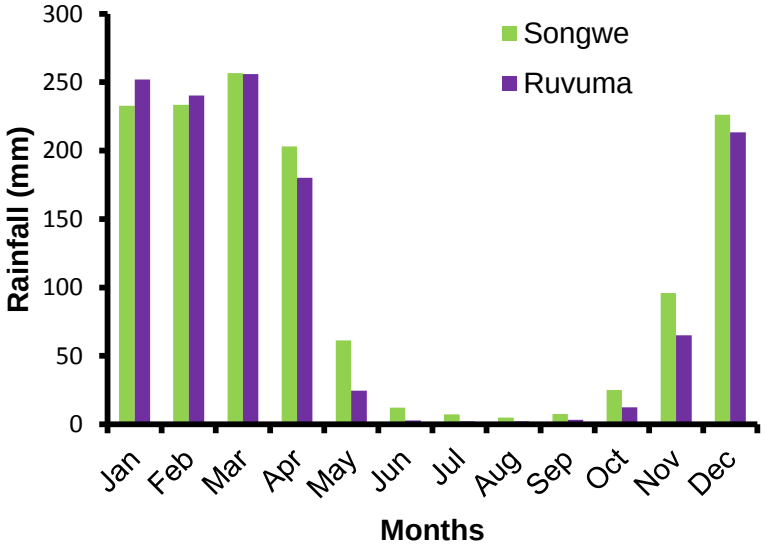

Figure 2.3: Monthly mean rainfall in the Southern Highlands zone

Within the Arabica coffee-growing regions, wards and villages were also purposively selected based on coffee production level (according to production data maintained by the local Agricultural Marketing Cooperative Societies (AMCOS)). This approach enabled the selection of villages that were fully involved in coffee production. A

total of 14 villages from 7 districts and 14 wards were involved in this study (Table 2.1).

Table 2.1: Selected villages and sample size

Zone	District	Selected Wards	Selected Village	Sample Size(n)
Northern (Kilimanjaro)	Hai	Masama kati	Isuki	14
		Machame Narumu	Usari	13
	Rombo	UshiriIkuini	Ushiri	17
		Nanjara	Kibaoni	13
	Siha	Karansi	Kandashi	13
		Kashashi	Kirisha	16
	Moshi dc	Mwika Kaskazini	Kinyamvuo	19
		Uru Kaskazini	Njari	22
Northern (Arusha)	Arumeru	Leguruki	Nkoasena	19
		Maruvango	Shishton	15
Southern (Songwe)	Mbozi	Itumpi	Ikonya	21
		Bara	Itumpi	19
Southern (Ruvuma)	Mbinga	Luwaita	Luwaita	16
		Utiri	Utiri	25
Total				242

2.3.2 Sample size and procedure

Lists of smallholder coffee growers were obtained from AMCOSs and filtered on the basis of age (40–60 years), experience in growing coffee (more than 10 years) and minimum number of coffee trees (450). The sample size was calculated using Yamane (1976) formula for calculating sample size from a population and a total of 242 households were obtained.

This formula takes into account the size of the population and the desired level of confidence, making it a practical tool for researchers in social sciences. While there are other sample size formulas available, the Yamane formula is popular due to its ease of use and applicability to a wide range of research studies in social sciences

$$n = \frac{N}{1+N(e2)} \frac{N}{1+N\,(e^2)} = \frac{611}{1+611\,(0.05^2)} = 241.741 \approx 242 \quad \text{(i)}$$

Where, n = sample size, N = population size (list of selected coffee growing households) = 611, and e = level of precision (95% confidence interval, level of precision will be 5%).

The respective sample for each village was allocated using proportionate sampling procedure (Ndambiri *et al*., 2012: Yamba *et al.,*2019). Simple random sampling technique was also adopted to randomly select household heads from the various villages (Ndambiri *et al*., 2012) such that each farmer had an equal opportunity of being selected for the study.

2.3.3 Data collection

The survey used Open Data Kit (ODK) software installed on smart phone hand set and Samsung Galaxy Note 7 Tablet. This technology facilitated reduction in data-entry errors and sped up data management and cleaning. The survey was designed to measure farmers' perceptions on climate change using a structured questionnaire. Before launching the survey, the questionnaire was pretested. Data collected from the survey included internal factors (demographic variables, farming systems, farmers' perception of climate change, and time aware of climate change) and external factors (extension services and sources of weather information). In order to collect data on farmers' perceptions of climate change, farmers were asked whether they had observed any long-term changes in temperature and rainfall over the last 10–30 years. Secondary data on rainfall and temperature were acquired from Lyamungu and Burka Coffee estate (Northern Highland zone) and Mbimba and Mbinga (Southern Highlands zone). Data from Lyamungu, Mbimba and Mbinga were acquired from the offices of the Tanzania Meteorological Agency (TMA), while data from Burka Coffee estate were acquired from a private operator.

2.3.4 Data analysis

Descriptive and inferential statistics namely frequencies, percentiles, Chi-square contingency test, and t-test were performed in STATA 13.0 (Stata Corp LP, College Station, TX, USA) and SPSS 21.0 (IBM-SPSS Inc, Chicago, IL, USA) software. A binary logistic regression model also was used to assess farmers' perception of climate change as influenced by family, farm, and external variables and to determine factors affecting households' decision to adapt to climate change.

Logistic regression is useful for situations in which you want to be able to predict the presence or absence of a characteristic or outcome based on values of a set of predictor variables. It is similar to a linear regression model but is suited to models where the dependent variable is dichotomous (Yamba *et al*., 2019). According to Esayas (2019), the dependent variable (i.e., perceived climate change, Y = 1 or not perceived climate change, Y = 0) was taken as a combination of an increase in temperature being accompanied by a decrease in rainfall. Following the assumption of standard logistic probability distribution, similar to the previous studies, including Amadou *et al*. (2015) and Yamba *et al*. (2019); a binary logistic model was applied, mainly to identify factors affecting farmers' perception of climate variability and change over agroecological zones (AEZs). This model uses Maximum Likelihood Estimation (MLE) procedure to ensure that the probabilities are bound between 0 and 1. The binary logistic model was regressed on a set of explanatory variables hypothesized based on literature and data availability that were considered to affect farmers' perception of climate change (Table 2.2).

Table 2.2: Variables hypothesized to affect farmers' perception of climate change

Variable	Description	Value	Expected Sign
Household head	Sex of the head of the farm household	1=male; 0=female	+/−
Education level	Level of education attained by the head of the household	(1=No formal edu., 2= Pri edu., 3= ODL educ., 4= ADL edu., 5=College, 6= University)	+
Farming experience	Number of years of farming experience for the household head	Years	+
Crop failure experience	If household has experienced crop failure due to water shortage	1=yes, 0= no	+
Farm size	Size of the household farm	ha	
Extension	If household has access to extension services	1=yes, 0= no	+
Climate information	Access to weather condition	1=yes, 0= no	+
Time aware of climate change	The time in years that the head of the household was aware of climate change	past two years, past five years, past seven years and more)	+/−

Missing values in the rainfall and temperature data set were determined according to the "3/5" rule (Amadou *et al*., 2015). Taking into account this rule, the missing values in the temperature data set ranged between 5 and 19 %, while that of rainfall ranged between 1 and 5 %. The obtained missing values were estimated using the multiple imputation method due to its characteristics to account for uncertainty about the imputed values (WMO, 1989). Rainfall Anomaly Index (RAI) analysis was used for the analysis of annual rainfall variability (Ayanlade, *et al*., 2017). The statistical anomalies approach (Yamba *et al.,* 2019) was used to analyze the temperature for the 40-year period from 1979 to 2018, focusing on temperature patterns. Average values for temperature and rainfall for the 40-year period (climatological normal) served as the basis for the assessment for the

stipulated period. Rainfall Anomaly Index (RAI) positive and negative values were calculated using Equations (ii) and (iii).

$$RAI = +3\ (\frac{RF - MRF}{MH10 - MRF}) \quad \text{(ii)}$$

$$RAI = \ -3\ (RF - MRFML10 - MRF) \quad \text{(iii)}$$

Where RAI is the Rainfall Anomaly Index; RF is the rainfall for the year in question; MRF is the mean actual rainfall for the total length of the period; and MH10 and ML10 are the mean of the 10 highest and lowest (respectively) values of rainfall (RF) of the period.

Using these variables, the empirical specification of the binary logistic model was described as,

$\mathrm{Ln}(\mathrm{P}/1-\mathrm{P))}$ = β_o+ $\beta_1$household head + $\beta_2$edu1 + $\beta_3$edu2+ $\beta_4$edu3 + $\beta_5$edu4 + $\beta_6$edu5 + $\beta_7$farming experience+ $\beta_8$crop_failure + $\beta_9$farmsize + β_{10}extension services + β_{11}climate information + β_{12}1 year climate change awareness β_{13}2 years climate change awareness + β_{14} 5 years climate change awareness + β_{15} more than 7 years climate change awareness + ε_i

(iv)

Where

β_i = coefficients of the independent variables, ε_i = disturbance term

- Dependent variable in the perception of climate change equation: The natural log of the probability of perceiving climate change (P) due to the influence of variables hypothesized in Table 2.2 divided by the probability of not perceiving (1-P).
- Dependent variable in the adoption of adaptation practices equation: The natural log of the probability of adopting adaptation practices (P) due to the influence of variables hypothesized in Table 2.2 divided by the probability of adopting adaptation practices without the influence of the variables hypothesized in Table 2. 2 (1-P).
-

2.4 Results

2.4.1 Characteristics of the households

Among the 242 sampled households, 90% were headed by men and 10% were headed by women. Respondents from Northern Highlands zone were of the age group between 41 and 70 years, while those of

the Southern Highlands zone was dominated by those between 41 and 60 years (Table A2). Chi-square results indicate that variations in farmer's age across the districts were significant, $\chi 2$ (26, N=242) = 30.98, P ≤ 0.05. The land-holding size also significantly varied across the districts $\chi 2$ (26, N =242) = 22, P ≤ 0.01. The majority of the respondents from the Northern Highlands zone had a farm size between 0.5 and 1ha, while those from the Southern Highlands zone had farm sizes between 1 and 2ha (Table A2). The study also showed significant variations (P ≤ 0.05) of the respondent's education level between the districts, $\chi 2$ (36, N =242) = 62.13, P ≤ 0.05. As indicated in Table 2A, the Northern Highlands zone had the highest number of farmers with formal education as compared to the Southern Highlands zone. On the other hand, respondents had farming experience between 20 and 39 years (Table A2) with significant variations $\chi 2$ (36, N =242) = 26.5, P ≤ 0.05 among the districts.

Results also indicate significant variations between male and female respondents in terms of time aware of climate change (P ≤ 0.1) and sex of the household head (P ≤ 01) (Table 2.3). There were also lack of significant variations (P ≥ 0.05) in terms of education level, access to climate information and extension services between male and female respondents.

Table 2.3: Characteristics of male and female respondents in the Southern Highlands zone (%)

Characteristics	Male n =60	Female n = 21	Chi-square	P-value
Time aware of climate change				
One year	10	5		
Two years	12	33	10.31	0.067
Five years	42	19		
Seven years	2	10		
Ten years	23	14		
Household head			56.97	0.000
Head of the household	100	24		

Note n= number of households, P ≤ 0.1, P ≤ 0.05, P ≤ 0.01show there was significant difference.

Similarly, in the Northern Highlands zone, the Chi-square test indicated a lack of significant variations (P ≥ 0.05) in terms of education level and access to extension services between male and female respondents. However, significant variations between male and female respondents were observed in the time aware of climate change (P ≤ 0.05), sex of the household head (P ≤ 0.01), and access to climate information (P ≤ 0.1) (Table 2.4). Most of the respondents (89 %) were aware of climate change, while 11 % did not know what climate change is. Among the subset of 89 %, 146 (91 %) of the respondents were from the Northern Highlands and 69 (85 %) from the Southern Highlands.

Table 2.4: Characteristics of male and female respondents in the Northern Highlands zone (%)

	Male	Female		
	n = 127	n = 34	Chi-square	P-value
Access to climate information				
Farmers with access to climate information	78.74	64.71	2.878	0.090
Time aware of climate change				
One year	24.41	26.47		
Two years	23.62	23.53		
Five years	26.77	11.76		
Seven years	7.09	2.94	12.707	0.026
Ten years	12.60	11.76		
Household head				
Head of the household	100	53		
Not the head of the household	0	47	66.359	0.000

Note n= number of households, P ≤ 0.1, P ≤ 0.05, P ≤ 0.01 show there was significant difference.

Significant variations between time aware of climate change, sex of the household head, access to climate information and the perceptions of temperature increase and rainfall decrease were also observed in the Southern (Table 2.5) and Northern (Table 2.6) Highlands zones. Furthermore, out of 242 respondents, 79 % had access to climate information mostly through media such as TV, radio, and mobile phones. On the other hand, there were significant differences (t=1.9367, P ≤ 0.01) among farming households with

access to climate information in the Northern Highlands zone (76 %) as compared to those in the Southern Highlands zone (86 %). Among the 242 respondents, 163(67 %) farmers perceived climate change by a way of change in intensity of the climate variables (increase in temperature and decrease in rainfall). There was also significant difference (t=7.636, P ≤ 0.01) between respondents with positive perceptions of climate change (increase in temperature and decrease in rainfall) and those with negative perceptions of climate change. However, there was no significant difference (t = 1.0316, P ≥ 0.05) between farmers with positive perceptions of climate change in the Northern (70%) and those from the Southern Highlands zone (63 %).

Table 2.5: Farmers' perceptions of increase in temperature and decrease in rainfall as influenced by time aware of climate changes, sex of the household head, and access to climate information in the Southern Highlands zone (%)

	Temperature increase			Rainfall decrease		
	n=61	χ^2	P value	n=55	χ^2	P-value
Time aware of climate changes						
Past 1 year	10			11		
Past 2 years	18			15		
Past 5 years	46	86.21	0.000	44	89.21	0.000
Past 7 years	5			4		
Past 10 years	21			27		
Sex of the household head						
Male	80	13.26	0.001	87	19.15	0.000
Female	20			13		
Access to climate information						
Respondents with access	90	4.73	0.094	87	6.22	0.045
Respondents without access	10			13		

Note: χ^2= Chi-square test, n= number of households, P ≤ 0.05, P ≤ 0.01 shows there was significance.

Table 2.6: Farmers' perceptions of increase in temperature and decrease in rainfall as influenced by time aware of climate change, sex of the household head, and access to climate information in the Northern Highlands zone (%)

	Temperature increase			Rainfall decrease		
	n = 133	χ^2	P- value	n= 119	χ^2	P-value
Time aware of climate change						
Past 1 year	30			34		
Past 2 years	26			28		
Past 5 years	29	92	0.000	26	71	0.000
Past 7 years	5			3		
Past 10 years	11			9		
Sex of the household head						
Male	94	14	0.001	92	10	0.006
Female	6			8		
Access to climate information						
Respondents with access	84	37	0.000	85	27	0.000
Respondents without access	6			15		

Note: df = degree of freedom, χ^2= Chi-square test, n= number of households, P ≤ 0.05, P ≤ 0.01 shows there was significance.

2.4.2 Comparing smallholder farmers' perception with meteorological data

Farmers' perceptions were compared with the results of the historical trends from meteorological data. Fig. 2.4 shows farmers' perceptions of changing in rainfall amount categorized based on their respective districts. Many famers (above 70%) felt declining rainfall in their areas, with the exception of farming households from Mbinga districts where only 62% had a similar feeling of rainfall decline. Looking at the meteorological data from two districts one from Northern Highlands zone (Hai) and another from the Southern Highlands zone (Mbozi), we find that approximately half of the years within the study period experienced below average annual rainfall.

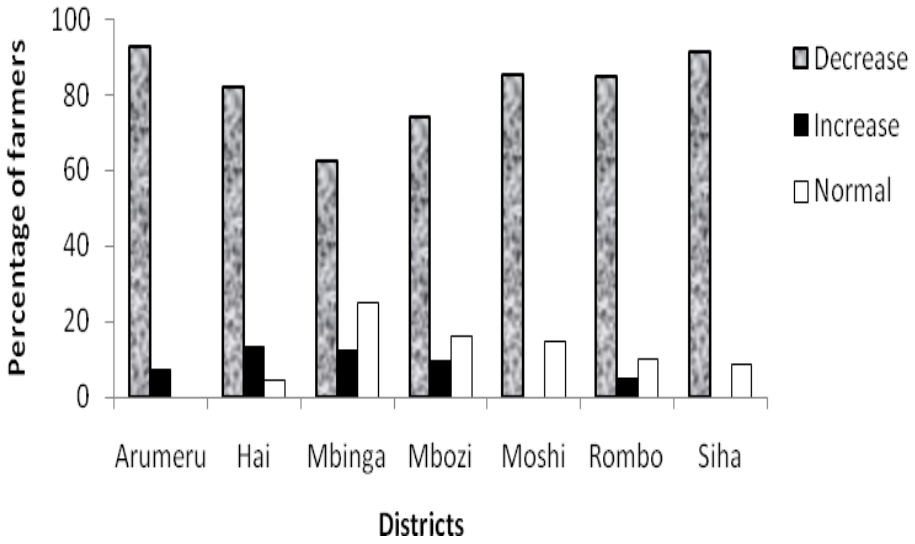

Figure 2.4: Farmers' perceptions of rainfall

The average rainfall amount for Lyamungu was 1447.79 mm, while the highest average annual rainfall was 2194 mm recorded in 2006 and the lowest was 670 mm recorded in 1989. For the case of Mbimba, the average rainfall amount was 1342.79 mm, the highest average annual rainfall was 1693 mm recorded in 1994, while the lowest was 630 mm recorded in 1981. Fig. 2.5 and 2.6 reveal that there is persistent high variability in annual rainfall based on a 5-year moving average. The 5-year moving average trend lines are not consistent throughout the 40-year period. The RAI for Lyamungu indicates that in the first and second decades, only five years respectively recorded an average rainfall above the average for the entire period. In the third decade and fourth decades, only 4 and 3 years respectively recorded an average rainfall above the average of the 40-year period. On the other hand, the RAI for Mbimba reveal that in the first and second decades, six years recorded an average rainfall above the average for the entire period. In the third decade and fourth decades, only 3 and 2 years respectively recorded above-average rainfall of the 40-year period. Hence, the fourth decade (2009–2018) was the driest of all four decades in both sites.

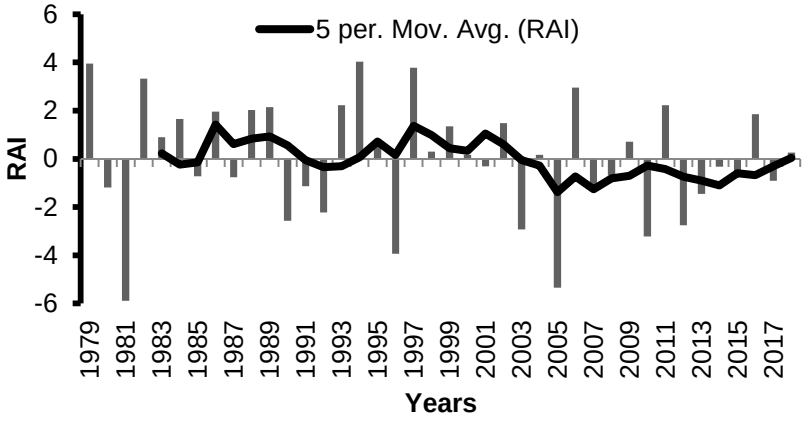

Figure 2.5: Rainfall Anomaly Index and 5-year moving average analysis for Lyamungu-Northern Highlands zone from 1979 to 2018

(**Source:** Author's construct using data from TMA)

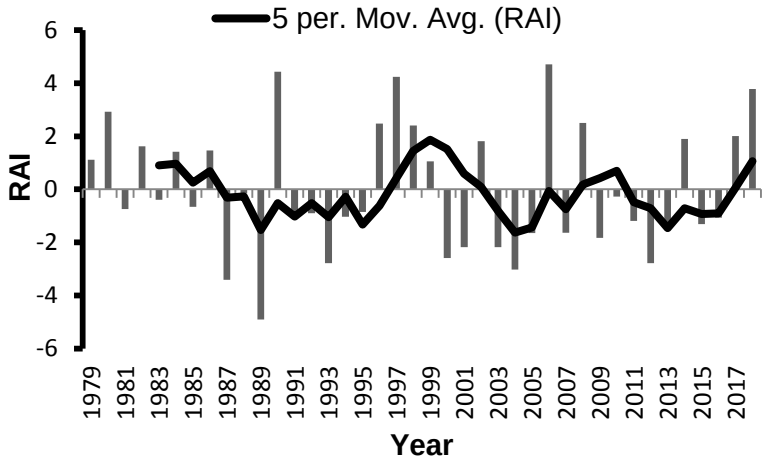

Figure 2.6: Rainfall Anomaly Index and 5-year moving average analysis for Mbozi-Southern Highlands zone from 1979 to 2018

(**Source:** Author's construct using data from TMA)

The majority of coffee farmers (more than 70%) from both the Northern and Southern Highlands felt an increase in temperature with the exception of Mbinga district, where only 67.7% of farmers

perceived an increase in temperature (Fig. 2.7). In the study period, the mean temperature for Lyamungu and Mbimba were 19.85 °C and 18.76 °C, respectively. Temperature values for the 40-year period were erratic, as indicated in Fig. 2.8 and 2.9 The highest average temperature for the four decades at Lyamungu was 20.47 °C, which was recorded in 2012, while the lowest for the period was 18.45 °C in 1979. At Mbimba, the highest average annual temperature was 20.5 °C recorded in 2010, while the lowest was 17.45 °C recorded in 2001. The yearly averages at Lyamungu (Hai district) from 2003 to 2018 were all above the average, while at Mbimba (Mbozi district), they were above from 2005 to 2018 for the 40-year period under study. Hence, the mean temperatures at Lyamungu (Northern Highlands zone) and Mbimba (Southern Highlands zone) have been increasing during the study period.

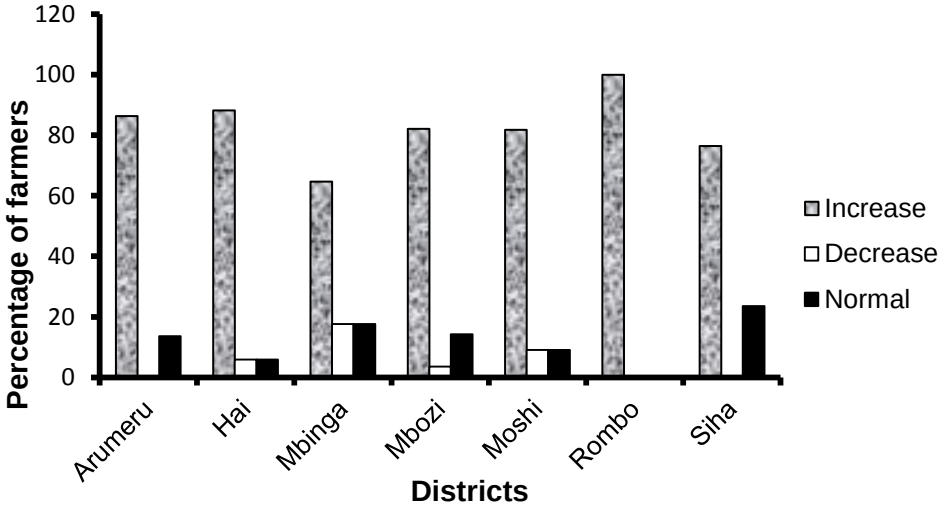

Figure 2.7: Farmers' perceptions of temperature

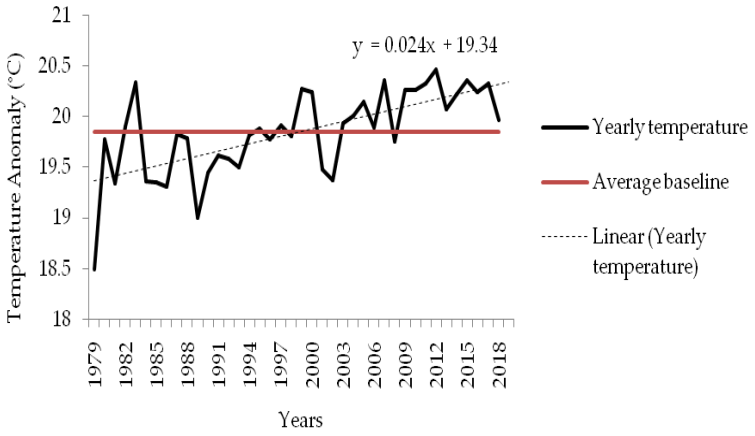

Figure 2.8 Mean annual temperature anomalies for Lyamungu (Northern Highlands zone) from 1979 to 2018

(**Source:** author's construct using data from TMA).

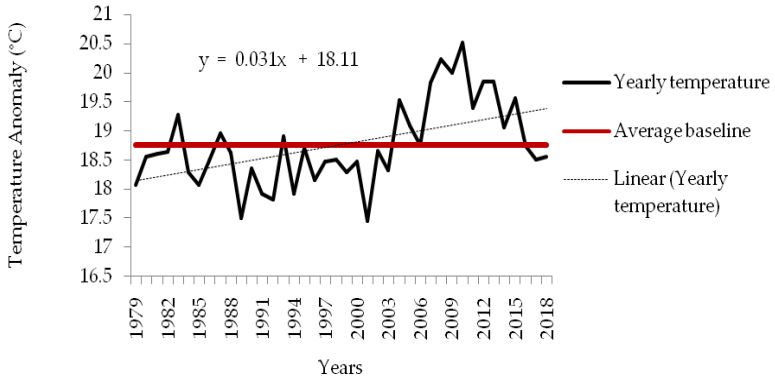

Figure 2.9 Mean annual temperature anomalies for Mbimba Southern Highlands zone) from 1979 to 2018

(Source: author's construct using data from TMA).

2.4.3. Perceived Impacts of Climate Change on Coffee Farming

Farming households noted climate change impact in terms of reduction of coffee yield (89 %), increased crop insect pest (79 %), increase crop diseases (63 %), late coffee flowering (63 %), and crop failure due to water shortage (59 %). Variations in climate change impacts across the two zones were significant ($P \leq 0.05$) except for reduction in coffee yield ($P \geq 0.05$) (Table 2.7).

Table 2.7: Climate change impacts in coffee farming

	Northern Highlands zone	Southern Highlands zone	χ^2	df	P-value
Late coffee flowering	57	74	9.98	2	0.007
Reduced coffee yield	89	88	0.174	1	0.677
Crop failure	64	49	4.747	1	0.029
Coffee pest increase	82	73	5.85	2	0.054
Coffee disease increase	57	75	7.82	2	0.02

Note. df = degree of freedom, □^{2}= Chi-square test, P ≤ 0.05, P ≤ 0.01 shows there was a significant difference.

Another climate change impact pointed out by coffee farming households was prolonged harvesting period, which significantly varied, $\chi^2(9, N = 242) = 49.85$, P ≤ 0.01 across the two zones (Fig. 2.10).

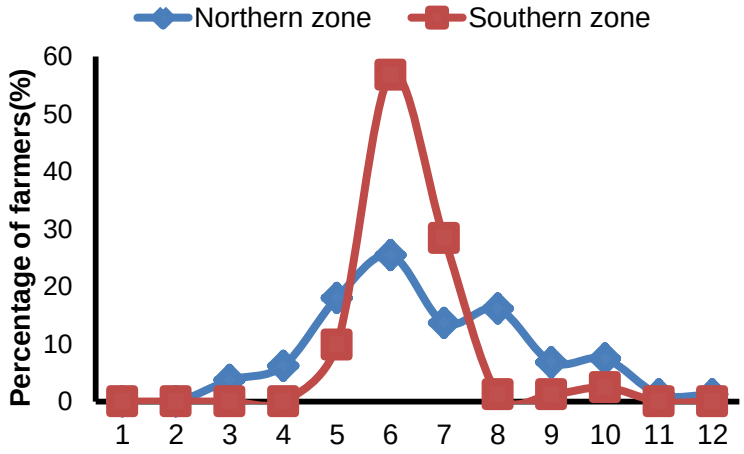

Figure 2.10: Coffee harvesting duration in the two zones

On the other hand, there were significant positive associations (P ≤ 0.05) among the increase in temperature, decrease in rainfall, and most of the climate change impacts mentioned by respondents (Table 2.8). There was also a significant negative association (P ≤ 0.05) between increases in coffee insect pest and diseases with reduction in rainfall. However, a lack of significant association (P ≥ 0.05) between late coffee flowering and increase in temperature was also observed. Reduction in yield as a result of climate change was reported to be significantly higher among male households than the female households.

Table 2.8: The association between climate change impacts and indicators of climate change

	Decrease in Rainfall	Increase in Temperature
Reduced rainfall	1	
Increase temperature	0.5421 (0.000)	1
Late flowering	0.1790 (0.005)	0.1059 (0.100)
Reduced yield	0.3917 (0.000)	0.3175 (0.000)
Crop failure	0.3400 (0.000)	0.1763 (0.006)
Insect pest increase	−0.1084 (0.092)	0.8230 (0.014)
Disease increase	−0.5060 (0.042)	0.2060 (0.008)

Note: P ≤ 0.1, P ≤ 0.05, P ≤ 0.01 indicate there was significance, P -value in parentheses.

Table 2.9 below indicates the results of the logistic regression model of farmers' perceptions of climate change. Male-led households positively perceived climate change (P ≤ 0.01) more than female-headed households. Positive perception of climate change was significantly influenced by farmers who were trained up to standard seven (P ≤ 0.05), and form four (P ≤ 0.1). Furthermore, farmers with more farming experience were also more likely to have positive perceptions of climate change than farmers with low farming experience (P ≤ 0.1). On the other hand, farmers who have experienced crop failure due to water shortage are more likely to have positive perceptions of climate change than farmers without such experience (P ≤ 0.01). Farmers' access to climate information also increases the probability of perceiving climate change positively (P ≤ 0.01). A positive perception of climate change was also significantly influenced by farmers who heard about climate change two years ago and five years ago (P ≤ 0.01).

Table 2.9: Factors influencing farmer's perceptions of climate change

Explanatory Variables	Odds Ratio	Std. Err.	z	P-value
Household head	10.72	5.49	4.63	0.000
Farming experience	1.030	0.02	1.85	0.065
Primary education	3.169	1.42	2.57	0.01
Ordinary secondary education	3.373	2.27	1.81	0.071
Time aware of climate change (2 years)	3.279	1.39	2.80	0.005
Time aware of climate change (5 years)	3.778	1.62	3.09	0.002
Access to climate information	4.915	1.87	4.18	0.000
Crop failure	4.664	1.63	4.41	0.000
_cons	0.011	0.01	−5.07	0.000
Log likelihood				
Number of observations				
Likelihood ratio test for zero slopes chi^2 (8)				
Probability > chi^2				
Pseudo R^2				

Note: P ≤ 0.1, P ≤ 0.05, P ≤ 0.01 shows there was significance

2.4.4 Farmers' responses to climate change

Soil and water conservation practices comprised the use of terraces, cut-off drains, and mulching. The results indicated that 67 (28 %) households used terraces in their coffee fields. This includes 49 % from the Northern Highlands zone and 46 % from the Southern Highlands zone. On the other hand, 31% of the respondents were using cut-off drains, which include 30 % from the Northern Highlands zone and 37 % from the Southern Highlands zone. Households that applied mulch in their coffee fields constituted 89 %. Irrigation practice was the least adopted practice in the study area; only 31 (13 %) households out of 242 were irrigating their coffee fields. This involved 27(17%) households from the Northern Highlands zone and 4 (5%) from the Southern Highlands zone. Dominant planted trees are *Grevillea robusta*, *Persea americana*, Albizia spp., and *Cordia africana*. The results also indicated that 41% of the farming households had started planting coffee varieties, which are tolerant to Coffee Berry Disease (CBD) and Coffee Leaf Rust Disease (CLR). However, still, of the majority of the farmers, 119 (73%) who perceived climate change still planted old coffee varieties, which are susceptible to CBD and CLR diseases.

From the surveyed soil nutrients sources, organic manure was the most widely applied nutrient source. About 55 % of the farming households who perceived climate change used organic fertilizer, while 56 % of those who did not perceive climate change were also using organic fertilizer. There were also significant differences ($P \leq 0.05$) in terms of most of the agronomic practices between the Northern and Southern Highlands zones with the exception of cut-off drains, which were not significantly different between the two zones ($P \geq 0.05$) (Table 2.10).

Table 2.10: Adoption of adaptation practices in the coffee-growing zones

Adaptation Practice	Northern Highlands zone	Southern Highlands zone	t-Statistic	P-value
	Mean Adopters (%)	Mean Adopters (%)		
Soil fertility management	94 (0.02)	80 (0.04)	3.267	0.001
Terraces	19 (0.03)	46 (0.06)	−4.610	0.000
Cut-off drains	28 (0.04)	37 (0.05)	−1.443	0.150
Mulching	94 (0.02)	70 (0.05)	4.49	0.000
Shade trees	96 (0.02)	70 (0.05)	5.920	0.000
Irrigation	17 (0.03)	5 (0.02)	2.63	0.009
Disease-resistant varieties	49 (0.50)	31 (0.46)	2.729	0.007

Note: $P \leq 0.1$, $P \leq 0.05$, $P \leq 0.01$ indicate that the means are significant different; standard deviation in parentheses.

2.4.5 Factors influencing household decisions to adapt to climate changes

Household decisions to adapt to climate change were significantly influenced by the gender of the household head, farm size, education level, farming experience, access to climate information, access to extension services, and time aware of climate change in different ways (Table 2.11). The probability of male-headed household to plant disease-tolerant varieties was higher than that of a female-headed household (β = 0.981, $P \leq 0.05$). Farming experience negatively influenced the adoption of disease-tolerant varieties (β =0.233 $P \leq 0.05$). There is a positive relationship between farmers with larger farm size and the adoption of disease-tolerant varieties (β = 0.233, $P \leq 0.05$) and carrying out soil and water conservation methods through the use of terraces (β = 0.303, $P \leq 0.01$), unlike for farmers

possessing small farm sizes. However, larger farm sizes decreased the probability of using mulches (β = −0.208, P ≤ 0.05).

Table 2.11: Factors influencing the decision to adapt to climate change

Adaptation practices	Factors influencing adaptation practices	B	Wald	P value	Exp (B)
Terraces	Farm size	.304	8.253	.004	1.36
	Extension services	.759	4.429	.035	2.14
	I year time aware of climate change	-2.261	13.09	.000	.10
	2year time aware of climate change	-1.188	6.41	.011	.31
	3year time aware of climate change	-.949	5.42	.020	.39
Manure	Extension services	.860	3.292	.070	2.36
	Extension services	.868	3.844	.029	2.38
	Experience in crop failure	1.083	4.780	.029	2.96
Cut-off drains	Extension services	.698	4.686	.030	2.01
	Farm experience	1.051	5.665	.017	2.86
	I year time aware of climate change	-1.197	6.035	.014	.302
Disease tolerant varieties	Farm size	.233	6.126	.013	1.26
	Farm experience	-.041	4.185	.041	.960
	Extension services	.567	3.670	.055	1.76
	Gender of the household head	.981	5.26	.022	2.67
Irrigation	2year time aware of climate change	1.220	3.998	.046	3.38
	Experience in crop failure	1.205	5.272	.022	.300
	Ordinary secondary education	2.669	4.525	.033	14.4
	Advanced secondary education	3.728	3.619	.057	41.5
Planting shade trees	Extension services	1.054	4.795	.029	2.87
	Farmers' age	-.068	4.141	.042	.934
Intensification of routine activities (pruning, pest and disease control)	I year time aware of climate change	2.279	6.381	.012	11.9
	2year time aware of climate change	1.991	7.358	.007	7.32
	5year time aware of climate change	2.677	8.332	.004	14.5

Note: P ≤ 0.1, P ≤ 0.05, P ≤ 0.01 shows there was significance.

From Table 2.11 above, access to extension services significantly enhanced the adoption of planting shading trees (β = 1.054, P ≤ 0.05), using cut-off drains (β = 0.698, P ≤ 0.05), soil fertility management (β= 0.868, P ≤ 0.05), and terraces (β = 0.759, P ≤ 0.05) rather than those who use these practices without access to extension services. Access to climate information significantly influenced the use of terraces (β = 0.772, P ≤ 0.1) and cut-off drains (β = 1.054, P ≤ 0.05). The adoption of irrigation practice was significantly influenced by farmers who were trained up to form four (β = 2.669, P ≤ 0.05), form six (β = 3.728, P ≤ 0.05), and university (β = 3.07, P <0.1). Recent climate change awareness significantly (β = ≤ 0.05) influenced the use irrigation practices and intensification of routine activities (pruning insect pest control and disease control).

2.5 Discussion

2.5.1 Perceptions and impacts of climate change in the northern and southern Highlands of Tanzania

The majority of farmers from the two major Arabica coffee growing zones in Tanzania were aware of climate change and had positive perceptions of climate change (increase in temperature and decrease in rainfall). These findings are in agreement with previous studies conducted in Tanzania by Mkonda *et al*. (2018) and Ruben *et al.* (2018). The average annual linear trend for the four decades vividly shows that temperature at Lyamungu (Northern Highlands zone) and Mbimba (Southern Highlands zone) has been increasing. The meteorological data on rainfall also reveal that rainfall amount had decreased just as the respondents perceived. The consistency of farmers' perceptions with meteorological data in terms of temperature increase and rainfall decrease has also been reported by Mkonda *et al*. (2018) and WMO (1989).

The findings revealed also that there was an association between reduction in coffee yield, crop failure, and increases in coffee insect pests and diseases with climate change indicators (increase in temperature and decrease in rainfall). Environmental conditions have a definite impact on the densities of insect pests such as Coffee Berry Borers (CBB) and black coffee twig borer (BCTB (Danielle, 2018). Teodoro *et al.* (2008) also found that CBB positively correlated with

temperature and coffee tree density. However, less rainfall in general may mean less bacterial blight, CBD, and CLR, since these diseases thrive in humid conditions. Another climate change impact reported by farmers was a prolonged harvesting period. According to Jasogne et *al.* (2013), unpredictable rains caused coffee to flower at various times throughout the year, leading to the continuous harvesting of small quantities of coffee. This is because coffee plants require well-distributed annual rainfall and a dry period not exceeding five months. Coffee flowers in response to rainfall occurrence following a period of moisture stress.

The study also indicates that female farming households felt the impact of climate change just the same as male counterparts, with exceptions in the reduction in yield, which was felt more by male households. It was also revealed that female engage themselves more with routine activities in the field, such as weeding, pruning, and harvesting, but the ones who take the produce to the market are the males. Therefore, this could be the reason why male households noted that there is reduction in yield as compared to female households. From this observation, both male and female are affected by climate change, although in different ways.

2.5.2 Farmers' response to climate change

Some coffee farmers have adapted agronomic practices relevant to climate change. Response actions include planting shade trees, the use of disease-tolerant varieties, soil fertility management, soil and water conservation practices, and irrigation practices. These farming practices and techniques have also been proposed for adapting coffee farming to climate change by Kajembe *et al.* (2017). The findings reveal more adoption of soil fertility management, including mulching, the use of shade trees, irrigation, and the use of disease-tolerant varieties in the Northern Highlands zone as compared with the Southern Highlands zone. Terracing practice was the only agronomic practice highly used in the Southern Highlands zone as compared with the Northern Highlands zone.

Response practices such as planting shade trees reduce the amount of heat reaching the coffee crop and ensure that the loss of soil

moisture through direct evapo-transipiration is minimized (Mugagga, 2017). On the other hand, planting disease-tolerant coffee varieties avoids diseases such as CBD and CLR, which could be aggravated by changes in temperature and rainfall. According to Chemura *et al*. (2014) inorganic fertilizers are most effective at high water levels, while manure performs better than inorganic fertilizers under low water levels, partly due to the former's ability to increase soil water retention.

2.5.3 Factors influencing households' perceptions of climate change and household decisions to adapt to climate change

2.5.3.1 Gender of the household

According to different scholars, males move from one place to the other in such a way that they can meet people and mass media to share experiences and ideas about contemporary climate trends (Abrha & Simhadri, 2015; Yamba *et al.,* 2019). On the other hand, Ndambiri *et al.* (2012) reported female-led household as having a higher probability of perceiving climate change than male-led households. Other studies reported a lack of significant variation between male and female-headed households on the perception of climate change (Esayas, 2019; Deressa *et al.,* 2011; Habtemariam, 2016). Therefore, gender is not always positively associated with perception of climate change; rather, it is a mixed factor depending on the environmental issues studied (Ndambiri *et al*., 2012). However, this study suggests that both male and female households have been affected by climate change, although in different ways. Therefore, it is important to conduct research using both male and female participants, because the conclusions that we reach with one group might not be representative of what the other group experiences.

Male households have a high probability of planting disease-tolerant varieties rather than female-headed ones. Probably, this is due to the fact that men are wealthier than women and so they can afford to buy diseases-tolerant varieties. From the discussion with farming households from both zones, it appeared that coffee has traditionally been considered a "man's" crop and is still perceived as such by many people. Hence, it is easier for male-headed household to even

uproot the old coffee varieties and replant the new tolerant varieties than it is for female-headed households. This is in agreement with the findings of Ruben *et al.* (2018) in the southern Highlands of Tanzania where by in the majority of households, it is the male head that controls any income earned from coffee and can decide how it is spent. Whether other members of the household are consulted will depend on the dynamics of the household.

2.5.3.2 Education Level

Overall, the results showed that educated farmers had a higher probability of perceiving climate change than illiterate farmers. In addition, the findings revealed that the majority of the households who engaged themselves in farming activities had attained a primary education level and only few had studied up to university level. These findings are in contrast with the findings from Yamba *et al.* (2019), who reported farmers with post primary education to have a higher probability of perceiving climate change than those with primary education. According to Yamba *et al*. (2019), 61% of the farmers who perceived climate change that means increase in temperature and decrease in rainfall had attained post primary education compared with 33% who had primary education. In this study, 71% of the respondents with positive perceptions of climate change had attained a primary education level, and only 29% of the respondents had attained post primary education. Level of education significantly influenced the use of irrigation practices. This is in agreement with other studies on factors influencing the adoption of adaptation practices by the household (Komba & Muchapondwa, 2012; Mugagga, 2017), which indicated that farmers with education were fully aware of adaptive options to choose from. However, in this study, the influence of the level of education on the decisions to adopt adaption practices was very low, which may be due to the fact that the majority of farmers had attained primary education, which maybe was not enough to influence the choice of adaptation practices. According to Bangay and Blum (2010), it is not just education that is needed but a high-quality education which is interdisciplinary and holistically fosters critical thinking and problem solving. Therefore, it is important for the institution that provides education to support not only the provision of curriculum content but also learning, which involves

knowledge and skills as well as development of the individual and communities' capacity to deal with climate uncertainty.

2.5.3.3 Farming experience

Farming experience influences farming households to have positive perceptions of climate change. This is because experienced farmers have better skills in farming techniques and management and hence are able to detect any changes in climatic conditions resulting from variability in climate. The fact that education and farming experience had a greater association with positive perception of climate change implies the capability of such farmers to better access information than to those with less experience and low education (Abrha & Simhadri, 2010). It was also found out that farmers with many years of farming experience were reluctant to plant disease-tolerant varieties. Thus, experienced farmers have a reduced likelihood of using disease-tolerant varieties. These findings are in contrast with those of Yamba *et al.* (2019), which indicated that experienced farmers have greater skills in farming techniques and management and are more able to detect any change in climatic conditions or change in crop production level resulting from variability in climate compared with inexperienced ones. The findings of this study reveal also that, it is not easy for the experienced and aged farmers to replace the old coffee varieties with the new varieties, as they depend on them to run their life, and the new varieties will take up to three years to give them the crop. Thus, proper education on how farmers can adopt new technology such as planting new coffee varieties should be given to each group of farmers from each region as some of these farmers may lack proper information about the new technology. According to TaCRI (2011), farmers can replace their coffee trees by rows allowing them to get some yield from the old trees while waiting for the new ones to produce.

2.5.3.4 Crop Failure due to water shortage

It was observed that farmers who have experienced more crop failure due to water shortage are more likely to have positive perceptions of climate change than farmers without such experience. According to Yamba *et al*. (2019), a rise in temperature in areas where farm production has already been hampered due to water shortage is likely to make farmers aware of adverse climate conditions. Water shortage

due to prolonged drought is one of the most adverse abiotic stresses that hinder plants' growth and productivity, threatening sustainable crop production (Razi & Muneer, 2021). Water shortage impairs normal growth, affects water relations and tends to reduce water-use efficiency in plants. Previous studies have also indicated that in dry lowland conditions the number of crop failures experienced determined farmers' perception of climate change (Asrat & Simane, 2018).

2.5.3.5 Access to climate information

Farmers' access to climate information increases the probability of having positive perceptions of climate change. Previously studies have also reported that farmers with better access to climate change information were more likely to perceive climate change (Bangay & Blum, 2010; Ndambiri *et al*., 2012). This relationship arises because farmers' access to information on climate change broadens their information base and hence their probability to perceive climate change (Yamba *et al*., 2019). These findings also show that the majority of the respondents who were aware of climate change accessed climate information through various media such as TV, radio, and mobile phones. Thus, economically secure farmers are also more likely to perceive climate change positively than those who are economically insecure (Abrha & Simhadri, 2015). Developing countries need more tangible and accessible climate information in order to improve farmer's resilience through the impacts of climate change (Ayanlade *et al.*, 2017). In this study, access to climate information positively influenced the use of terraces and cut-off drains. Farmers who access climate information are more likely to be aware that climatic conditions are changing. Farmers' access to climate information increases the possibility of farmers to perceive climate change and take remedial actions against climate change (Ndambiri *et al.,* 2012). This is probably why farmers who had access to climate information opted to use terraces and cut-off drains as remedial action toward climate change.

2.5.3.6 Time aware of climate change

Farmers who heard about climate change in most recent years are more likely to perceive climate change than those who heard about it

a long time ago. This is in agreement with Maddison (2006) who noticed that some famers place more weight on recent information. The time in which farmers obtained information about climate change significantly influenced the likelihood of using terraces, cut-off drains, irrigation, and intensification of routine activities (pruning, pest and disease control). Findings form this study reveal that awareness about climate change may be a positive way to lead to action as reported by Léger-Goodes *et al*. (2022) that, being aware about the environmental crisis leads to finding strategies to be more effective and cope with the Impacts.

2.5.3.7 Farm size

Perception of climate change in terms of increase in temperature and decrease in rainfall was not influenced by the size of the farm. However, farmers possessing larger farm sizes had a higher probability of cultivating disease-tolerant varieties and carrying out soil and water conservation activities through use of terraces and planting shade trees than farmers cultivating in small farm sizes. According to Gbetibouo (2009), farmers with larger coffee fields are more likely to adapt climate change adaptation practices because they have more capital and resources. Coffee farmers with larger farm sizes are able to adopt tolerant coffee varieties, as they can still keep their old varieties while establishing new varieties in other fields and gradually replant the whole area with tolerant varieties. Due to the fact that a coffee plant is perennial, taking up to three years for famers to start harvesting, it is difficult to uproot all old trees and replant new ones. In additions, farm size negatively influences the use of mulches. This could be due to the fact that the management of large farms requires more capital and resources; hence becoming difficult for smallholder farmers to obtain enough mulching materials for the bigger farms. A group of studies shows positive associations between farm size and farmers' adaptation responses (Belay *et al.,* 2017; Trinh *et al*., 2018). Another group of studies reports negative associations between farm size and adaptation responses to climate change (Amare & Simane, 2017; Uddin *et al.,* 2014). Previous studies have also reported that farm size inhibits farmers from choosing some adaptations such as irrigation and the use of short duration varieties (Khan *et al*., 2020). Overall, farm size is an influential factor for

farmers' adaptation responses to climate change. However, the directions and magnitudes of the influence of farm size are mixed with positive and negative associations.

2.5.3.8 Access to extension services

Access to extension services influenced farmers to plant shade trees in coffee fields as well as use cut-off drains, soil fertility management, and terraces than farmers growing coffee without access to such services. Farmers with access to extension services are more likely to perceive changing climatic conditions (Yamba *et al*., 2019) and to have knowledge of the various management practices that they can use to adapt to such changing conditions (Gbetibouo, 2009). However, in this study, access to extension services had no significant influence on the perceptions of climate change. Despite the great role of extension agents in disseminating knowledge and skills of how farmers should adapt to climate change, the majority of farmers reported not receiving any services from extension agents. Therefore, it is important for the policy makers to develop institutions that will enhance the access of extension services to farmers.

2.6 Conclusions

The results demonstrated that coffee farmers from the Northern and Southern Highland of Tanzania have experienced changes in climate (increase in temperature and decrease in rainfall). Moreover, climate change has already impacted coffee production in terms of reduction in yield, increase in coffee insect pests and diseases, late flowering, prolonged harvesting, and total crop failure in more adverse conditions.

Climate change will continue to affect farmers' livelihood unless adaptation measures are taken. Recent awareness of climate change, access to climate change information, education level and the sex of the household head, and farming experience are factors affecting farmers' climate change perceptions. Smallholder farmers have been responding to unpredictable weather patterns in different ways with their level of response being influenced by the gender of the household head, education level, farming experience, farm size,

access to extension services, and time aware of climate change information.

Based on these results, it is recommended to enhance access to timely and accurate weather information together with developing institutions that enhances access to education and extension services. Each group of farmers with different levels of education should also be trained or advised in a different way. The focus of education or training should be on attenuating the impacts of climate change through relevant adaptation measures in each coffee-growing region. The findings of this study are also applicable to other areas growing coffee under similar conditions. It was therefore, important to quantify the perceptions of farmers with regards to the impact of climate change on coffee production using meteorological data from Tanzania Meteorological Agency (TMA) and official historical data from Tanzania Coffee Board, a study which was conducted in chapter 3 of this thesis.

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CHAPER THREE

3.0 The Impacts of Current Climate Variability on Coffee Production in the Northern and Southern Highlands of Tanzania

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3.1 Abstract

Coffee is the most traded commodity in the world. In Tanzania, Coffee is the second largest traditional commodity. However, several climate changes studies have predicted that coffee production will be reduced as a result of climate change. Therefore, the study aimed to assess the impact of current climate change on Tanzania's Arabica coffee production and determine the most significant climatic variables, which influence coffee production in the respective regions. Global interpolated climatic database (Worldclim dataset) and official historical coffee production data from Tanzania Coffee Board for a period of 40 years (1970-2018) were used. Climatic parameters and coffee production were compared through descriptive statistics, correlation analysis, and multiple regressions. The Mann-Kendall method was used to detect significant trends in climatic data. The minimum temperature has been increasing at a higher rate than the maximum temperature in the Northern and Southern Highlands zones. 1 °C increase in minimum temperature (T_{min}) during short rains and annual mean temperature (T_{mean}) resulted in a significant coffee production decrease (-6,041 and -4,450 tons) in Kilimanjaro and Arusha regions respectively. In the Southern Highlands zone coffee production positively correlated with temperature. A significant reduction in coffee production due to a decline in long rains was also observed in the Kilimanjaro region. The warming and drought trends are likely to continue with significant implications on coffee production and this, calls for the development of suitable adaptation strategies to sustain production. Such strategies may include, re-adapting the coffee agronomic practices to climate change, improving water and nutrient use efficiency in coffee trees, and developing genetically improved coffee cultivars that will tolerate the impact of climate change.

Keywords: *Coffea arabica*, drought, temperature, Tanzania.

3.2 Introduction

Coffee is the second most important item in the world, in terms of trade, next to oil (Jayakumar *et al.,* 2017). The crop is produced in about 80 tropical countries (National Coffee Association (NCA), 2017), with an estimated 125 million people depending on it for their livelihoods in Latin America, Africa, and Asia (Osario, 2002). In Tanzania, coffee is the second-largest traditional commodity (TCB), 2021). It contributes 24% to the annual agricultural foreign exchange earnings and significantly contributes to tax revenue. The industry directly supports an estimated 2.4 million individuals in Tanzania (TCB, 2017) and several million more in similar agro-ecological conditions in neighboring Uganda, Kenya, Rwanda, and Burundi. Approximately 70% of the coffee produced in Tanzania belongs to the species *Coffea arabica* and 30% is *Coffea canephora*; the former is produced mainly in Ruvuma, Mbeya, Songwe, Arusha, and Kilimanjaro regions, and the latter in the Kagera region (TCB, 2021). For the case of *Coffea arabica*, the commercial varieties grown in Tanzania are Bourbon (N39) and Kents (K 423). The main production constraints for the commercial varieties are, however, high susceptibility to major coffee diseases like Coffee Berry Disease (CBD) and Coffee Leaf Rust (CLR). Due to the above problems, Tanzania Coffee Research Institute (TaCRI) has developed coffee hybrid varieties that are resistant to CLR and CBD (TaCRI, 2011).

The production and productivity of both species largely depend on the climate to attain high yields and quality (Killeen & Harper, 2016). Arabica coffee grows well in an area with an optimum temperature range of 18-21 °C (Magrach & Ghazoul, 2015) and annual rainfall range of 1200-1800 mm (Alegre, 1959). Due to its narrow climatic requirements coffee crop, is expected to be the most affected by the increasing temperatures (Malyadri, 2016) and reduced rainfall (Wagner *et al.,* 2021). According to IPCC (2014), the global climate has changed over the past century and is projected to continue changing throughout this century. Furthermore, global circulation models (GCMs) all point to higher mean temperatures and changes in precipitation regimes. Africa is one of the continent's most severely affected by climate change due to its geographical characteristics of having the majority of land lying across the warming tropics (Sridhar

& Rao, 2014). In this continent, the temperature is projected to rise faster than the rest of the world, which could exceed 2 °C by mid-21st century and 4 °C by the end of the 21st century (Niang *et al.,* 2014). East Africa will be increasingly affected by climate change in the coming decades, with temperatures already increasing and predicted to rise further (Adhikari *et al.,* 2015; Craparo *et al*., 2015). Countries within East Africa are also experiencing reduced rainfall due to the shortening of long rains (Wainwright *et al*., 2019). As a part of the tropical region, Tanzania has experienced sustained warming particularly since 1970 (IPCC, 2007). Based on downscaled climate models, Tanzania is projected to experience a mean temperature increase of 2-4 °C by 2100 (IPCC, 2007; Läderach *et al.,* 2012).

The increase in temperatures and precipitation shortages has negative impacts on coffee flowering and fruiting. However, global studies indicate that precipitation factors such as annual and seasonal precipitation are of less importance compared with temperatures in determining suitability (Ovalle-Rivera *et al.,* 2015; Rao, 2016). In Tanzania, research has shown that coffee yields are especially affected by elevated night temperatures (Craparo *et al.,* 2015) and droughts due to a shift in seasons (Wagner *et al.,* 2021). It is predicted that in Tanzania every 1 °C increase in minimum temperature will result in annual yield losses of nearly 140 kg ha^{-1} (Craparo *et al.,* 2015). The severity of pests and disease spread is likely to increase with advancing climate change, a significant challenge in coffee production (Jaramillo *et al*., 2011). According to Ovalle-Rivera *et al.* (2015), the influence of weather variations on coffee-producing countries is predicted to be negative. This will jeopardize coffee quantity and quality hence endangering coffee producers who occupy 90 percent of the population and their livelihoods mostly rely on coffee.

Climate change projections also suggest that some areas would lose suitability for growing coffee while others would gain from temperature increases and possibly in rainfall (Ovalle-Rivera *et al*., 2015). According to Killeen and Harper (2016), there would be a change in coffee production areas because suitable areas will become too warm or prone to periodic drought. Furthermore, Ovalle-

Rivera *et al.* (2015) in their study documented future global loss of Arabica coffee area by 2050 as follows: Mesoamerica (30 %), South America (16-20 %), and Africa (9-25 %). They have also reported that Mexico from Mesoamerica and Brazil from South America would lose about 29% of its suitable Arabica coffee growing areas respectively. Pacific countries such as India and Vietnam will also experience a loss of suitability areas and be highly affected. Davis *et al.* (2012) proposed a substantial reduction in the area suitable for Indigenous Arabica varieties in Eastern Africa. Land suitable for Arabica coffee in East Africa is predicted to shift from 400-2000 m above sea level to 800-2500 m above sea level. Moreover, there would be a modest change in the suitability of the areas in Ethiopia, Kenya, Rwanda, and Burundi that currently grow Arabica coffee. Tanzania and Uganda would lose suitable areas at elevations below 1400 m above sea level. For the case of the Northern Highlands of Tanzania, the optimum coffee-producing zone would need to shift upwards attitudinally by 150-200 m, to sustain coffee quality and quantity (Craparo *et al.,* 2015). However, this pushes coffee into a higher altitudinal zone that currently hosts substantial biodiversity of (mostly protected) forest species (Hemp, 2005), thus limiting upslope coffee expansion in northern Tanzania and indeed much of the coffee regions in tropical countries.

Farmers at lower elevations will no longer be able to grow quality coffee and may have to abandon it. This suggests that actors along the coffee supply chain will have to adapt to the changes that climate change will bring. According to Stafford *et al*. (2011), farmers can adjust by making incremental adaptations and innovations based on their experiences to deal with climate variability. Incremental adaptation occurs in a short timeframe at lower altitudes, whereas the same areas may undergo transformative adaptation in the long term. At higher altitudes incremental adaption may be needed in the long term based on two adaptation strategies to two levels of climate change (incremental adaptation for lower levels of progressive climate change and transformative adaptation for higher levels of progressive climate change), Läderach *et al.* (2017) has developed a two-dimensional adaptation framework in time and space for coffee production in Nicaragua. According to the author the same principle

and framework are applicable across coffee-growing regions around the world, as the patterns of decreasing exposure with higher altitudes are the same globally; only the magnitude and timeframe changes. In Vietnam, Phuong Le and Nguyen (2018), identified adaptation processes more broadly as long-term strategies and analyzes temporary coping responses to drought of coffee growers.

Different studies indicate that smallholder coffee farmers have been responding to climate change impacts through a range of interventions, including agronomic practices such as planting shade trees, pruning, planting drought-tolerant varieties, and application of organic fertilizers (Kajembe *et al*., 2016; Mbwambo *et al.,* 2021; Wagner *et al.,* 2018). In the study by Pham *et al*. (2019), the most common adaptation and management practices include different agroforestry systems, either through intercropping or shading followed by irrigation and efficient use and management of water. Another common adaptation and management practices against climate change is the development of new cultivars that are drought and heat-stress resistant and/or pest and disease tolerant. Other measures included the relocation of coffee plantations to more bio-climatically suitable areas, crop insurance, off-farm livelihoods and shifts from Arabica to Robusta or cocoa. According to Mbwambo *et al*. (2021) the adaptation measures used by smallholders' coffee farmers in the Northern and Southern Highlands of Tanzania are in the order of; use of shade tree, use of mulching, use of organic manure, planting disease resistance varieties, use of cut-off drains, use of terraces and irrigation. However, according to Craparo *et al*. (2015), the increase in T_{min} challenges the common notion that shade trees are always a beneficial aspect of climate change adaptation. Furthermore, responses towards adopting adaptations practices have been influenced by factors such as education level, farming experience, farm size, access to extension services, and time awareness of climate change information (Mbwambo *et al.,* 2021). Even though, in Tanzania, the general feeling is that the climate has been changing over the years and may be responsible for current low production and productivity (Craparo *et al.,* 2015; Mbwambo *et al.,* 2021; Wagner *et al.,* 2021), this perception has largely remained anecdotal, with limited assessment covering the whole country's

coffee-growing areas. Studies by Craparo *et al.* (2015) and Wagner *et al*. (2021) dealt with specific coffee-growing zones and pointed to the possible future climatic trajectories in those zones. Nevertheless, climate change studies are necessary for the formulation of climate change adaptation strategies for coffee farming in Tanzania, which does not exist yet. This study used official historical coffee production data to understand whether the general production patterns have any bearing on the historical climatic trends in major Arabica coffee growing areas in Tanzania.

3.3 Materials and Methods

3.3.1 Description of the study area

The study area is comprised of two major Arabica coffee growing zones. The Northern Highland zone involved the Kilimanjaro region (Hai, Moshi rural, Siha, and Rombo Districts) and Arusha Region (Arumeru, Longido, Monduli, and Karatu Districts). The Southern Highland zone included the Songwe region (Mbozi and Ileje districts), Mbeya (Mbeya and Rungwe districts), and Ruvuma (Mbinga, Songea, and Nyasa districts) (Figure 3.1). In these zones, Arabica coffee production is exclusively rain-fed. The Northern Highlands zone is characterized by a bimodal rainfall pattern, while the Southern Highland zone experiences a unimodal rainfall pattern.

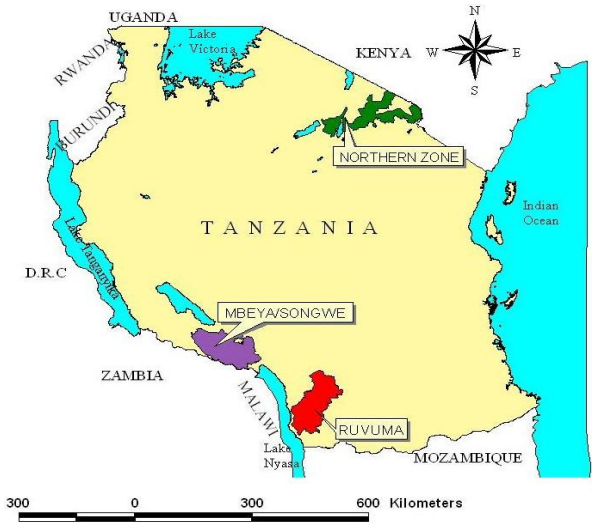

Figure 3.1: Map of Tanzania indicating study locations (callouts)

3.3.2 Data collection

Monthly minimum temperature (T_{min}), maximum temperature (T_{max}), and precipitation for the period between 1979-2018 were collected from the global interpolated climatic database (Worldclim dataset). The Worldclim dataset was cropped using the Tanzania country boundary layer mask. Tanzania map was also masked with the boundaries from the major Arabica coffee growing areas and served into shapefiles, which were then used to clip Worldclim datasets on the Tanzania mask. The dataset is available at a spatial resolution of 2.5 minutes (equivalent to 21 km^2 at the equator). Each download is a "zip" file containing 120 GeoTiff (.tif) files, for each month of the year for 10 years (Fick & Hijmans, 2017). The observed station datasets (rainfall and temperature) were also acquired from Lyamungu and Burka Coffee estate (Northern Highland zone) and Mbimba and Mbinga (Southern Highlands Zone). Data from Lyamungu, Mbimba, and Mbinga were acquired from the offices of the Tanzania Meteorological Authority (TMA), while data from the Burka Coffee estate were acquired from a private operator. The observed station dataset was used to evaluate the performance of gridded climatic data. Coffee production (tons per region) for five regions (Ruvuma, Mbeya, Songwe, Kilimanjaro, and Arusha) for 40 years (1979-2018) was obtained from official records of the Tanzania Coffee Board.

3.3.3 Data analysis

Missing values in the rainfall and temperature dataset from TMA were determined according to the "3/5" rule (WMO, 1989). The temperature data set had missing values ranging between 5 and 19%, while that of rainfall ranged between 1 and 5%. They were estimated using the multiple imputation method due to its characteristics to account for uncertainty about the imputed values. The performance of gridded datasets (Worldclim) was evaluated statistically using Mean Bias (MB). Mean Bias Error (MBE) shows bias from the mean, thus the approach to zero of this parameter indicates that the method simulates reality well and far from zero shows high deviation and inaccuracy (Hassan *et al.,* 2020).

$$\text{Mean Bias} = 1/n \sum_{1}^{n} y_i - o_i \qquad \text{(i)}$$

Where, y and o represent observed and predicted values respectively and n is the number of targeting data used for testing. The results in Table 3.1 indicate that the Worldclim dataset performed well in depicting the study areas dataset.

Table 3.1: Comparison of observed and gridded climatic data using Mean Bias (MB)

Dataset	Northern Highlands zone		Southern Highlands zone	
	Kilimanjaro	Arusha	Mbeya and Songwe	Ruvuma
Rainfall (mm)	-0.205	2.227	0.979	2.979
T_{min}	-4.823	0.823	-1.652	1.7034
T_{max}	0.380	2.783	0.865	2.474

Note. T_{max}= Maximum temperature; T_{min} = Minimum temperature.

Descriptive statistics (frequencies and percentiles), correlation analysis, and multiple regressions were performed in STATA 13.0 (StataCorp LP, College Station, TX, USA) and SPSS 21.0 (IBM-SPSS Inc, Chicago, IL, USA) software. The rank-based nonparametric Mann-Kendall (Mann, 1945; Kendall, 1975) method was applied to the long-term climatic data to detect statistically significant trends. In this test, the null hypothesis (H_0) was that there has been no trend in rainfall and temperature over time; the alternative hypothesis (H_1) was that there has been a trend (increasing (+) or decreasing (-) over time. In the Northern Highlands zone, correlation analysis was used to examine the relationship of long rains, short rains, and annual rainfall with coffee production. T_{min} (°C), T_{max} (°C), and T_{mean} (°C), both in the long rains, short rain seasons, and annually were also correlated with coffee production. In the Southern Highlands zone, the climatic parameters (rainfall, T_{min} (°C), T_{max} (°C), and T_{mean} (°C) were also correlated with coffee production in the growing season and annually. On the other hand, a multiple regression model was used to see the effect of independent variables (amount of rainfall and temperature) on the dependent variable (amount of coffee produced in tons). The model with the best statistical quality and highest adjusted R-squared was chosen. Regressors with higher P-values (smaller t-statistic values) were excluded one by one. If the exclusion of a regressor produced a positive change in the adjusted R squared value, it was left out and

subsequently tried with the next regressor that had the highest P-value. Regressors with the highest p-values were excluded until the change in the adjusted R-squared was negative (Gay *et al.,* 2006). Mbeya and Songwe were one region (Mbeya) before they split in 2015. Therefore, to have a 40-year coffee production data, these two regions (Mbeya and Songwe) were combined. The regression equation is represented as;

$$Y= B_o + B_1X_1 + B_2X_2 + \ldots + B_n X_n \quad \text{(ii)}$$

Where, Y= Dependent variable (Coffee (t)); B_o= Intercept; $B_{(1-n)}$ = Coefficients of regression line; $X_{(1-n)}$ Predictor variables (rainfall and temperature parameters).

3.4 Results

3.4.1 Monthly, Seasonal and Annual Analyses of Temperature and Rainfall

3.4.1.1 Northern Highlands Zone

The average annual total rainfall for the past 40 years (1979-2018) in Kilimanjaro and Arusha regions was found to be 1435.77 mm and 733.4 mm respectively (Appendix A3). In the Kilimanjaro region, the highest amount of rainfall was 2131.5 mm observed in 2006, which is higher than the long-term average of 1979-2018 by 695.73 mm. Nevertheless, out of 40 years, 22 years were below the average annual rainfall. In the Arusha region, the highest amount of rainfall was 1033 mm in 1988 which is higher than the long average of 1979-2018 by 299.6 mm. In addition, in the Arusha region, 23 years were below the average annual rainfall. T_{mean} in Kilimanjaro and Arusha regions were observed to be 19.67 °C and 20.3 °C respectively (Appendix A3).

Over the 40 years, T_{max} in the Northern Highlands zone has been increasing significantly ($P \leq 0.001$) at the rate of 0.018 °C $year^{-1}$and 0.017 °C $year^{-1}$in Kilimanjaro and Arusha regions respectively (Fig. 3.2 and 3.3). Arusha and Kilimanjaro regions have also experienced a significant ($P \leq 0.01$) increase of T_{max} during the long rain season at the rate of 0.01 °C $season^{-1}$. The short rains season, on the other hand, has been characterized by significant ($P \leq 0.01$) increases of T_{max} (0.02 °C $season^{-1}$) in Kilimanjaro and Arusha regions. The study

has also revealed a significant ($P \leq 0.01$) increase in T_{min} at the rate of 0.023 °C year^{-1} in the Kilimanjaro and Arusha regions (Fig. 3.4 and 3.5). Furthermore, a significant ($P \leq 0.01$) increase in T_{min} during the short rain season was observed at Kilimanjaro and Arusha regions at the rate of 0.03 °C season^{-1}. Significant ($P \leq 0.01$) increase in T_{min} during the long rain season was also observed in the Arusha region only at the rate of 0.02 °C season^{-1}. The results from the Mann-Kendall trend analysis for the Kilimanjaro region indicate statistically significant positive trends ($P \leq 0.05$) for T_{max} in all months while for T_{min} only two months (March and April) showed insignificant trends ($P \geq 0.05$). In the Arusha region, significant positive trends for T_{max} were observed in most of the months except for February. For the case of T_{min}, only two months (April and November) did not show positive significant trends. Mean warming for the Arabica growing regions of Northern Tanzania over the 40 years (1979-2018) has been + 0.819 °C (Kilimanjaro) and + 0.702 °C (Arusha).

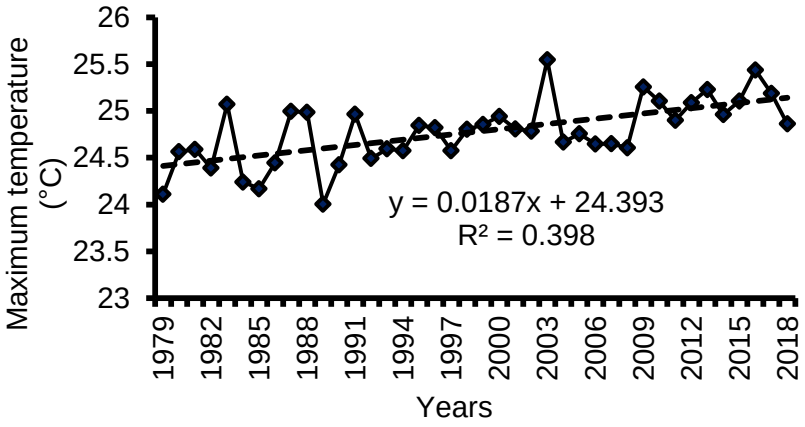

Figure 3.2: Annual temperature trends (°C) for Tmax in Kilimanjaro regions from 1979-2018

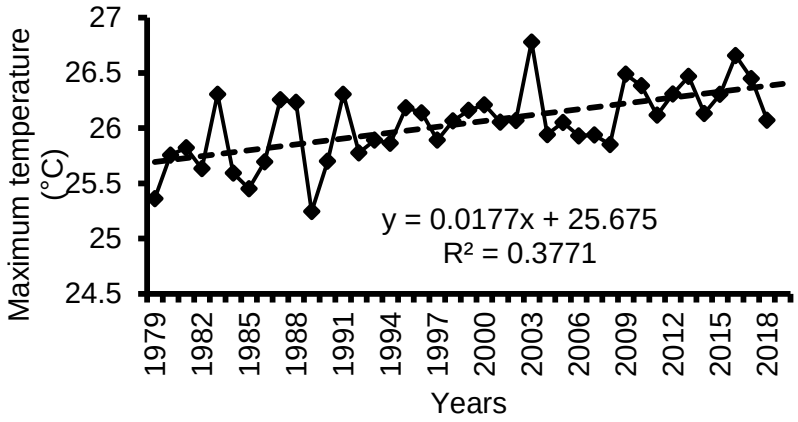

Figure 3.3: Annual temperature trends (°C) for Tmax in Arusha region from 1979-2018

The study has also revealed a significant ($P \leq 0.01$) increase in T_{min} at the rate of 0.023 °C $year^{-1}$ in the Kilimanjaro and Arusha regions (Fig. 3.4 and 3.5). Furthermore, a significant ($P \leq 0.01$) increase in T_{min} during the short rain season was observed at Kilimanjaro and Arusha regions at the rate of 0.03 °C $season^{-1}$. Significant ($P \leq 0.01$) increase in T_{min} during the long rain season was also observed in the Arusha region only at the rate of 0.02 °C $season^{-1}$. The results from the Mann-Kendall trend analysis for the Kilimanjaro region indicate statistically significant positive trends ($P \leq 0.05$) for T_{max} in all months while for T_{min} only two months (March and April) showed insignificant trends ($P \geq 0.05$). In the Arusha region, significant positive trends for T_{max} were observed in most of the months except for February. For the case of T_{min}, only two months (April and November) did not show positive significant trends. Mean warming for the Arabica growing regions of Northern Tanzania over the 40 years (1979-2018) has been + 0.819 °C (Kilimanjaro) and + 0.702 °C (Arusha).

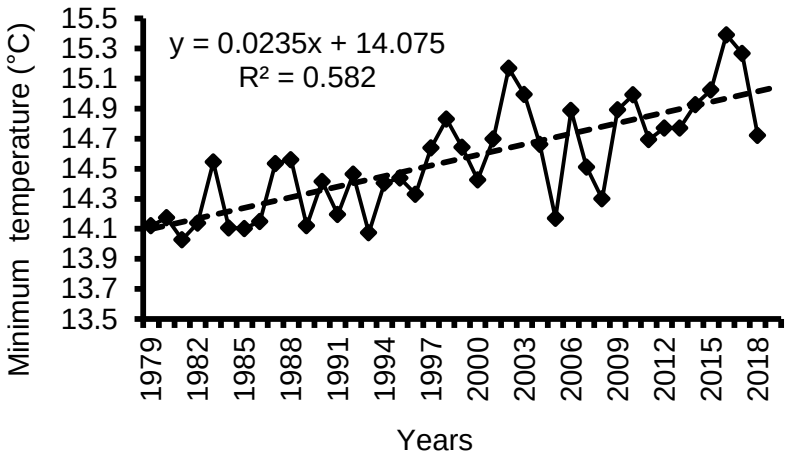

Figure 3.4: Annual temperature trends (°C) for Tmin in Kilimanjaro regions from 1979-2018

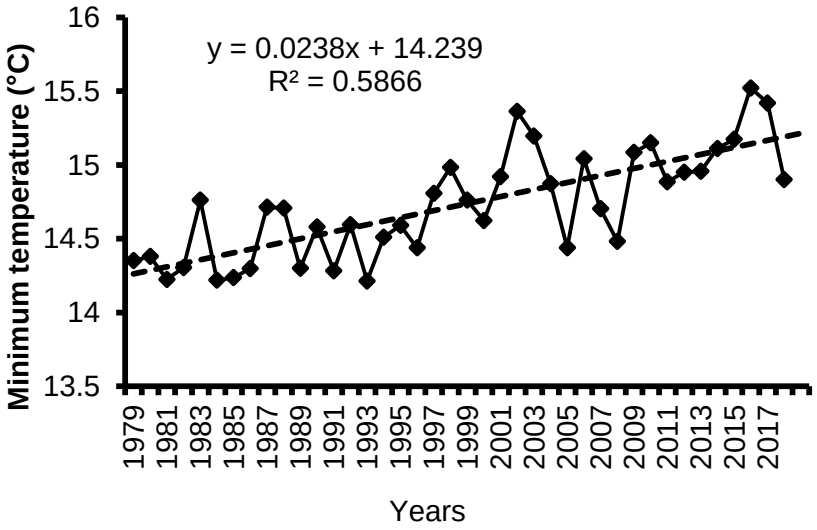

Figure 3.5: Annual temperature trends (°C) for Tmin in Arusha regions from 1979-2018

Furthermore, the highest T_{max} was observed in the Arusha region (30.67 °C) (Figure 3.6) followed by the Kilimanjaro region (30 °C) in February (Figure 3.7). Furthermore, the months of June, July, and August had the lowest T_{max} (20-22 °C). The highest T_{min} was observed

in April in Kilimanjaro (17.4 °C) and Arusha (17.7 °C) regions while the lowest T_{min} was in July and August (12 °C) (Fig. 3.8 and 3.9). The long rains season in Kilimanjaro and Arusha regions has experienced lower T_{max} (26.5 °C) as compared to T_{max} in the short rains (27.5 °C).

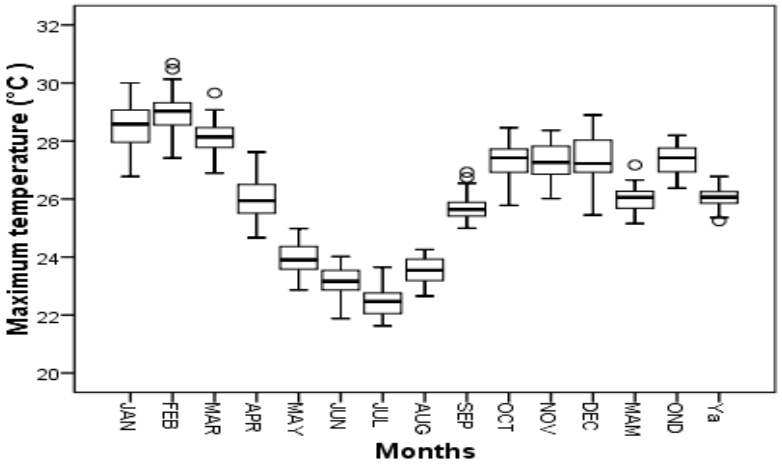

Figure 3.6: Box and Whisker plot of maximum temperature (°C) in Arusha region from 1979-2018

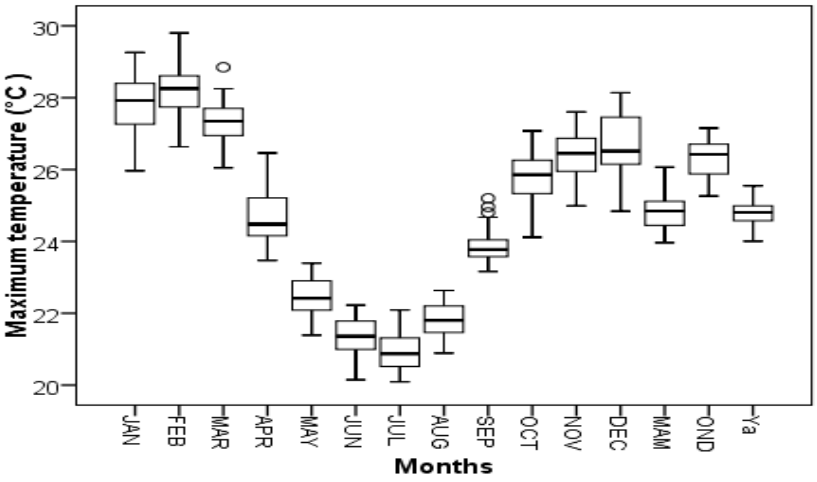

Figure 3.7: Box and Whisker plot of maximum temperature (°C) in Kilimanjaro region from 1979-2018

Note. MAM= long rain season made up of March, April, and May; OND= Short rain season made up of October, November, and December; Ya = Annual

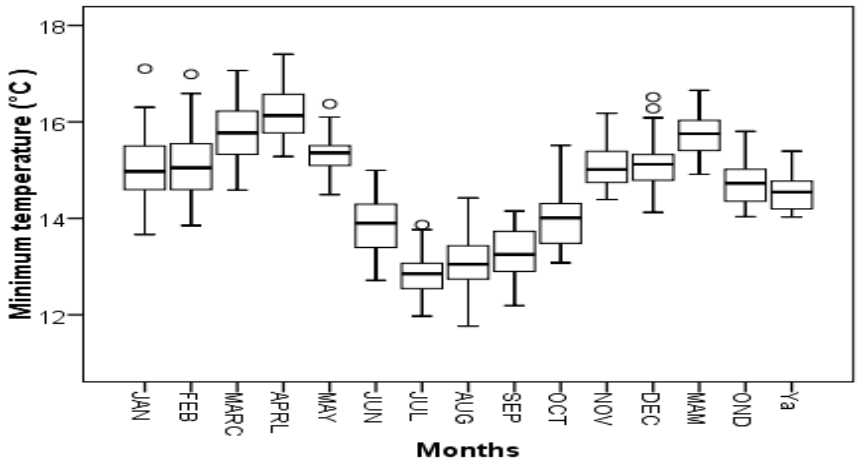

Figure 3.8: Box and Whisker plot of minimum temperature (°C) in Arusha region from 1979 to 2018.

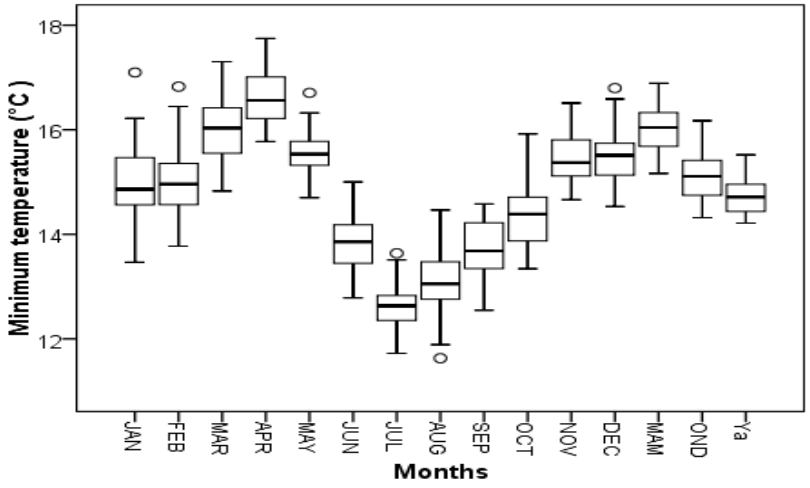

Figure 3.9: Box and Whisker plot of minimum temperature (°C) in Arusha region from 1979 to 2018

Note. MAM= long rain season made up of March, April, and May; OND= Short rain season made up of October, November, and December; Ya = Annually.

Annual rainfall has been decreasing at a higher rate in the Kilimanjaro region (-7.77 mm year^{-1}) than in the Arusha region (-2.14 mm year^{-1}) (Fig. 3.10 and 3.11). However, annual rainfall decrease in the Northern Highlands zone, were not statistically significant (P ≥ 0.05). Nevertheless, a significant decrease in rainfall (P ≤ 0.05) has been observed during the long rain season in the Kilimanjaro region (14.65 mm season^{-1}) and the Arusha region (-3.29 mm season^{-1}). Short rains, on the other hand, have been increasing significantly (P ≤ 0.05) in the Arusha region only at the rate of 2.2 mm season^{-1}.

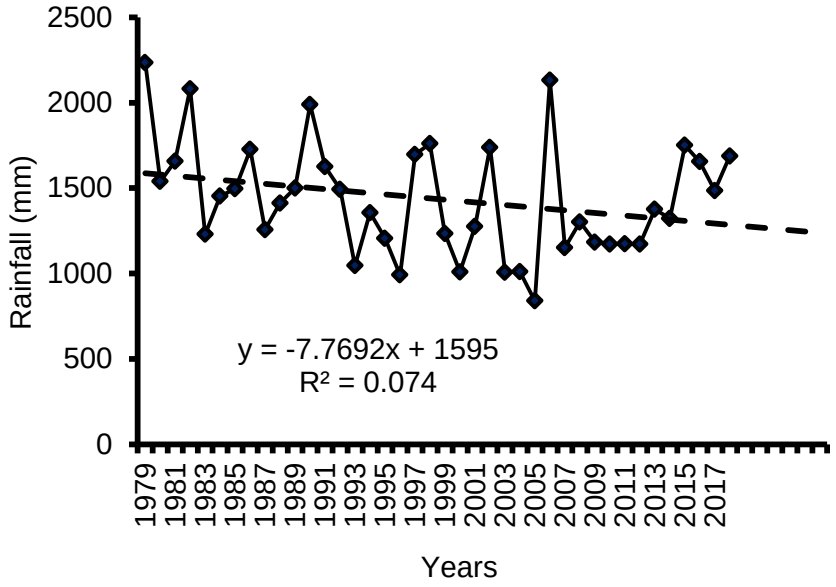

Figure 3.10: Yearly total rainfall (mm) in Kilimanjaro from 1979-2018

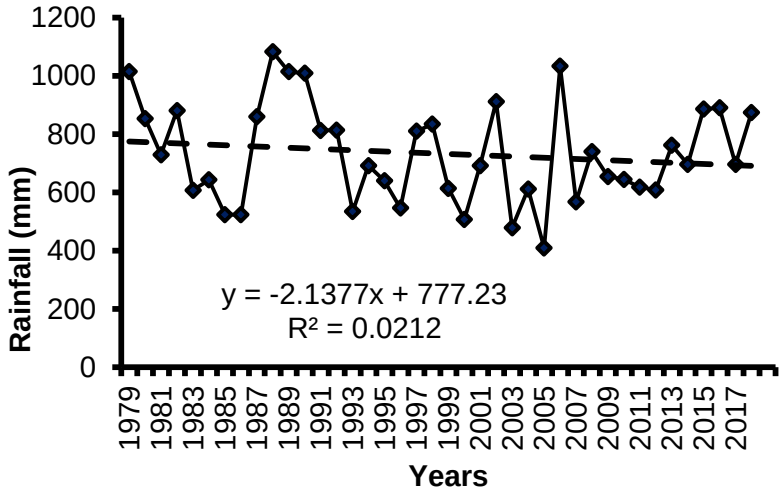

Figure 3.11: Yearly total rainfall (mm) in Arusha regions from 1979-201

Kilimanjaro region received a higher amount of rainfall in April and May while the Arusha region received a higher amount of rainfall in March and April (Fig. 3.12 and 3.13). On the other hand, of all the months it was the month of April that had less rainfall variability in Kilimanjaro (Coefficient of variation (CV) = 39.53%) and Arusha (CV = 44.34%) regions. In the Kilimanjaro region, the monthly highest CV was in the order of September (94.9%) >August (87.6%) >July (81.2%) > October (73%) >January (72%). The highest CVs in Arusha were in the order of September (87.8%) > August (85.3%) > October (78%) > July (76%) > June (70%). On the other hand, short rains in Kilimanjaro and Arusha regions had higher CV (44.11% and 45.76%) as compared to long rains (29.36% and 31.29%) respectively. When the CV for the annual rainfall was calculated, it was the least in the Kilimanjaro region (23.26%) followed by the Arusha region (23.39%) (Fig. 3.14).

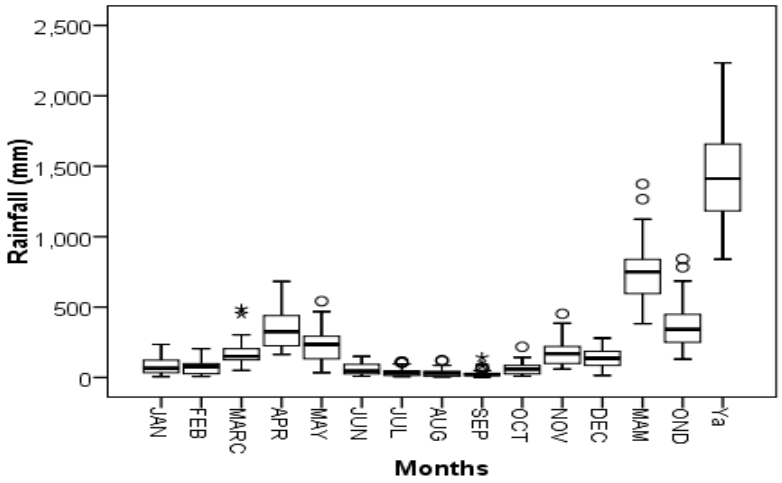

Figure 3.12: Box and Whisker plot of monthly rainfall (mm) in Kilimanjaro region from 1979 to 2018

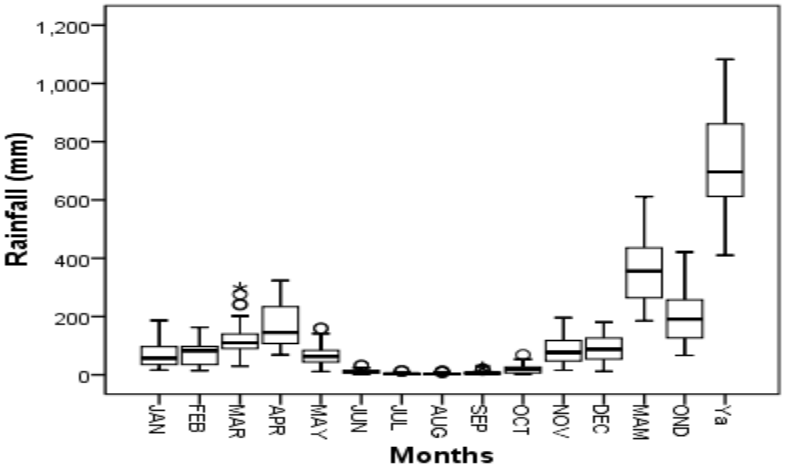

Figure 3.13: Box and Whisker plot of monthly rainfall (mm) in Arusha region from 1979 to 2018

Note. MAM= long rain season made up of March, April, and May; OND= Short rain season made up of October, November, and December; Ya = Annually.

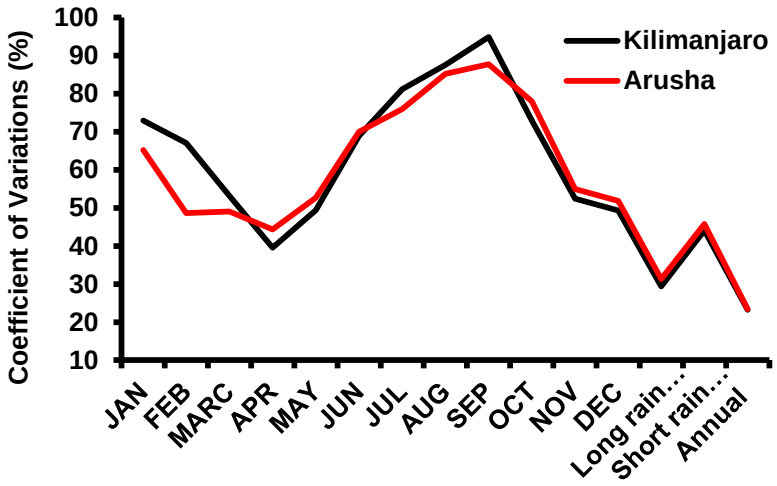

Figure 3.14: Coefficient of variation (CV) for the monthly rainfall in the 40 years (1979-2018) in the Northern Highlands zone

3.4.1.2 Southern Highlands Zone

The average annual total rainfall for the past 40 years (1979-2018) in Mbeya-Songwe and Ruvuma regions was found to be 1306.09 mm and 1203.74 mm respectively (Appendix A.1). In the Mbeya-Songwe region, the highest amount of rainfall was 2036.51 mm observed in 1979, which is higher than the long-term average of 1979-2018 by 730.42 mm. On the other hand, in the Ruvuma region, the highest amount of rainfall was 1588.55 mm in 1979 which is higher than the long average of 1979-2018 by 384.81 mm. Furthermore, more than half of the years in the Southern Highlands zone received rainfall that was below the average annual rainfall. The T_{mean} in the Mbeya-Songwe and Ruvuma regions was 19.44 °C and 21.44 °C respectively (Appendix A.3). T_{max} has been increasing significantly ($P \leq 0.01$) at a rate of 0.011 °C and 0.014 °C $year^{-1}$in Mbeya-Songwe and Ruvuma regions respectively (Fig. 3.15 and 3.16). Moreover, T_{max} significantly ($P \leq 0.01$) increased at the rate of 0.005 °C per rainy season in the Mbeya and Songwe regions. Ruvuma region has also experienced a significant increase ($P \geq 0.01$) of T_{max} at the rate of 0.008 °C $season^{-1}$.

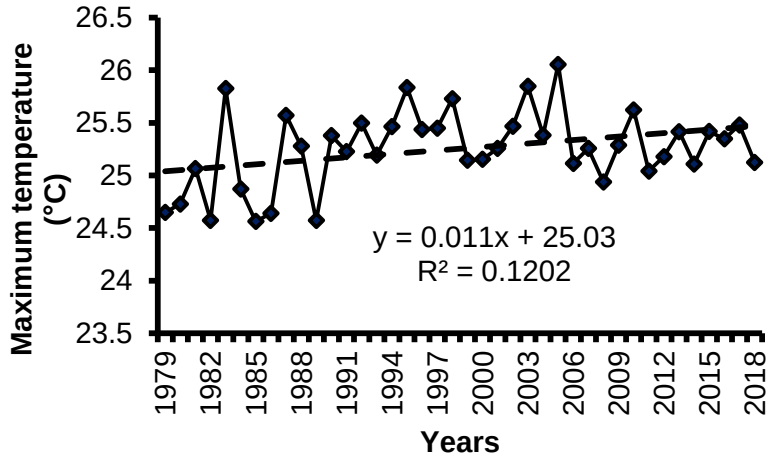

Figure 3.15: Annual temperature trend (°C) for T_{max} in Songwe-Mbeya regions from 1979-2018

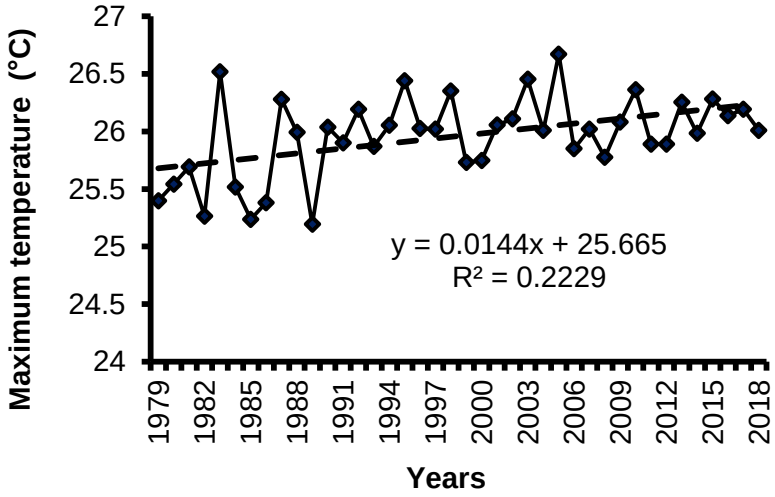

Figure 3.16: Annual temperature trend (°C) for T_{max} in Ruvuma from 1979-2018

Significant ($P \leq 0.01$) increases in T_{min} at the rate of 0.016 °C and 0.017 °C $year^{-1}$ have also been observed in Mbeya-Songwe and Ruvuma regions respectively (Fig. 3.17 and 3.18). However, T_{min} increased insignificantly ($P \geq 0.05$) during the growing season in the Mbeya, Songwe, and Ruvuma regions. Mean warming for the Arabica growing regions in the Southern Highlands zone over the last 40-year

period (1979-2018) has been +0.507 °C (Mbeya and Songwe) and +0.624 °C (Ruvuma).

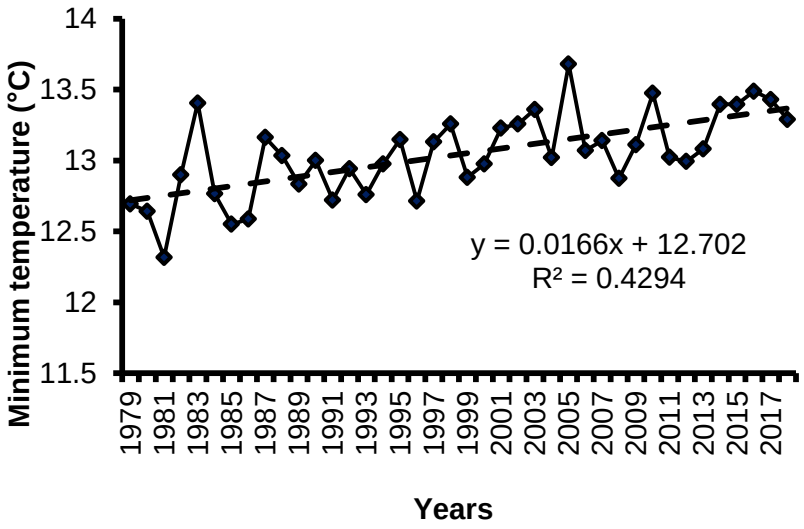

Figure 3.17: Annual temperature trend (°C) for T_{min} in Songwe-Mbeya regions from 1979-2018

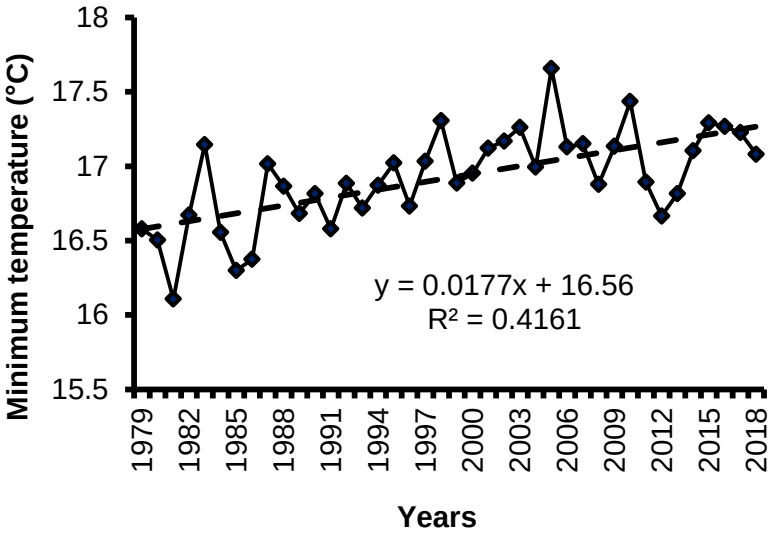

Figure 3.18: Annual temperature trend (°C) for T_{min} in Ruvuma regions from 1979-2018

Seven months in the Mbeya and Songwe regions have shown significant positive trends in T_{max} ($P \leq 0.05$). However, only the months of August and October exhibited significant positive trends in T_{min} ($P \leq 0.05$). In the Ruvuma region, seven months exhibited a significant upward trend in T_{max} and T_{min}. In this zone, October and November have been the hottest months in terms of T_{max} (Fig. 3.19 and 3.20). The months of June and July on the other hand had the lowest T_{max} up to 22 °C. The highest T_{min} (17 °C) was also observed in January and February in Mbeya and Songwe regions while in the Ruvuma region the T_{min} of above 20 °C was also observed in the same months. On the other hand, Mbeya and Songwe regions had the lowest T_{min} (8 °C) in July followed by the Ruvuma region (11 °C) in the same month (Fig. 3.21 and 3.22).

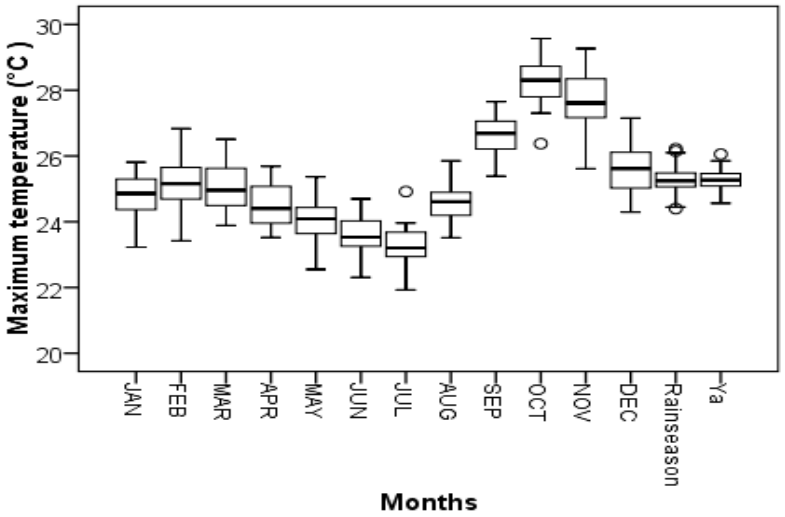

Figure 3.19: Box and Whisker plot of maximum temperature (°C) in Mbeya and Songwe regions from 1979 to 2018

Note. Ya = Annual

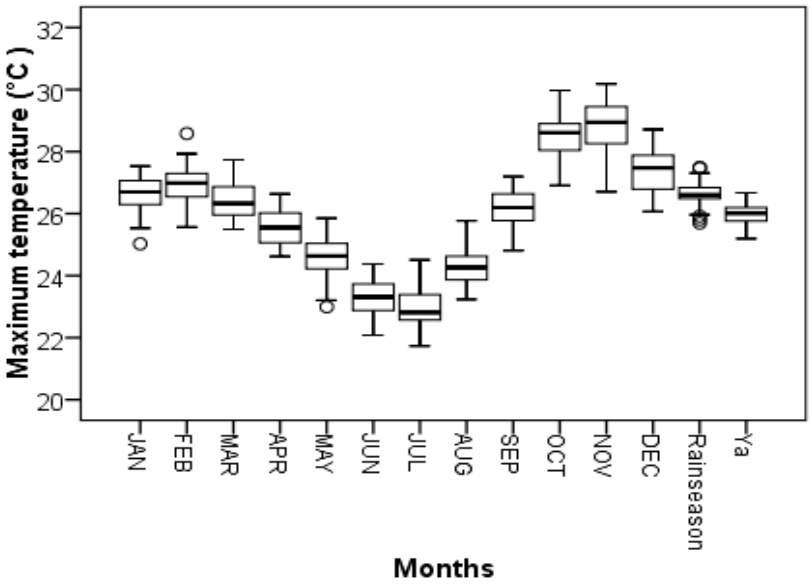

Figure 3.20: Box and Whisker plot of maximum temperature (°C) in Ruvuma region from 1979 to 2018

Note. Ya = Annual

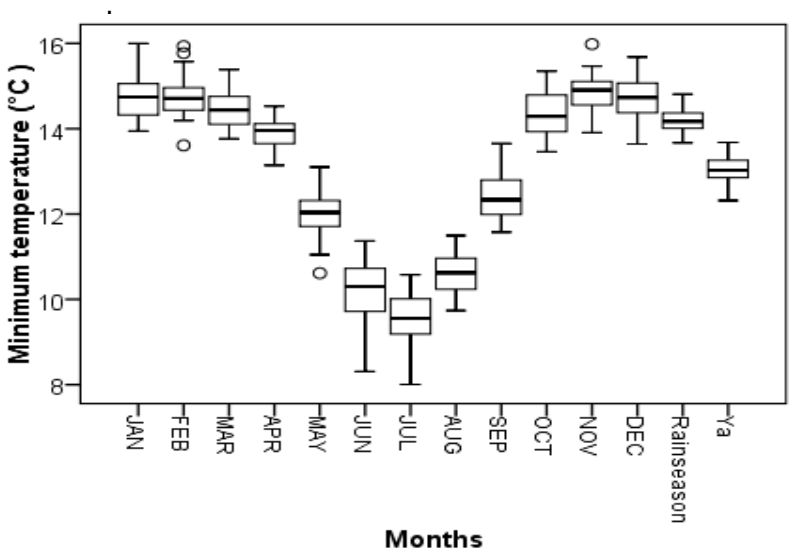

Figure 3.21: Box and Whisker plot of minimum temperature (°C) in Ruvuma region from 1979 to 2018

Note. Ya = Annual.

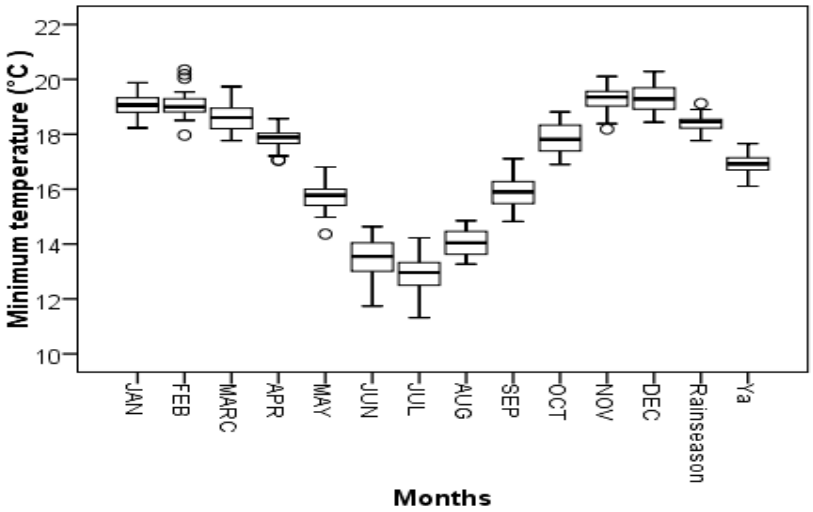

Figure 3.22: Box and Whisker plot of minimum temperature (°C) in Mbeya and Songwe regions from 1979 to 2018

Note. Ya = Annual.

The findings from this study also revealed an insignificant decrease of rainfall by 2.59- and 2.06-mm year^{-1}in the Mbeya-Songwe and Ruvuma regions respectively ($P \geq 0.05$) (Fig. 3.23 and 3.24). Significant negative trends ($P \leq 0.05$) in the monthly rainfall were detected in March and July in the Ruvuma region. An insignificant decrease of rainfall ($P \geq 0.05$) has also been observed during the rainy season at Mbeya and Songwe regions (-2.54 mm season^{-1}) and Ruvuma region (-2.14 mm season^{-1}).

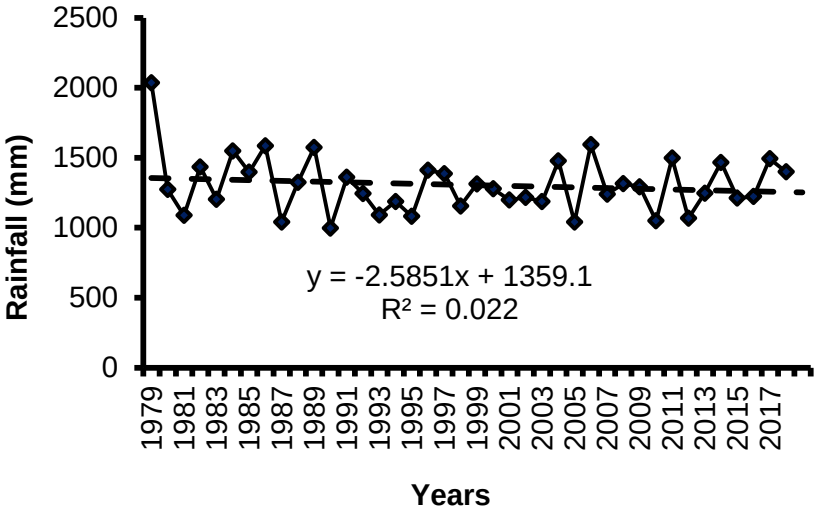

Figure 3.23: Yearly total rainfall (mm) in Songwe-Mbeya regions from 1979-2018

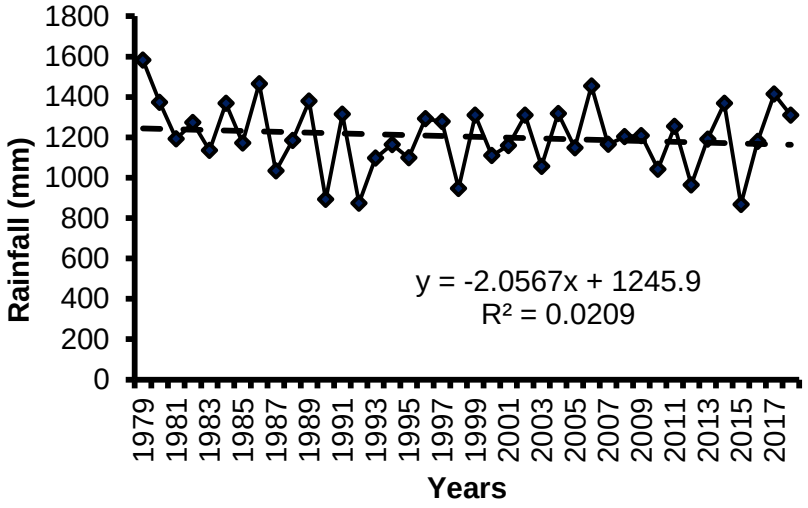

Figure 3.24: Yearly total rainfall (mm) in Ruvuma region from 1979-2018

Fig. 3.25 and 3.26 indicate that Mbeya-Songwe and Ruvuma regions received a higher amount of rainfall during December, February, and March. On the other hand, the amount of rainfall received in April and May in the Mbeya-Songwe regions was higher as compared to the

amount of rain received in the Ruvuma region. Furthermore, January had less rainfall variability both in Mbeya-Songwe regions (CV=19.4%) and Ruvuma region (CV= 21%) (Fig. 3.27). Five months with higher CV in Mbeya and Songwe regions were in the order of October (CV = 79.6%) >September (CV = 73.2%) > May (CV = 62.7%) > November (CV = 60.2%) > June (CV= 57.9%). In Ruvuma region the five months with higher CV were in the order of June (CV = 95.3%) > July (CV = 87.1%) > October (74.4%) > September (73.5%) > May (64.7%). The findings also revealed higher rainfall variability in the rain season in Mbeya (CV = 15.6%) than in the Ruvuma region (CV = 13.8%). When the CV for the annual rainfall was calculated, it was highest in Mbeya and Songwe regions (15.8%) followed by the Ruvuma region (13.8%).

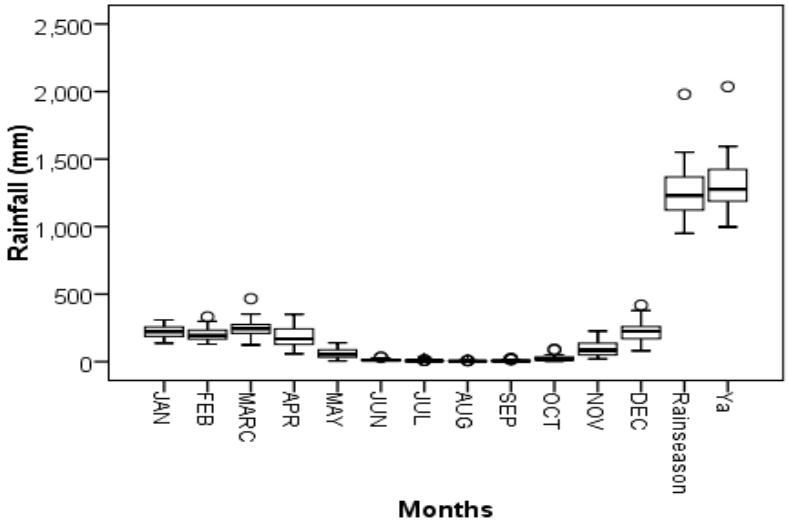

Figure 3.25: Box and Whisker plot of monthly rainfall (mm) in Mbeya and Songwe regions from 1979 to 2018;

Note. Ya = Annually.

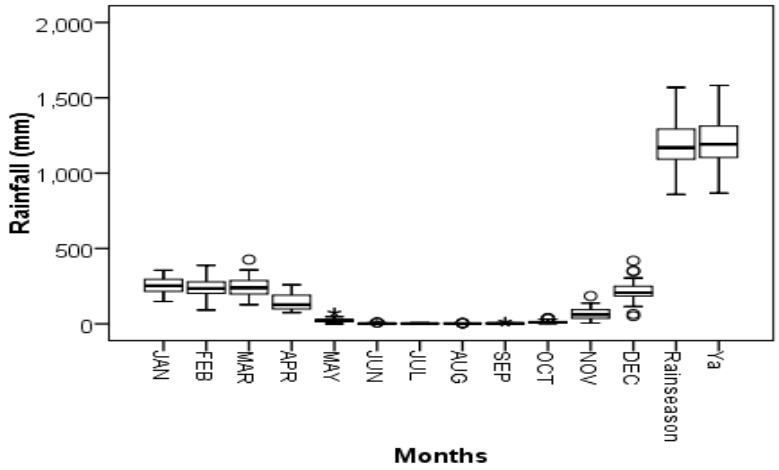

Figure 3.26: Box and Whisker plot of monthly rainfall (mm) in Ruvuma region from 1979 to 2018;

Note. Ya = Annually.

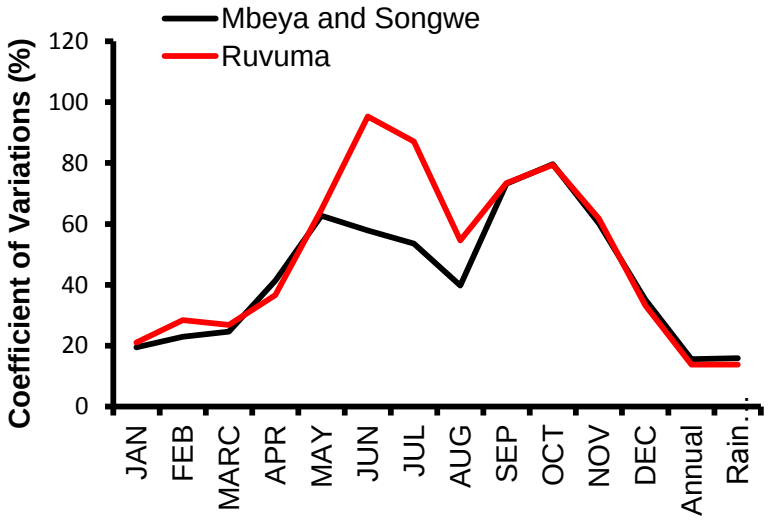

Figure 3.27: Coefficient of variation for the monthly rainfall in the 40 years (1979-2018) in the Southern Highlands zone

3.4.2 Coffee Production Records

Based on the 40 years (1979 to 2018), coffee production data from Tanzania Coffee Board (TCB), a decreasing trend has been observed in the Northern Highlands zone (Fig. 3.28 and Table 3.2) while the

Southern Highlands zone has shown an increasing trend (Fig. 3.29 and Table 3.2). The maximum coffee production in the Songwe region was 15,826 tonnes in the year 2012 while in Ruvuma the maximum production was 16,104 tonnes, in 2017. On the other hand, maximum coffee production in Kilimanjaro and Arusha region was 27,077 to and 11,974 tonnes respectively in 1980 and since then the production has fallen.

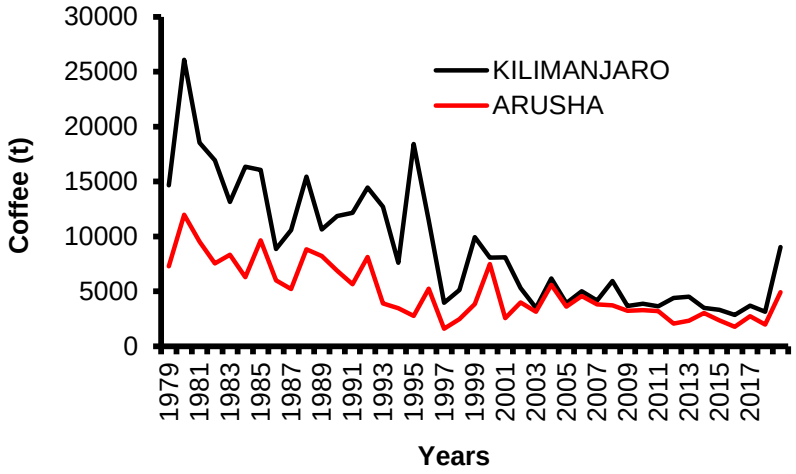

Figure 3.28: Northern Highlands zones yearly coffee production trends 1979 to 2018

Source: Tanzania Coffee Board (TCB)

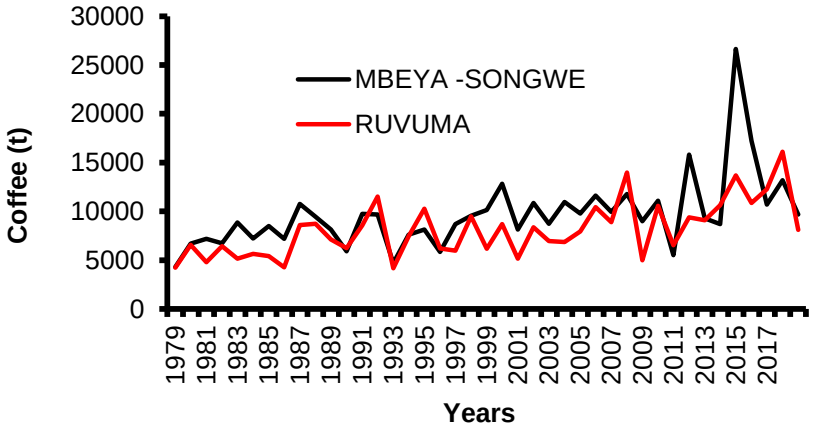

Figure 3.29: Southern Highlands zones yearly coffee production trends 1979 to 2018

Source: Tanzania Coffee Board (TCB)

Total percentage change calculated from the trends of coffee production in the Northern zone indicates that over the 40 years coffee production has been declining at about 94.52% and 82.37% in Kilimanjaro and Arusha regions, respectively. On the other hand, coffee production in Ruvuma and Mbeya-Songwe regions has been increasing at about 55% and 21% respectively (Table 3.2).

Table 3.2: Analysis of coffee production trend from 1979 to 2018 in the Northern and Southern Highlands Zones

	Northern Highlands		Southern Highlands	
	Kilimanjaro	Arusha	Mbeya/Songwe	Ruvuma
Annual Production (t)	9040	4934	8683	8113
Minimum production (t)	2847	422	2022	2022
Maximum production (t)	27077	11974	15826	16104
Trend (tons/ year)	-415	-177	54	158
Total change calculated from the trend (t/40 years)	16185	6910	6197	2114
Total change calculated from the trend (%)	95	82	55	21

Note. Total change is the difference between the trend line value of the first and last year.

3.4.3 Relationship between Climatic Data and Coffee Production

3.4.3.1 Correlation analysis

The relationship between the amounts of coffee (t) produced and the amount of rainfall (mm) was positively significant ($P \leq 0.05$) during the long rain season at Kilimanjaro and Arusha region. Results also showed a significant negative relationship ($P \leq 0.05$) between the amount of coffee produced and average T_{min} long and short rain season and average T_{min} in Kilimanjaro and Arusha regions. Furthermore, the analysis indicates a significant negative relationship ($P \leq 0.05$) between the annual average T_{max} and the amount of coffee produced in both regions. Average T_{max} had also a significant relationship ($P \leq 0.05$) with coffee production during short rain in the Kilimanjaro region and during long rain in the Arusha region. Pearson correlation analysis also resulted in the negative correlation between Annual mean temperature and coffee production in Arusha and Kilimanjaro regions (Table 3.3).

Table 3.3: Pearson correlation values for the amount of coffee (t) and climatic data in the Northern Highlands zone

		Coffee production in Kilimanjaro	Coffee production in Arusha
T_{min} short rain	Pearson correlation	-0.694**	-0.558**
T_{min} long rain		-0.472**	-0.427**
Average T_{min}		-0.700**	-0.628**
T_{max} short rain		-0.321**	-0.440**
Average T_{max}		-0.518**	-0.553**
T_{mean}		-0.654**	-0.708**
Long rains		0.347*	0.320*

*Note.**: Significant at 0.05 level; **: Significant at 0.01 level; T_{min}= Minimum temperature, T_{max} = Maximum temperature, T_{mean} = Average temperature.

Table 3.4 indicated a significant positive relationship ($P \leq 0.05$) between average T_{min} rain season, annual average T_{min}, T_{mean}, and the amount of coffee produced at Songwe-Mbeya and Ruvuma regions. The analysis also shows the positive relationship between the annual averages T_{max} and the amount of coffee produced in the Ruvuma region. No significant correlation between coffee production and rainfall ($P \geq 0.05$).

Table 3.4: Pearson correlation values for the amount of coffee (t) and climatic data in the Southern Highlands zone

		Coffee production in Mbeya -Songwe	Coffee production in Ruvuma
T_{min} rain season	Pearson correlation	0.316*	0.334*
Average T_{min}		0.457**	0.464**
Average T_{max}		0.216	0.360*
T_{mean}		0.351*	0.434**

Note. T_{min}= Minimum temperature, T_{max}= Maximum temperature, T_{mean} = Average temperature. *: Significant at 0.05 level; **: Significant at 0.01 level.

3.4.3.2 Regression analysis

(1) Northern Highlands Zone

In the Kilimanjaro region, three independent variables were significantly predictive of coffee production according to ANOVA statistics [F (3, 37) =21.04, P ≤ 0.01]. The model's percent of explaining the variance in coffee production in the Kilimanjaro region was found to be 63% (R^2 = 0.63). In the regression analysis results, the absolute value of Beta indicates the order of importance of the independent variables. The variable with the highest beta value is the relatively most important independent variable. Therefore, analysing the contributions made by the independent variables in the model, it was found that T_{min} short rain season made the biggest contribution with the value of (Beta = 0.473). It was followed by the average T_{min} and long rains respectively (Table 3.5).

Table 3.5: The relationship between coffee production (t) and temperature range (°C) in the Kilimanjaro region

	Un standardized Coefficients		Stand. Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	162367	24283.43		6.69	0.000
Long rains	6.794	2.716	0.263	2.50	0.017
T_{min} short rain	-6040.778	1853.90	-0.473	-3.26	0.002
Average T_{min}	-4761.400	2356.51	-0.302	-2.02	0.051

Note. B= Un standardized Beta; t= Statistical T; T_{min}: Minimum temperature.

Based on the regression analysis results, the regression equation is represented as,

Coffee (t) in Kilimanjaro region = 162367.5 + 6.79 (long rains) − 6040.78 (T_{min} short rain) − 4761.4 (Average T_{min}) (iii)

The regression relationship between climatic data and coffee production in the Arusha region was also highly significant and the model a good fit for the data [F (5, 32) = 9.454, P ≤ 0.01]. Five independent variables were found to predict coffee production significantly in the region. Analysing the relationship, it was found that the model's degree of explaining the variance in the dependent variable was 58% (R^2= 0.57.5). The contribution of the independent variables to the model was in the order of T_{mean} > average T_{min}>T_{min} long rains >T_{max} short rain > long rains. Although the contribution made by T_{mean} was the only one significant, the contribution made by other independent variables entered the model due to the property of regression analysis, and they were found to make the smallest contributions to the model (Table3. 6).

Table 3.6: The relationship between coffee production (tons) and temperature range (°C) in the Arusha region

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	124095	27647.361		4.49	0.000
T_{min} long rain	2326	1320.826	.374	1.76	0.087
Average T_{min}	-3160	2082.941	-.440	-1.51	0.138
T_{max} short rain	-758	581.811	-.159	-1.30	0.201
T_{mean}	-4450	2035.176	-.486	-2.19	0.036
Long rains	3.090	2.807	.136	1.10	0.279

Note. B = Un standardized Beta; t = Statistical T; T_{min}: Minimum temperature; T_{max}= Maximum temperature; T_{mean} = Average temperature.

Based on the regression analysis results, the regression equation is represented as,

Coffee (t) in Arusha region = 124095.221 + 2326.180(T_{min} long rain) – 3160.907(Average T_{min}) −757.535 (T_{max} short rain) −4450.107 (T_{mean})+3.090(long rains) (iv)

(2) Southern Highlands Zone

The regression relationship for Mbeya-Songwe regions was highly significant and a good fit of the data [F (2, 38) = 6.05, P ≤ 0.01]. The regression model showed that 24% (R^2 = 0.241) of the changes in the coffee production in the Mbeya-Songwe regions are explained by the combined effect of T_{min} rain season and average T_{min}, Among the two independent variables, average T_{min} made the biggest contribution to the model as compared to T_{min} during the rainy season (Table 3.7).

Table 3.7: The relationship between coffee production (t) and temperature range (°C) in Mbeya and Songwe regions

	Un standardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	-47651	28393.560		-1.69	0.102
T_{min} rain season	-5325	4177.780	-.377	-1.27	0.210
Average T_{min}	10192	3825.841	.789	2.66	0.011

Note. B = Un standardized Beta; t = Statistical T; T_{min}: Minimum temperature.

Based on the regression analysis results, the regression equation is represented as;

Coffee (t) in Mbeya-Songwe regions = -47650.738 − 5324.462(T_{min} rain season) −10191.939 (Average T_{min}) (v)

The regression model for Ruvuma region was also highly significant and a good fit for the data [F (2, 38) = 7.52, P ≤ 0.01]. The model showed that 28% (R^2= 0.284) of the changes in the coffee production are explained by the combined effect of T_{min} rain season and average T_{min}. As observed in the Mbeya-Songwe regions, the average T_{min} resulted in the biggest contribution as compared to T_{min} long rains in Ruvuma region (Table 3.8).

Table 3.8: The relationship between coffee production (tons) and temperature range (°C) in the Ruvuma region

	Unstand. Coefficients		Stand. Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	-33353	25688		-1.298	0.202
T_{min} rain season	-6892	3627	-.700	-1.900	0.065
Average T_{min}	9949	3289	1.113	3.024	0.004

Note. B = Un standardized Beta; t = Statistical T; T_{min}: Minimum temperature.

Based on the regression analysis results, the regression equation is represented as,

Coffee (t) in Ruvuma region = -33352.587− 6891.895(T_{min} rain season) −9949.119 (Average T_{min}) (vi)

3.5 Discussion

3.5.1 Climate variability

The decline in long rain in the Northern Highlands zone of Tanzania is characterized by the shortening of the rainy season which is caused by earlier cessation as the result of a decline of rainfall in April and May. Earlier studies also show a decline in the March-to-May seasonal rainfall over eastern Africa (Maidment *et al.,* 2015; Rowell and Booth 2015; Wainwright *et al*., 2019), however, with drying in March, April, and May (Niang *et al*., 2014). Contrary to the findings, the study by Wagner *et al*. (2021) indicated a significant increase in the amount of rainfall during May and a reduction of rainfall in April around Mt. Kilimanjaro over the last 19 years (2001-2019). On the other hand, according to Wainwright *et al*. (2019), the observed decline in Eastern African long rains is characterized by shortening of the rainy season (with late-onset and earlier cessation) rather than by a decrease in the peak daily rainfall. Different observations observed in different studies can be explained by large regional and local variability in precipitation (Dai, 2018; Macleod & Caminade, 2019), and therefore changes observed in other parts of Tanzania or East Africa do not necessarily contest with what is experienced in Arusha and Kilimanjaro regions.

The suggested link to the decrease in rainfall is the rapid warming of the Indian Ocean which causes an increase in convection and precipitation over the tropical Indian Ocean, contributing to the decrease in rainfall over the continental land surface (Lemma & Megersa, 2021). Over the last three decades rainfall has decreased by around 15% over eastern Africa, in the main growing season (March and May/June) (Williams *et al.,* 2012). On the other hand, the increase in short rain observed in the Arusha region (Northern Highlands zone) could be the result of extreme Indian Ocean Dipole (IOD) events which affect the short rainy season from October to December (Shelleph Limbu & Guirong, 2019). With increasing global

mean temperature, the frequency of extreme positive IOD is expected to significantly increase (Cai *et al.,* 2018). The increase in short rains in the Arusha region (Northern Highlands zone) conform with projections from different General Circulation Models (GCMs) which are broadly indicating increases in annual rainfall in Ethiopia (Niang *et al.,* 2014), but these increases are largely due to increased rainfall in the October-December period in southern Ethiopia (McSweeney *et al*., 2010). Moreover, despite the prediction that annual precipitation will increase in East Africa (Adhikari *et al*., 2015: Wainwright *et al.,* 2019), our findings indicate a decrease (not significant) in annual rainfall in the coffee-growing areas of the Northern Highlands zone for the four past decades (1979-2018). The decrease of long rains in the Northern Highlands zone has a direct link with the decline in annual rainfall over the area. According to Liebmann *et al*. (2014) “long rains” season [March-May (MAM)] is a manifestation of a long-term decline in rainfall totals. In addition, there has been no such downward trend in the “short rains” [October-December (OND)], but this season has continued to exhibit large year-to-year variability, which at times has exacerbated the impact of the long rains decline. This explains why coffee farmers in the Northern Highlands zone perceived drought increase (Mbwambo *et al*., 2021) despite the short rain increase. This is where successful adaptation measures are critical (Wagner *et al.,* 2019). Furthermore, coffee-growing farmers, in the Southern Highlands zone are also confronted with reduced rainfall which occurs during the growing season and annually. As in Craparo *et al*. (2015), the decrease in rainfall in the Southern Highlands zone was not statistically significant. Moreover, the study revealed that half of the study period has been experiencing low rainfall (rainfall below long-term annual average). However, even though there has been low rainfall in the coffee-growing area, irrigation has been used at a low scale. The study conducted by Mbwambo *et al.* (2021) found that over 40 years (1979-2018), only about 17% of coffee farmers in the Northern and 5% in the Southern Highlands zone used irrigation practices in their coffee fields. Other adaptation practices used by coffee farmers in the Northern Highlands zone were in the order of shade trees (96%) > Mulching (94%) > cut-off drains (28%) and Terraces (14%). In the southern Highlands zone, adaptation practices

were in the order of shade trees (70%) > Mulching 70%) > Terraces (46%) and cut-off drains (37%) (Mbwambo *et al.,* 2021).

The study revealed further that, there have been increasing trends in monthly, seasonal, and annual temperature in the two zones with T_{min} increasing at a higher rate than T_{max}. These findings are in agreement with those from the Northern part of Tanzania (Craparo *et al*., 2015), Ethiopia (Mekasha *et al*., 2014), Kenya (Omondi *et al.,* 2014), and Uganda (Nsubuga *et al.,* 2014) which reported that mean warming is primarily driven by substantial increases in the daily minima composition compared with daily maxima. According to Niang *et al.* (2014), this is an indicator of continued warming. Additionally, according to the observed results, the T_{mean} in the Northern and Southern Highlands zone of Tanzania seems to have reached the upper limit of the mean temperature bracket (18-21°C) suitable for coffee cultivation (Wrigley,1988).

3.5.2 Effect of climate change on coffee production

The decline of coffee production in the Northern Highlands zone is linked to the decrease in long rains and the increase of T_{min}. Generally, both, long and short rains are very important in the reproductive phase of the coffee plant. On one hand, the short rains in October trigger flowering in coffee plants after the dry spell period (Jassogne *et al.,* 2013), and on the other hand, long rainy season (March to May) if delayed and inadequate will negatively affect the expansion stage, during which rainfall is required to sustain berry development. Normally, in the Northern Highlands zone coffee crop enters the reproductive phase during the short rain season (October-December) and so the crop becomes more sensitive to temperature during this period. Generally, high night temperatures increase the rate of respiration so the assimilates which could be used for growth and yield are reduced (Bapuji Rao *et al*., 2014: Nagarajan *et al.,* 2010). Drought and high temperatures during this period in the Kilimanjaro region will cause fruit abortions, increased bean defects, reduced berry growth, and acceleration of ripening, leading to a reduction in coffee yield and quality (Craparo *et al.,* 2020; Wagner *et al*., 2021). The study of Craparo *et al*. (2015), reported similar findings that yield in the Northern Highlands zone is decreasing as the results

of the increase in T_{min}, however, in their study, there was no relationship between yield decrease and decrease in long rains as observed in this study.

Additionally, although T_{mean} affected coffee production in the Arusha region, it was T_{min} that accelerated the increase of T_{mean} Therefore, the decrease in coffee production observed in the Northern Highlands zone which is experiencing reduced rainfall is aggravated by higher T_{min} in the area. The inclusion of more shade trees might help to reduce heat stress (Kajembe *et al.,* 2016), however, conservation of heat during the night challenges the common notion that shade trees are always a beneficial aspect of climate change adaptation (Craparo *et al.,* 2015). Other strategies may include, re-adapting the coffee agronomic practices to climate change, use of technologies that will improve water and nutrient use efficiency in coffee trees, and developing genetically improved coffee varieties that will tolerate the impact of climate change.

On the other hand, coffee production in the Southern Highlands zone positively correlated with temperature even though T_{mean} is already out of the optimum range. The observed positive correlation could be explained by the fact that there was no significant decrease in rainfall during the growing season (November to May) and annually. Moreover, the Southern Highlands zone is also characterized by very low T_{min} and T_{max} in June, July, and August. The low temperature in these months can reduce the negative impact of high temperature during the growing seasons. However, from all climatic parameters, it was only the average T_{min} that resulted in a significant increase in coffee production in the Southern Highlands zone. Nevertheless, the findings from this study revealed further that, if T_{min} during the growing season will continue to increase in the Southern Highlands zone, coffee production will also be affected, as the inclusion of this parameter improved the model in both regions of the Southern Highlands zone. Generally, the findings from this study conform to the perceptions of farmers in the Northern and Southern Highlands zone reported by Mbwambo *et al*. (2021), that reduced rainfall and/or increase in temperature have resulted in coffee production decline. Other non-climatic factors may have contributed to the increase in

coffee production in the Southern Highlands zone as discussed below.

3.5.3 Other factors affecting production

Despite the positive relationship between low coffee productions with weather-related problems, the sharp decrease in coffee production noted in the Northern Highlands zone is likely to have been magnified by factors other than climate change per se. Bureau for Agricultural Consultancy and Advisory Service (BACAS) (2005) noted that the nationalization of estate farms in the Northern Highlands zone contributed to the decline in coffee production in the zone, which used to produce 50% of total coffee in 1972/73 due to the dismal performance under primary cooperatives. Another possible factor is the farmers' disincentive to invest in coffee due to the historic price slump of 1980-2002. The slump, from an average of 5 USD lb^{-1} in 1980 to 0.77 USD lb^{-1} in 2002 (Drip Beans, 2020) caused a lot of problems to those who depend on coffee for their livelihoods, including farmers. They could barely meet the cost of production and as a result, production fell steadily, with the area under coffee also declining.

Another area for consideration is land holding per small holder family. BACAS (2005) reported that households owning less than 2 ha in the Northern zone were almost 70% of the sampled households while in the Southern zone they were only 32%, implying that land is scarcer in the northern zone, particularly so in Kilimanjaro. Mbwambo *et al.* (2021) also reported that the majority of the smallholder coffee farmers from the Northern Highlands zone possess farm sizes between 0.5 and 1ha, while those from the Southern Highlands zone had farm sizes between 1 and 2 ha. Due to land scarcity, coffee farmers may opt to intercrop coffee with other crops and this can reduce the number of coffee trees per area, hence low production. Also, the rate of planting new trees in the Northern Highlands zone is reported to be less than that of the Southern Highlands zone, because the aging coffee trees are owned by the elderly who are naturally risk-averse. These indicate that may be the increase in coffee production observed in the Southern Highlands zone, apart from being favoured by climatic factors, has been further boosted by

the replanting of new coffee trees and adoption of new, high-yielding varieties.

3.6 Conclusion and Recommendations

There has been a decline in long rains and a rise in T_{min} which ultimately affected coffee production in the Northern Highlands zone. The Southern Highlands zone, on the other hand, has not yet suffered from the impact of climate change. Nevertheless, T_{min} is increasing at a higher rate in the area and it may affect the production of coffee shortly. Therefore, without sufficient adaptation measures, coffee production in the Northern Highlands zone will be reduced and the famous brand of Kilimanjaro Coffee will disappear from the Market. This calls for public and private sectors to invest in climate change adaptation strategies that will better sustain this important industry and the livelihoods of millions of smallholder farmers who depend on it. The emphasize should also be given by the Arabica coffee growing region which may have already suffered yield losses due to climate change. Such strategies may include, re-adapting the coffee agronomic practices to climate change, improving water and nutrient use efficiency in coffee trees, and developing genetically improved coffee cultivars that will tolerate the impact of climate change.

Nevertheless, despite the fact that it is important for coffee growers to adapt these adaptations measures there still limited knowledge on the extent to which these agronomic practices can bring about resilience of coffee cropping systems. This is because some of these agronomic practices were developed long time ago before the climate change was a concern. It was therefore imperative to evaluate the performance of some agronomic practices used by coffee farmers as adaptation measure to climate change in chapter 4 of this thesis.

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CHAPTER FOUR

4.0 Evaluation of field performance of compact coffee variety under selected propagation methods and soil fertility amendment practices in the Northern Zone, Tanzania

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4.1 Abstract

The use of vegetative propagules of *Coffea arabica* has been an important tool for the large-scale multiplication of improved coffee varieties in Tanzania. However, the effects of the current propagation methods on resultant coffee tree growth and yield have not been studied in sufficient detail, to warrant long term adoption. This study compares field performance of three types of seedlings propagules (cuttings, grafting and seed) when combined with 75g NPK (20:10:10) $tree^{-1}$, 37.5g NPK + (10 and 20 Kg Farmyard manure) $tree^{-1}$. Two split plot experiments laid out in a Randomized Complete Block design (RCBD) with three replications were established at Lyamungu-Kilimanjaro region and Burka-Arusha region based on the existing climatic gradient. Such data as, soil organic carbon, soil texture, growth characteristics, yield component and coffee yield were collected in the period from 2019-2022. Cuttings-propagated plants outperformed seed and grafted–counterparts in all aspects (growth characteristics and yield) ($p < 0.05$). This could be due to greater physiological maturity of cutting propagated plants, causing earlier production capability through earlier development of aerial parts. Cuttings-propagated plants had the highest yield 2800 and 3600 Kg ha^{-1} green coffee at Burka and Lyamungu sites respectively. The grafted-propagated plants had the lowest green coffee yield 800 and 1700 Kg ha^{-1} at Burka and Lyamungu sites respectively. It is also concluded that, cuttings-propagated plants under the age of 4 years with the same rooting age as seed and grafted propagated plants perform better in the field than seeds and grafted propagated plants. A longer experimental period is recommended to satisfactorily monitor the response of the types of seedlings propagated through seed, grafting and cuttings above the age of four year assuming that at a later age the coffee tree will have reached its maximum production and so more nutrients and water will be required.

Keywords: Arabica coffee, Cutting propagules, Farm yard manure, Grafted propagules, Seed propagules, Tanzania.

4.2 Introduction

Coffee is one of Tanzania's primary agricultural export commodities accounting for about 5 % of total exports value, and generating export

earnings averaging USD 100 million per annumover the last 30 years (TCB, 2017). The industry provides direct income to more than 400,000 farmer households and thus supporting the livelihoods of an estimated 2.4 million individuals. Average yearly production over the past thirty years has stagnated at a level of about 50,000 tons, while yields have continuously decreased, thus contributing to low farm gate prices, and the development of rural poverty (TCB, 2020). As a way to overcome the problem of low productivity, improved coffee varieties which are high yielding, resistant to disease with best beverage quality have been developed by the Tanzania Coffee Research Institute (TaCRI) (Kilambo *et al.,* 2012).

In order to expedite the adoption of the improved Arabica hybrids, TaCRI uses three seedling multiplication techniques namely; clonal propagation (use of cuttings), grafting and manual hybridization (TaCRI, 2011). TaCRI is producing compact hybrid seeds so that farmers can also use coffee seeds as a means of propagating hybrid coffee as they used to do with traditional varieties. Seeds have good viability if stored properly and considered an economical way to obtain trees that are sufficient (TaCRI, 2011; Wrigley, 1988). On the other hand, cutting-propagation ensures maximum uniformity in crop, grain maturation, plant vigor and higher crop yield (Weigel and Jurgens, 2002). Moreover, the capability to be multyplied throughout the year is another desirable traits of cuttings propagated plants (Junqueira *et al*., 2006). However, dispite the advantages obtained by planting cuttings propagated plants, there are shortcomings that arise including shallow roots system. A few cuttings-propagated plants have resuted into allometric growth, exhibiting unbalanced growth between aerial parts and root systems and this cause plant death in many cases. Moroever the study by Bragança *et al.* (2010) observed sigmoidal growth where there is no relationship between the foliar biomass and the total plant biomass.

For the case of grafting method, the scions of improved hybrid varieties are grafted on the rootstocks of traditional coffee varieties (TaCRI, 2011), thus exploiting the shoot characteristics of the new varieties and the root characteristics of the traditional varieties. The study by Oliveira *et al*. (2004), indicated that grafting technique

results into plants with balanced growth and provide plants roots that originate from sexual reproduction. According to Oliveira *et al*. (2004), grafting propagation method results into a new biomass of plants which contribute to the increase in coffee productivity. Vegetative propagation techniques have been used for mass multiplication of improved arabica coffee in Tanzania, following major achievements made by TaCRI in the development of coffee varieties that are resistant to coffee berry disease (CBD) and coffee leaf rust (CLR) for Arabica and coffee wilt disease (CWD) for Robusta (Teri *et al*., 2011). However, the field performance of cuttings and grafted propagated compact coffee variety have not been studied in details to guarantee their long term adoption.

Soil fertility management is an important factor for successful crop production in all agricultural commodities. For the case of coffee, there are two sources of nutrients (inorganic and organic) that can be applied in coffee field (Maro *et al*., 2014). The most common sources of organic manure used in crop production are livestock dung (Farm yard manure), composted and green crop residues (Satyanarayana *et al.,* 2002). Soil fertility amendment practices in Tanzania involves application of 75-215 g of N : P: K (20:10:10), 60-175 g of CAN/ASN or 30-100g of urea per tree depending on production level of coffee tree and season of the year (short rain/long rain). Phosphates fertilizer (TSP, DAP or SSP) in combination with 10 kg of farm yard manure (FYM) are used as planting fertilizer (TaCRI, 2011). Therefore, it is only at planting time that inorganic fertilizer is integrated with FYM. However, according to Jobe (2003) and Stockdale *et al*. (2002), the best remedy for soil fertility management is a combination of both inorganic and organic fertilizers, where the inorganic fertilizer provides nutrients and the organic fertilizer mainly increases soil organic matter and improves soil structure and buffering capacity of the soil.

Additionally, Chemura *et al*. (2014) indicated that, at high water level inorganic fertilizers perfom better than organic fertilizer. On the other hand, better perfomance of organic manure occur under low water levels. This could be due to their capacity to improve soil phisyical

properties which increase soil water retention. The combined application of inorganic and organic fertilizers, usually termed integrated nutrient management, is widely recognized as a way of increasing yield and or improving productivity of the soil sustainably (Mahajan *et al.,* 2008). Beneficial effect of integrated nutrient management in mitigating the deficiency of many secondary and micronutrients have been demonstrated by Mahajan *et al.* (2008) and Singh, (2000). According to Tilahun-Tadesse *et al.* (2013), identifying the optimum dose of integrated nutrient application is, however, required for maintaining adequate supply of nutrients for increased yield.This research study was, therefore, conducted to 1) compare field performance of three types of seedlings propagules (cuttings, grafting and seed); 2) asses the combined effect of organic and when combined with 75g NPK (20:10:10) tree^{-1}, 37.5g NPK + (10 and 20 Kg Farmyard manure) tree^{-1} for improved productivity of the coffee in the Northern Highlands zone of Tanzania.

4.3 Materials and Methods

4.3.1 Description of the study area

The study was conducted in the Northern Highlands Zone of Tanzania along the slopes of Mt. Kilimanjaro (Hai district) and Mt. Meru (Arusha district), both characterized by a bimodal rainfall pattern. Hai district represented areas with optimum conditions for growing coffee in the current time (rainfall above 1 200 mm per year and average temperature range of 22 ºC for the past four decade). Annual rainfall in Arusha region ranges from 800 to 1000 mm and an average temperature range of 22.38 ºC. In both areas, soils are deep, well drained, brown to red sandy loam to sandy clay loam. The long rain ocuurs in March, April and May (MAM) and the short rainy season in October, November and December (OND). Rainfall variability, is mainly caused by rapid warming of the Indian Ocean which causes an increase in convection and precipitation over the tropical Indian Ocean, contributing to the decrease in rainfall over the continental land surface, north-south movement of the Intertropical Convergence Zone (ITCZ) (Diem *et al*., 2014). El-Niño Southern Oscillation (ENSO); though relief features like Mount Kilimanjaro and Mt. Meru play a role in small-scale variations in rainfal.

4.3.2 Experimental design

Two split plot experiments laid out in a Randomized Complete Block design (RCBD) with three replications were established in the two areas with a climatic gradient. The first scenario comprised an area with optimum climatic conditions for growing coffee (Hai district) while the second scenario represents areas where optimum climatic conditions for growing coffee are supposed to have already changed (Arusha district). Type of seedling was treated as main factor with three levels (cutting seedlings, grafted seedlings and seed seedlings). On the other hand, Fertilizer management practice were treated as sub factor, again in three levels; 1 = normal application of fertilizer per tree (75 g of NPK 20:10:10), 2 = 20 Kg of farmyard manure (FYM) + half dose of normal inorganic fertilizer rate and 3 = 10 Kg of FYM + half dose of normal inorganic fertilizer rate).

4.3.3 Coffee seedling development

Three types of coffee seedlings were developed in a manner that they have the same age. Therefore, the seeds for the seed seedling were planted the same time with the seeds for the rootstock. The cutting for developing the cuttings seedlings were also planted at this time. This was to ensure that the roots for the three types of seedlings are of the same age. Following the procedure described in TaCRI (2011), grafted seedlings were developed from the rootstock of old variety (KP 423) and the scion of improved compact coffee variety. Cutting seedlings were developed from the cuttings of compact coffee variety and seed seedlings were developed from compact coffee seeds (Plate 4.1).

(a) (b) (c)

Plate 4.1: Seedling multiplication methods used: Cutting (a), grafting (b) and seed (c)

4.3.3.1 Seedling planting and management

Seedlings were transplanted in the field in April, 2020 at a depth of 60 × 60 cm holes using a spacing of 2 m x 1.5 m as recommended by TaCRI (2011). A border row of the same coffee varieties was planted around the experimental area to overcome border effects on the experimental units as recommended by Tesso *et al.* (2011). Replicates were separated by the 3 m border. The total number of experimental units per replication was 108 whereas the plot size was 1920 m^2. The number of experimental units per replication was reduced to 99 at the end of year one and 90 at the end of year 2 before the harvest. The number of experimental units was reduced because some plants were cut off for the determination of root: shoot ratio. The experiment was conducted from July2019 to July 2022. FYM was applied only once during the experiment while NPK fertilizer treatment was applied twice in the year (during the long rain and short rain). Agronomic practices such as weeding, insect and pest control were carried out uniformly in all plots as recommended by TaCRI (2011).

4.3.4 Data collection

4.3.4.1 Growth characteristics

All the growth characteristics and yield components data were collected at the end of 12 and 22 months after planting. The plant height was measured from the base of the stem to the plant apex using graduated ruler (Assis *et al.,* 2014; Tefera *et al*., 2016). The diameter of the main stem was measured at 5 cm above the ground using Vernier Calliper (Assis *et al.,* 2014; Tefera *et al.,* 2016). The length of bearing primary branches was measured from the point of attachment to the main stem to the apex using graduated ruler as an average value of four longest bearing primaries per plant (the final length was multiplied by two to get the canopy width). Number of internodes was counted as an average value from the longest bearing primaries per plant. Total number of primary branches was estimated by counting the total number of primary branches per plant. The last three parameters followed Esther and Adomako (2010). Coffee trees to be used for root: shoot ratios determination was taken through excavation method where all the roots were dug and removed from the soil. Substrates in the roots of the plants were gently washed off. The fresh weight of shoots and roots was recorded immediately after

removing the free surface moisture with soft paper towels. Shoot and root samples were then oven dried at 85 ºC for 48 h, and weighed for dry weight. The root/shoot ratio was calculated as the root dry weight/shoot dry weight (Li *et al*., 2018).

4.3.4.2 Yield and yield components

The number of berry clusters or number of fruiting nodes was determined as an average number of berry clusters per plant from four heavily bearing primaries at the middle across all directions (Etienne and Betrand, 2001). Yield was obtained by harvesting mature red cherries to get fresh weight for each tree per treatment using gravimetric scale. The skin and pulp of the cherry were removed using wet process method. The parchments were then dried to a moisture content of 11 % (TaCRI, 2011). Parchment coffee means the green coffee bean contained in the parchment skin; to find the equivalent of parchment coffee to green coffee, the net weight of the parchment coffee was multiplied by 0.80 as recommended by ICO (2011).

4.3.4.3 Soil data

Soil sampling for the determination of texture and organic carbon was done prior and after trial establishment. Bulk soil samples for the determination of organic carbon and texture were collected with hand-auger from the depths of 0 -30 cm at Lyamungu and Burka sites**.** Soil samples for Soil Moisture Content (SMC) determination were taken at depth of 0-10cm using core sampler. A total of 27 soil samples were collected from each Trial.

4.3.5 Data Analysis

4.3.5.1 Soil analysis

4.3.5.1.1 Chemical and physical properties of the soil

The collected soil samples were analysed at Lyamungu Soil Laboratory. The bulk soil samples were air-dried, ground and sieved through 2 mm sieve (Nunez et al., 2011) and analysed for organic carbon (by Walkley-Black wet digestion method). Texture was analysed by using the Bouyoucos Hydrometer method (NSS, 1990).

4.3.5.1.2 Soil moisture content

Immediately after receiving soil sample in the lab, a known weight of fresh sample was measured (W1), the sample was then evaporated in a ventilated oven at 105^{o}C for eight hours to obtain constant weigh (W2). Moisture content was calculated using the following formula;

$$\%\ \text{Moisture content} = ((\text{W1} - \text{W2})/\text{W2}) * 100 \quad \text{(i)}$$

4.3.5.2 Growth characteristics, yield and yield components

Data collected were subjected to analysis of variance (ANOVA) using STATISTICA Software version 6.311 using the following statistical model for the spilt plot design as described by Kuehl (2002) (Eq. ii). Treatment means were separated using Tukey' HSD at 0.05 significance level.

$$Y_{ijk=}\ \mu + \alpha_i + P_k + d_{ik} + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijk}. \quad \text{(ii)}$$

Where:

μ = is the general error mean; α_i = the effect of the ith level of factor A; P_k = the effect of the kth block; d_{ik} = the whole-plot random error; β_j = effect of the jth level of factor B, $(\alpha\beta)_{ij}$ = the interaction effect between factors A and B; ε_{ijk}= is the sub-plot random error.

4.4 RESULTS

4.4.1 Soil organic carbon and Soil Moisture content (SMC)

Lyamungu (Hai district) and Burka (Arusha district) are characterized by loam and Sandy Loam soil respectively. The Organic carbon (OC) content of the soil was affected differently by soil fertility management practices (Table 4.1). Before treatments application Lyamungu and Burka had 2.34 % and 2.42 % OC respectively.

Table 4.1: Soil organic carbon (%) at Lyamungu and Burka after treatment application

Treatments	Lyamungu	Rating*	Burka	Rating*
75 g of N.P.K (20:10:10)	2.34	Medium	2.54	Medium
37.5 g of N.P.K (20:10:10)+ 10Kg FYM	4.13	High	2.93	Medium
37.5 g of N.P.K (20:10:10)+ 20Kg FYM	4.48	High	4.04	High

* Ratings by Sys *et al.* (1993)

There was significant difference (P≤ 0.05) in SMC taken on Jun 21st 2021 due to soil fertility management practices and lack of significant difference (P ≥ 0.05) in other sampling dates at Burka and Lyamungu sites. However, despite lack of significance, 37.5 g NPK + 20 Kg of FYM resulted into higher SMC than other soil fertility management practices in all the sampling dates. (Fig 4.1 and 4.2).

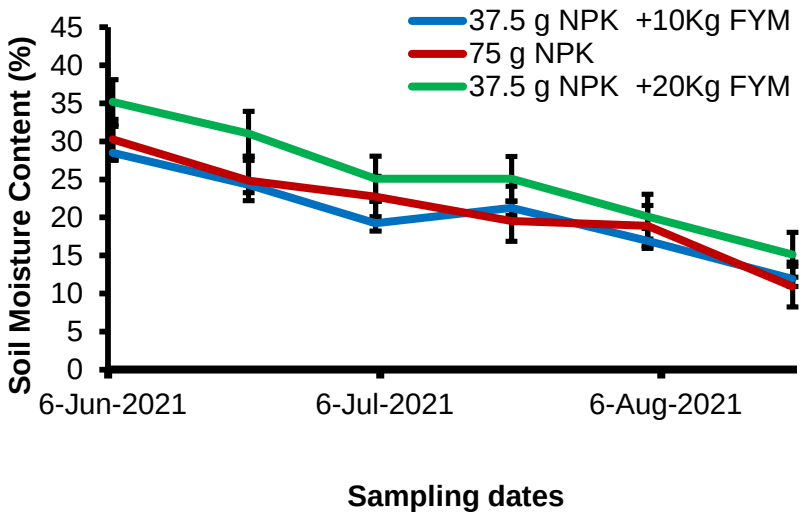

Figure 4.1: Soil moisture content due to different soil fertility management practices at Burka

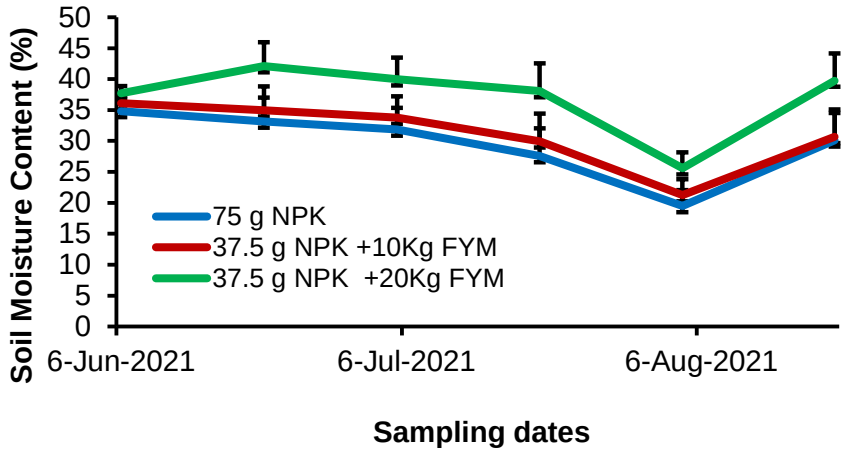

Figure 4.2: Soil Moisture Content due to different soil fertility management practices at Lyamungu

4.4.2 Effects of Type of Seedling and Soil Fertility Management Practices on Growth and Yield Components at Burka

Growth characteristics and yield components were significantly ($P \leq 0.05$) affected by type of seedlings (Fig. 4.3, 4.4, 4.5 and 4.6), but insignificantly affected by the soil fertility management practices. Twelve months after planting, cutting- propagated plants produced plants which were significantly better ($P \leq 0.05$) than seeds and grafted propagated plants in terms of number of primary branches, number of berry cluster, number of internodes, plant height, canopy width and stem girth. However, after 22 months of planting, plant height, stem girth and canopy width did not differ significantly between grafting and seeds propagated plants but the two differed significantly from the cuttings propagated plants.

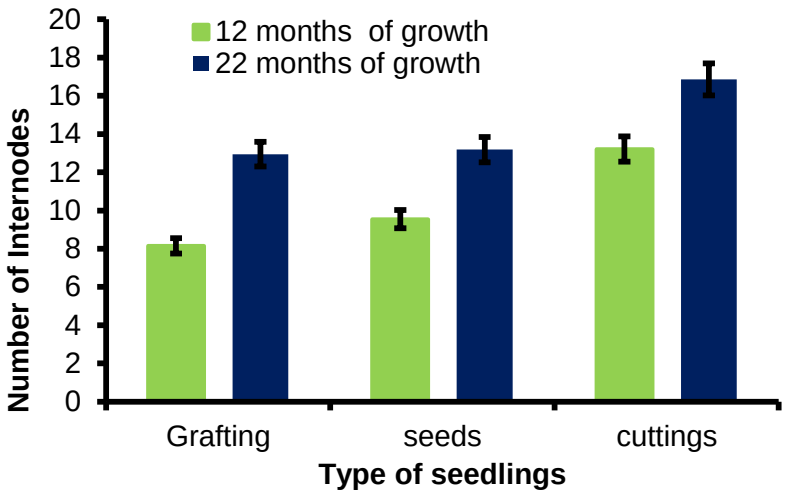

Figure 4.3: Effect of types of seedlings (cuttings, seeds and grafting) on number of internodes at Burka site

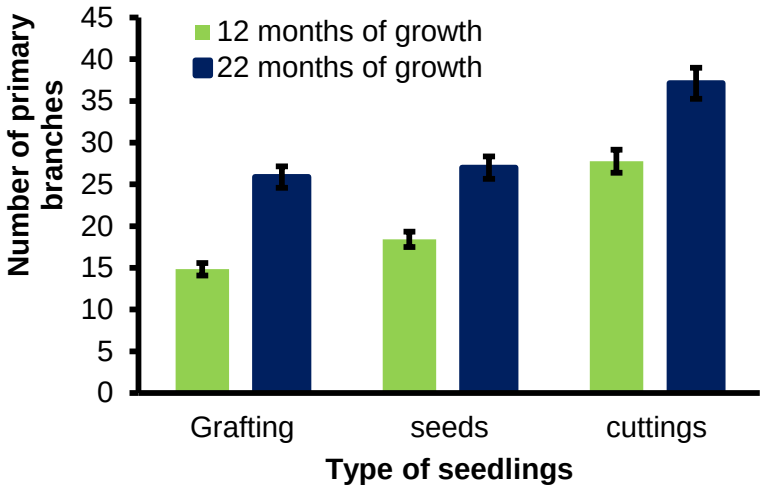

Figure 4.4: Effect of types of seedlings (cuttings, seeds and grafting) on plant height at Burka site

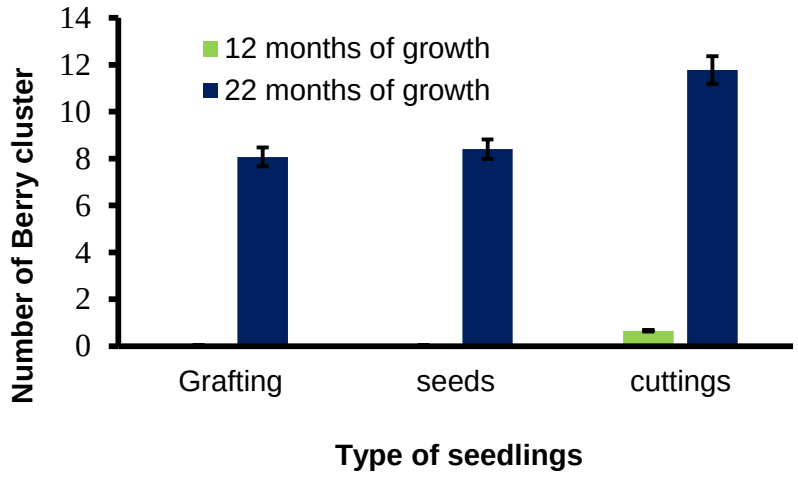

Figure 4.5: Effect of types of seedlings (cuttings, seeds and grafting) on number of berry cluster at Burka

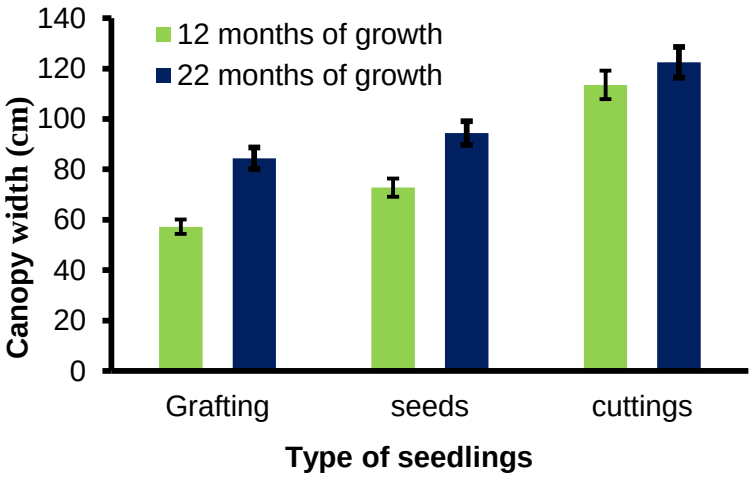

Figure 4.6: Effect of types of seedlings (cuttings, seeds and grafting) on canopy width at Burka

4.4.3 Effects of type of seedling and soil fertility management practices on growth and yield components at Burka

Type of seedlings (cutting, seed and grafting) produced growth characteristics and yield components that are significantly different ($P \leq 0.05$) (Fig. 4.7, 4.8, 4. 9 and 4.10). During the twelve months of growth, cuttings propagated plants produced significantly ($P \leq 0.05$) tallest coffee plants with the wider canopy and a greater number of primary branches than coffee plants propagated through seeds and grafting. However, grafted-propagated plants significantly differed ($P \leq 0.05$) from the other two types of seedlings (seeds and cuttings) in terms of stem girth during the first 12 months after planting, On the other hand, after 22 months of growth stem girth did not differ significantly ($P \geq 0.05$) among the three types of seedlings. Furthermore, insignificant ($P \geq 0.05$) difference between growth characteristics and yield components as a results of soil fertility management practices were observed.

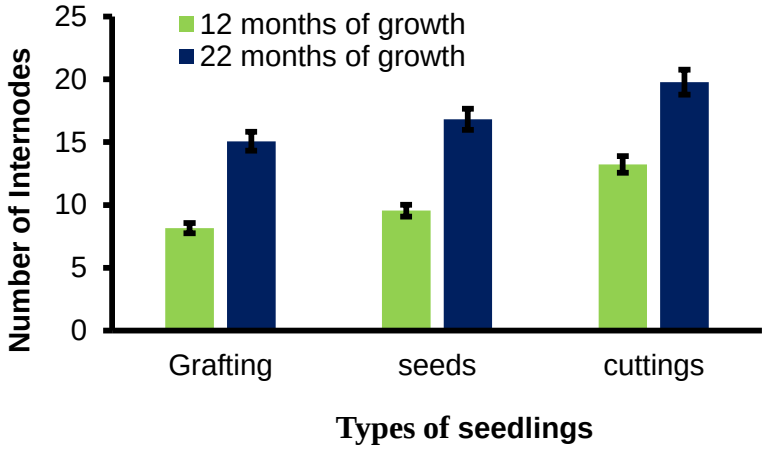

Figure 4.7: Effect of types of seedlings (cuttings, seeds and grafting) on the number of internodes at Lyamungu

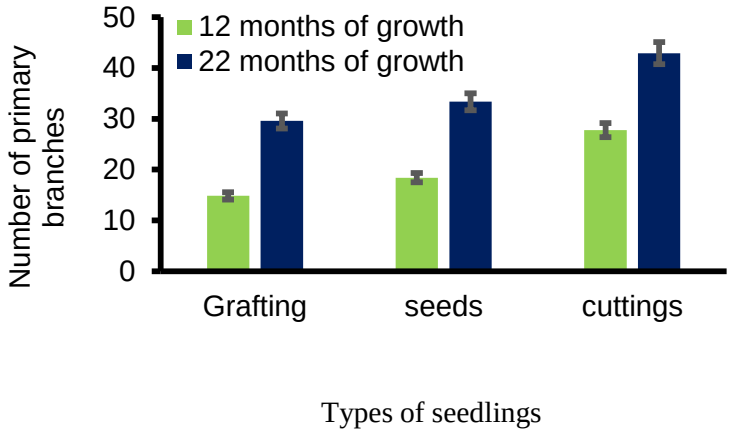

Figure 4.8: Effect of types of seedlings (cuttings, seeds and grafting) on the number of primary branches at Lyamungu

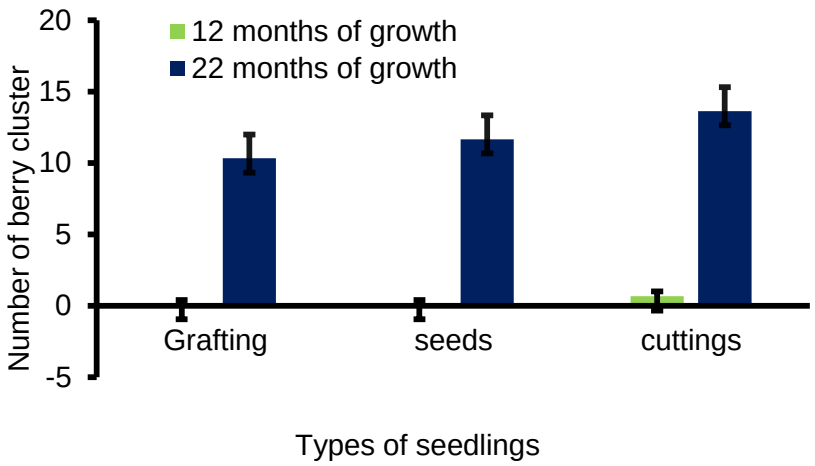

Figure 4.9: Effect of types of seedlings (cuttings, seeds and grafting) on number of berry cluster at Lyamungu

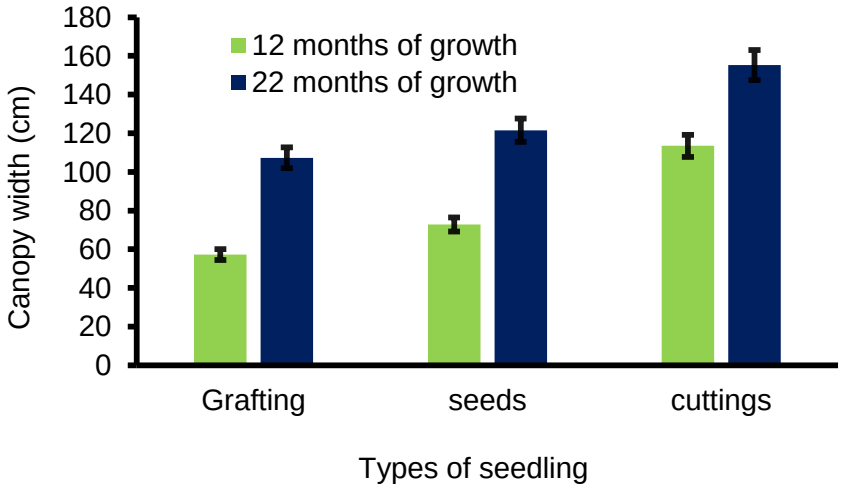

Figure 4.10: Effect of types of seedlings (cuttings, seeds and grafting) on canopy width at Lyamungu

4.4.4 Effects of type of seedling and soil fertility management practices on root: shoot ratio at Lyamungu and Burka

Moreover, the results indicates significant difference in root : shoot ratio across the time in both sites (Fig. 4.11 and 4.12). Twelve months after planting coffee plants propagated by cuttings, seeds and grafting varied significantly ($P \leq 0.05$) in term of root: shoot ratio at Burka and

Lyamungu sites. The study also revealed lack of significance difference (P ≥ 0.05) in root: shoot ratio between seed and grafted propagated plants 22 months after planting, however the two types of seedling differed significantly from cuttings propagated plants at Lyamungu site. At the end of 22 months after planting most cuttings-propagated plants had root: shoot ratio ranging between 1:8 and 1:9.5 and for seed propagated plants was 1:5 and 1:8 while grafted propagated plants ranked last in root: shoot ration ranging between 1:4.5 and 1:6. Furthermore, 22 months after planting there was no significance difference of root: shoot ratio between seeds and grafting propagated plants at Lyamungu, however the root: shoot ratio of the grafted propagated plants was significant different from that of cuttings propagated plants

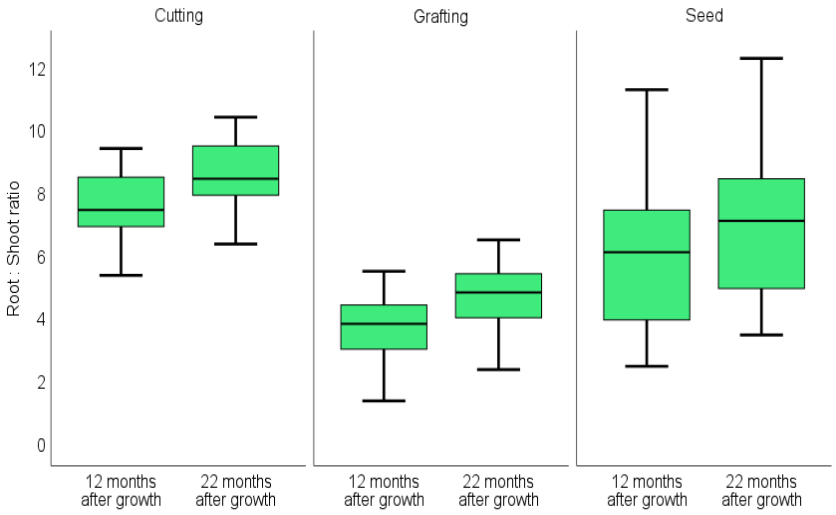

Figure 4.11: Effect of cutting, seeds and grafted propagated coffee plants on root: shoot ratio at Burka site

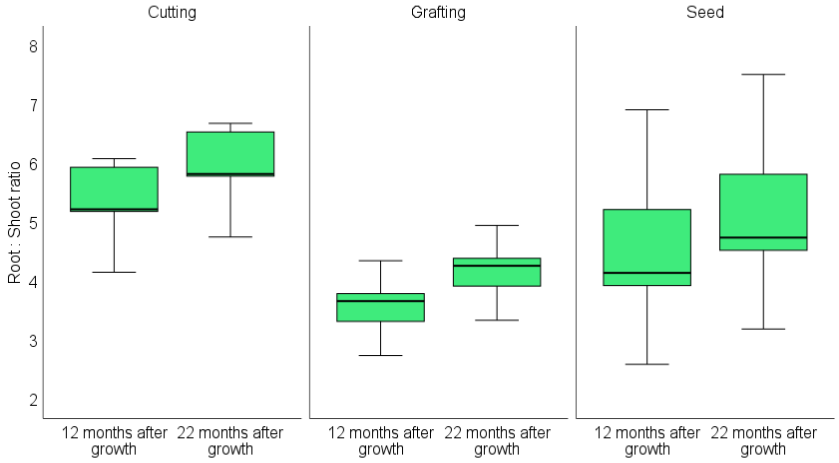

Figure 4.12: Effect of cutting, seeds and grafted propagated coffee plants on root: shoot ratio at Lyamungu site

4.4.5 Coffee yield

There was significant difference (P≤ 0.05) between coffee yield produced by cuttings-propagated plants and coffee yield produced by seed and grafted propagated plants at Lyamungu and Burka (Fig 4.13). Cuttings-propagated plants had the highest yield during the study period ranging between 1800 -2800 green coffee Kg ha^{-1} for majority of cuttings propagated plants at Burka site and 3000-3600 green coffee Kg ha^{1-} at Lyamungu site. Majority of seed-propagated plants had the green coffee yield ranging from 1400 -1600 and 1800-2800 Kg ha^{-1} at Burka and Lyamungu sites respectively. Furthermore, Grafted-propagated plants had the lowest coffee yield which ranged from 600-800 Kg ha^{-1} at Burka site and 700-1700 Kg ha^{-1} at Lyamungu (Fig 4.13).

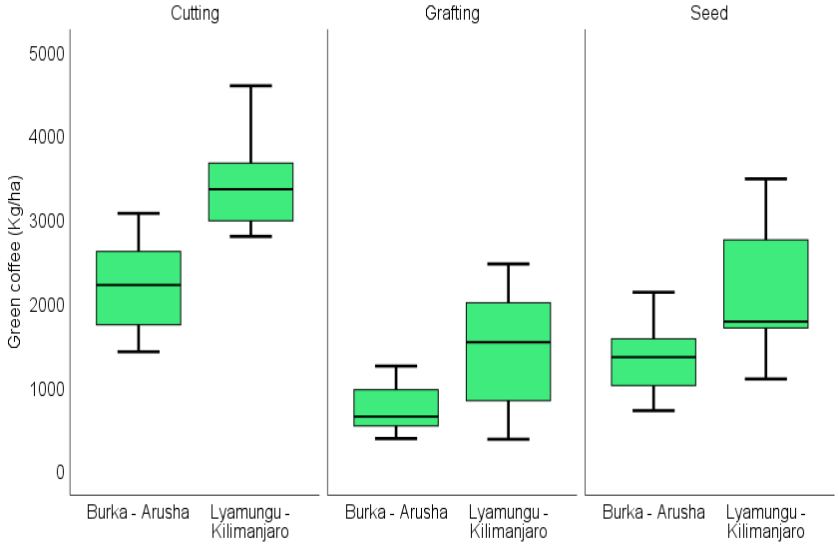

Figure 4.13: Effect of types of seedlings on coffee yield

Furthermore, despite lack of significance difference (P≥ 0.05) between soil fertility management practices and seedling types, the combination of cuttings- propagated plants and half dose of inorganic fertilizer plus 20 Kg of FYM produced the highest coffee yield at Lyamungu and Burka sites. Similary the combination of 37.5 g of NPK and grafted propagated plants resulted into higher yield at Burka while at Lyamungu grafted propagated plants combned with 37.5 g NPK produced higher yields. Significance difference in green coffee (Kg ha^{-1}) was observed between Lyamungu and Burka sites.

Table 4.2: Comparison of Green coffee (Kg ha^{-1}) at Burka and Lyamungu

Treatments		Green coffee yield Kg ha^{-1}	
Type of seedling	Fertilizer options	Lyamungu	Burka
Cuttings	75 g of N.P.K (20:10:10)	3502	2195
Seed	75 g of N.P.K (20:10:10)	2090	1469
Grafting	75 g of N.P.K (20:10:10)	1333	771
Cuttings	35.7 g of N.P.K (20:10:10)+10Kg FYM	3214	2096
Seed	35.7 g of N.P.K (20:10:10)+10Kg FYM	1944	1050
Grafting	35.7 g of N.P.K (20:10:10)+10Kg FYM	1513	690
Cuttings	35.7 g of N.P.K (20:10:10)+20 Kg FYM	3603	2297
Seed	35.7 g of N.P.K (20:10:10)+20 Kg FYM	2225	1529
Grafting	35.7 g of N.P.K (20:10:10)+20 Kg FYM	1438	805
Mean		2318	1434
Standsrd Error		295	209
t-test			2.32
P-value			0.035

4.5 Discussions

The content of Soil Organic Matter in the soil increased with the increase in farmyardmanure in the soil both in Kilimanjaro and Arusha regions. Positive relatioship was also observed between amount of soil moisture content in the soil and the level of organic matter in the soil. Hence, plots that were applied with irnorganic fertizer alone resulted into low soil moisture content than those applied with farmyard manure. Soil organic matter improves soil physical proparies by providind organic bindinding agents which tend to increase water holding capacity of the soil (Chemura *et al*., 2014). Previous research have also imdicated that optimum level of organic matter in the soil provides farmers with insuarance against climate change through a gain in yield stability and more resilient production (Nyalemegbe *et al*., 2009). Indeed, higher soil organic matter content increase yild gains from favarable conditions and reduces yield losses due to harsh enviromental conditions.

The superiority of cuttings propagated plants when compared with grafted plants can be due to the higher amount of reserve found in cutting-propagated plants compared to the grafted and seed propagated plants. The three types of seedling were established at the same time in the sense that the roots from both types of seedling would be of the similar age, therefore at the time when the KP-423 seeds to be used as the rootstock were sown it was the time that cuttings seedlings were also established. However, the KP-423 coffee seedlings were grafted with improved compact coffee variety when they were five months and it took three months after grafting for the new growth to start. When the grafted seedlings were recovering from the injury of grafting their counterpart cuttings were growing in the nursery and increasing their biomass. Therefore, it is possible that at the time when the seedlings were established in the field, cuttings –propagated seedlings had enough reserve which was directed to produce biomass for the aerial pats, allowing cutting-propagated plants to excelled in all growth characteristics against the same grafted material. This finding is in agreement with that of Partelli*et al*. (2014).

However, our findings are in contrast with that of Andrade Junior *et al.*(2013) where in their study they found conilon grafted plants to be superior to cuttings propagated plants. In the study of Andrade Junior *et al.* (2013), cuttings seedlings were established 90 days after the establishment of the rootstock. Therefore, at the moment of grafting on day 90, there was already a rootstock radicular system that have exhibited satisfactory growth. Thus, it is possible that the entire reserve of the graft was directed to produce biomass for the aerial parts, ensuring their expressive growth against the same clone materials. Gemmel (1991), indicated that differences resulting from these types of seedlings tend to decrease over time as the trees mature Therefore, caution should be exercised when the studies are conducted in young trees.

In their study, Carvalho *et al*. (2008) found that plants propagated through vegetative methods had better plants characteristics than seed-propagated onces. Such, studies have also shown that, plants with higher height tend to have a higher number of pleiotropic

branches (Carvalho *et al.,* 2008). The findings of this study also show that cuttings-propagated plants entered reproductive stage earlier than seed and grafted-propagated plants. Partelli *et al.* (2014), pointed out that plants derived from cuttings have earlier production capability. Thus, these plants were able to develop a higher number of productive (plagiotropic) branches sooner than seed and grafting-propagated plants. The plagiotropic branches of a coffee plant present several nodes where the flower buds will be formed and then fruits (Vezy *et al.,* 2020). Therefore, the plagiotropic branches have direct relationship with the difference in yield obtained in the three type of seedlings.

The findings of this study indicate also an increase in root : shoot ratio across time, a characteristic of vegetation in early successional phases as the plants were still young and the upper part of the plants was more developed than the roots. There is no fixed "(tops to roots) ratio" in coffee trees, but generally the ratio of tops to roots may be figured to be 8:1 for a matured coffee trees of 7 years old (Guiscafré-Arrillagaand Gómez, 1938). In this study cuttings propagated plants at 12 months attained the root: shoot ratio of 1:9.5. This may lead to inbalanced growth biomass between the roots and the shoots. Other studies have also indicated that, a few cuttings in the field may exhibit allometric growth, exhibiting uneven relationships between their aerial parts and radicular systems and in many cases resulting in the death of the plants. Bragança *et al.* (2010) also observed sigmoidal growth for conilon coffee where there is no balance between the foliar area and the total biomass of the plant.

Furthermore, the combination of FYM and half dose of inorganic fertilizer produced growth and yield characteristics that are comparable with the recommended inorganic fertilizer rates. The comparative performance of integrated fertilizer to inorganic fertilizers has also been reported by Chemura *et al*. (2014) and Nyalemegbe *et al*. (2009) who concluded that combining poultry manure with inorganic fertilizers resulted in similar yields in rice as those obtained from using inorganic fertilizers alone. Moreover, Maro and Mbwambo, (2020) in their study to explore the behavior and usability of the new

model SAFERNAC over the coffee growing areas in Tanzania found that the difference in yield between NPK 160:80:80 alone and a combination of NPK 80:40:40 (half dose) plus 5 tons' manure was not significant. Moreover, according to Mbwambo *et al.* (2021) there is limited knowledge on the extent to which the current agronomic practices can bring about resiliency of coffee cropping systems. Therefore, long term experiments are important to generate data set that will allow the quantification of stability for different agronomic management practices. Yield stability cannot directly be measured in a single field experiment in a single year—it must be assessed based on measurements of yield over years and locations (Recklinge*t al*., 2021). Using field experiment to predict the outcome such as that of "what if" scenarios is costfuly and time consuming especially for perennial crops like coffee. Crop growth models may be used to simulate the relationship between plants and the environment to predict the expected yield for applications such as crop management and agronomic decision making, as well as to study the potential impacts of climate change on crop productivity. (Kasampalis *et al.*, 2018).

4.6 Conclusion and Recommendations

Integrated nutrients sources are able to provide sufficient nutrients to the three types of seedlings (cuttings, grafting and seed) for healthy coffee growth just as the recommended rates of inorganic fertilizer. Thus, the use of integrated fertility management could be the most attractive option given that apart from providing nutrients to the coffee plants the package also helps in improving water retention properties of the soil. Cuttings-propagated plants under the age of 4 years with the same rooting age perform better in the field than seeds and grafted propagated plants by producing plants with better characteristics in terms of plant height, plant vigour, canopy width, number of berry cluster, number of internodes and number of primary branches. The yield of cutting-propagated plants under the age of 4 years if established at the same time with seeds and grafted propagated plants is significantly higher than that of seed and grafted-propagated coffee plants.The presence of tap-root (seeds and grafts) or lack thereof (cuttings) has little effect if any on growth and yield of Arabica coffee under the age of 4 years. However, cuttings-

propagated plants have indicated inbalance growth between the above ground parts and the root biomass.

We recommend a longer experimental period to be conducted to satisfactorily monitor the response of the types of seedlings propagated through seed, grafting and cuttings above the age of four year assuming that at a later age the coffee tree will have reached its maximum production and so more nutrients and water will be required. Generally long term experiments are important to generate data set that will alow the quantification of stability for different agronomic practices. Yield stability, for example have to be measured over years and locations and not just in a single year. Using field experiment to predict such outcomes from long experimes is costifuly and time consuming especially for perial crops like coffee. Crop growth models may be used to simulate the relationship between plants and environment as well as studing the potential impacts of climate change on crop productivity. Therefore in order to determine the ability of type of seedlings (cuttings, seeds and grafted) and soil fertiliry management in adapting arabica coffee to climate change, a follow up study using crop growth model and future climate data was caried out in chapter five of this thesis.

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CHAPER FIVE

5.0 Exploring the ability of types of seedlings and soil fertility management practices in adapting *Coffea arabica* to climate change using DynACof model in Tanzania.

"The material contained in this chapter is in preparation for submission to a Journal"

5.1 Abstract

Even though climate change is becoming pervasive and copping options becomes necessary there is a limited knowledge on the extent to which the current agronomic practices would still hold/support coffee cropping systems in Tanzania. Downscaled climatic data from CORDEX-Africa were used to analyse how cuttings, seeds and grafted propagated coffee plants will respond to future climate change (2026-2056). Three Regional Climate Models (RCMs) from CORDEX-Africa were downscaled dynamically from three Global Circulation Models (GCMs). Percent bias, Root Mean Squared Error, and Skill Score based on MAE were used to assess performance of different models. Dynamic Agroforestry Coffee crop model (DynACof) which is a daily plot scale crop model was used to simulate crop yield. Projections indicate an increase in rainfall at the range of 0.2-13 % in the Northern Highlands zone. Minimum temperature is expected to increase at the higher rate than maximum temperature at the range of 1.36-1.64 ºC. Furthermore, projections indicate that when cuttings, seeds and grafted propagated plants are combined with farmyard manure yield reduction will be 35 % for cuttings and seeds and 10 % for grafted once. High reduction of yield observed on the cuttings and seeds propagated plants is probably due to their characteristics of high Specific Leaf Area (SLA), which result into high loss of water against small SLA observed in grafted propagated plants. The use of 37.5 Kg N: P: K (20:10:10) with either 10 or 20 Kg farmyard manure has no significant difference in attenuating the impact of climate change. It is therefore, recommended to distribute types of coffee seedlings based on the amount of rainfall and temperature of the area. Additionally, considering uncertainties which are associated with crop modelling further crop modelling studies to satisfactorily model the response of cutting, seeds and grafted propagated plants to climate change are also recommended.

Key words: *Coffea arabica*, Climate Change, CORDEX, Propagation techniques, Farm yard manure, Tanzania

5.2 Introduction

Climate change is a threat to survival of human beings as it has significant impacts on the environment, crop production, water resources, and livestock production (Araya *et al.,* 2015). According to Davis *et al.* (2012), global temperature has increased by an average of 0.74 °C in the last 100 years and this increase appears to have accelerated since 1970s. On the African continent, decadal analysis of temperature indicates increased warming trend over the last 50-100 years, with minimum temperature warming rapidly than maximum temperature (Niang *et al.,* 2014). Over the last 40 years (1979-2018), maximum and minimum temperatures in the Northern Highlands zone of Tanzania have increased at the rate of 0.02 °C and 0.023 °C $year^{-1}$ respectively (Mbwambo *et al.,* 2022) while according to Muthoni *et al.* (2019), significant decrease in annual rainfall (− 20 mm $year^{-1}$) has been recorded at Mount Kilimanjaro.

The agricultural sector will face serious challenges in the coming decades due to sensitivity of crops to water shortages and heat stress (Ramirez Villegas *et al*., 2012). Climate change impacts are expected to be higher for coffee plants, a crop that is grown by over 25 million mostly smallholder farmers in more than 60 countries throughout the tropics (Jayakumar *et al*., 2017) and the climate is what control where it can be grown (DaMatta & Ramalho, 2006). Increase in temperature due to climate change, reduces growth, flowering and fruiting of coffee plants (Craparo *et al*., 2015). Climate change will reduce global areas suitable for coffee by about 50% across emission scenarios; the world's dominant productions regions in Brazil and Vietnam may experience substantial reduction in areas available for coffee. (Bunn *et al.*, 2015)

Even though climate change is becoming pervasive and copping options becomes necessary (Lynch & St Clair, 2004), there is a limited knowledge on the extent to which the current agronomic practises would still hold/support coffee cropping systems (Mbwambo *et al.,* 2022). Moreover, adaptation strategies for coffee cropping systems have largely not been researched within the future time contexts through mechanistic modelling. Crop models can provide intuitions into challenges such as sustainability and how to cope with

the possible negative effects of climate changes (Spiertz, 2012). Crop models can also be used to predict crop yield (Kasampalis *et al.*, 2018).

Among the published dynamic coffee models, include (1) coffee agroecosystem model: I developed by Rodriguez et al. (2011), (2) dynamic model for coffee agroforestry systems developed by Van Oijen *et al*. (2010a) and (3) MAESPA model by Vezy *et al*. (2018). However, these models were not designed for large plots, long rotations and they lack energy balance and temperature of the canopy to drive the plant respiration and reproductive development. MAESPA model do not simulate growth and yield. In view of these shortcomings, Vezy *et al.* (2020) developed DynACof model which was designed to incorporate a plant-scale reproductive phenology formalism inspired by Rodríguez et al*.* (2011) but dependent on canopy temperature, with different sub-modules to adapt coffee and shade tree management, density and tree species, as in Van Oijen *et al.* (2010b), and meta models calibrated from MAESPA simulations for spatially-dependent variables, such as diffuse and direct light extinction coefficients, light use efficiency, leaf water potential, transpiration, and sensible fluxes (Vezy *et al.,* 2018). In a study to review existing models to simulate agroforestry systems, Kraft *et al*., 2021, reveals that DynACof model can predict climate change by 40 % and crop production by 50 %. DynACof can be easily adapted by users to other sites, other shade trees, other coffee varieties or managements by parameterizing the model accordingly. Adapting the model to other sites require mainly updating the site parameters (e.g., latitude, longitude, elevation), the soil properties (e.g., field capacity, pore fraction) and the meteorology.

In Tanzania there are only few studies that deal with climate change and crop modelling in coffee. Some of these studies include that of Rahn *et al.* (2018) who carried out a parameter sensitivity analysis of CAF2014 for application in Uganda and Tanzania. The aim of this study was to use climate scenario driven by the Hadley Global Environment Model 2 representative for the year 2050 under RCP 6.0 to study potential responses of the coffee plant to interactions of elevated [CO2], temperature, and water availability. The study also

explored the potential for adaptation to this scenario through shade management with results indicating that, shading importance increase with decrease in altitude. Another study by Craparo *et al*. (2015) used ARIMA model to quantify the impact of climate change on the Tanzania's arabica coffee production for the period from 1960-2010. The results of ARIMA model, indicated that average coffee production will drop to 145 ± 41 kg ha^{-1} (P = 8.45e-09) by 2060. However, these two studies differ from this study in about two aspects; the first aspect is the type of data used for future climates. Rahn *et al*. (2018) used data from GCMs to study the future climate of Mt. Kilimanjaro (Tanzania), this study uses RCMs due to their fine resolution against course resolution of GCMs. Rahn *et al.* (2018) used shade management as an adaptation option to climate change under RCP 6.0. Our study explores the ability of type of seedling (cuttings, seeds and grafted-propagated plants) and soil fertility management practices in adapting arabica coffee to climate change under RCP 4.5. On the other hand, Craparo *et al.* (2015), neither used GCMs, RCMs, and RCPs to obtain future climatic data or including adaptation practice during crop modelling. To the best of our knowledge, no study has used cuttings, seeds and grafted-propagated plants in crop modelling to evaluate response to changing climate up to the Near-term period (2026-2056) in Tanzania or even in East Africa.

Furthermore, Coordinated Regional Climate Downscaling Experiment (CORDEX) studies conducted in Tanzania include that of; Luhanga *et al.* (2018), assessing climate change projections in Tanzania through the use of climate simulations from three high resolution Regional Climate Models (RCMs). Ogega *et al.* (2020) also assessed the performance of 24 model runs from five Coordinated Regional Climate Downscaling Experiment (CORDEX) regional climate models (RCMs) in simulating East Africa's spatial-temporal precipitation characteristics under the representative concentration pathway (RCP) 8.5 scenario. Overall, RCA4 (r1i1p1) forced by CNRM-CERFACS-CNRM-CM5 and MPI-M-MPI-ESM-LR, REMO2009 (r1i1p1) forced by MPI-M-MPI-ESM-LR, and RCA4 (r2i1p1) forced by MPI-M-MPI-ESM-LR emerge as the top four RCM runs.

Climate change—rising temperatures, longer droughts, excessive rainfall—appears to threaten the sustainability of arabica coffee production (Van der Vossen, 2015). Therefore, imperative action is essential to address the issues of future climate changes, since they will have more impact on the perennial cropping systems, as previously shown for coffee than any other annual systems (Ovalle-Rivera *et al*., 2015). Adaptive capacity of coffee systems is a basic component required to collectively manage coffee resilience against climate change impacts. Resilience focuses on the capacity of systems to prepare for and withstand shocks and stress associated with natural hazards, and in particular with the inherent uncertainties associated with the magnitude, severity, and timing of hazard impacts or climate change (Tompkins *et al.,* 2008).

According to Lemma and Megersa (2021), Shade management is highly advisable when coffee is grown in less desirable areas, or in areas that will become affected by climate change. The main effects are decreasing air temperatures as much as 3 °C – 4 °C, decreasing wind speeds and increasing air humidity. Shading also helps avoid large reductions in night temperatures at high elevations. Breeding strategies aiming at F1 hybrid cultivars are now developed progressively elsewhere, firstly in Kenya (Ruiru 11(Walyaro, 1983)) Ethiopia (Ababuna (Bellachew, 1997)), central America (hybrd H3 (Bertrand *et al*., 1997). In Tanzania, Researchers initiated a program for developing F1 hybrids between high yielding varieties and Ethiopian germplasm (semi-wild) The developed FI hybrids are high yielding and disease resistant. The effective distribution of the F1 hybrid varieties in Tanzania started since 2007 (Teri *et al*., 2004) and the demand of coffee seedling is still high. Other adaptations strategies may include, re-adapting the coffee agronomic practices to climate change and improving water and nutrient use efficiency in coffee trees (Mbwambo *et al.,* 2022).

In order to expedite the adoption of improved Arabica hybrids in Tanzania, the Tanzania Coffee Research Institute (TaCRI), uses three seedling multiplication methods namely; clonal propagation, grafting propagation and manual hybridization (seed) (TaCRI, 2011). However, the effects of the current propagation methods on resultant coffee tree growth and yield have not been studied in sufficient detail

to guarantee that they will still support cropping system in the future time context. Generally, gains obtained through the planting of vegetative propagules, include maximum crop homogeneity, grain maturation, yield and the multiplication ability throughout the year (Junqueira *et al*., 2006). However, problems that arise from shallow root system can be observed in the cuttings propagated coffee plants (Bragança *et al.,* 2010). According to Partelli *et al.* (2014), plants derived from hybrid seeds and grafting are characterized by deep and vigorous root systems in one hand while on the other hand plants derived from cuttings lack tap root. The observed difference in these types of seedlings may result into different response towards adverse environmental conditions.

An overall objective of this work was to evaluate coffee seedlings derived from different propagation methods so as to identify the best seedlings for adapting Arabica coffee to adverse conditions caused by climate change using DynACof model. Specific objectives were (1) to determine historical and future climatic parameters in the Northern Highlands zone (2) to estimate coffee cultivar parameters and calibrate the DynACof model using field experimental data (3) to validate the DynACof model in simulating coffee yield under Northern Highlands zone conditions. (4) to simulate coffee yield under historical and future climatic conditions of the Northern Highlands zone.

5.3 Materials and Methods

5.3.1 Description of the study area

The study was conducted in the Northern Highlands Zone of Tanzania. Two administrative regions namely Kilimanjaro and Arusha were involved. Rainfall pattern in these regions is bimodal. Annual rainfall in Kilimanjaro region ranges from 1000 at low altitude to 2000 mm at high altitude. Arusha region, on the other hand, receive anual rainfal which ranges from 800 to 1000 mm. Hai district represented areas with optimum conditions for growing coffee in the current time (rainfall above 1 200 mm per year and mean temperature range of 20.2 for the past four decades (Mbwambo *et al.,* 2022). The study areas in Kilimanjaro region were from the altitude range between 1000-1731 m.a.s.l while those from Arusha were from 1185-1618 m.a.s.l. The volcanic slopes of Mt. Kilimanjaro and Mt. Meru has

resulted into soils that are deep, well drained, brown to red sandy loam to sandy clay. The major soil group in the regions are the Nitisol, Luvisols, Cambisols and Andosols (Msanya *et al.,* 2002).

5.3.2 Data collection

5.3.2.1 Future climate data

This study makes use of high-resolution climate simulation from Coordinated Regional Climate Downscaling Experiment program regional climate models (CORDEX-RCMs). CORDEX program is archiving output from a set of RCMs simulation over different regions in the world (Luhanga *et al.,* 2018). Three CORDEX-Africa RCMs (SMHI-RCA4, KNMI- RACMO22T and MPI-CSC-REMO2009) were downscaled dynamically from three GCMs; RCA4/CCCma-CanESM2, RACMO22T/ICHEC-EC-EARTH and REMO2009/MPI-M-MPI-ESM-LR.RCM simulated daily rainfall, maximum and minimum temperature data were obtained from the CORDEX project (https://esgf-node.llnl.gov/projects/esgf-llnl/). The CORDEX RCM data have a spatial resolution of 0.44°, which corresponds to a 50-km-by-50-km bounding box (Nikulin *et al.,* 2012).

The RCM datasets used in this study at daily scale consist of rainfall, minimum and maximum temperature for the RCM historical (1981–2011) and Representative Concentration Pathway (RCP) 4.5 projected (2026–2055) period. These RCMs were chosen because they were found to perform well over the sub- region with acceptable range of biases (Luhanga *et al.,* 2018). The CORDEX –RCMs and their driving GCMs used in this study are listed in (Table 5.1). From the gridded RCM model data, a representative value was extracted and bias-corrected using the CMhyd tool (Rathjens *et al*., 2016). CMhyd was designed to provide simulated climate data that can be considered representative for the location. Therefore, climate model data should be extracted and bias- corrected for each of the gauge locations. The tool has been tested using the CORDEX archive for different regions and provided satisfactory performance (Rathjens *et al.,* 2016). This study used linear scaling (LS) methods to correct the rainfall and temperature data due to their effectiveness in removing RCM bias in other studies (Fang *et al.,* 2015).

Table 5.1: Details of CORDEX –RCMs and the driving GCMs

No	RCM	Driving GCMs	Representative concentration pathways (RCPs)
1	KNMI Regional Atmospheric Climate Model, version2.2 (RACMO22T)	ICHEC-EC-EARTH	RCP4.5 from 2026–2055
2	SMHI Rossby Center regional Atmospheric Model (RCA4)	CCCma-CanESM2	RCP4.5 from 2026–2055
3	REMO2009	MPI-M-MPI-ESM-LR	RCP4.5 from 2026–2055

5.3.2.1.1 Statistical evaluation of bias-corrected RCMs

Percent bias (PBIAs), root mean squared error (RMSE) and skill score based on MAE (MAE-SS) were used to evaluate the performance of RCMs. Percent bias (PBIAs) is used to measure systematic bias between observed and RCM outputs variables in terms of percent Eq. (i). The 0 PBIAS indicates no systematic difference between simulated and observed amounts, whereas a large value of PBIAS indicates that the RCM output variable largely diverges from the observed one. A positive PBIAS indicates overestimation whereas a negative PBIAS indicates an underestimation of the observed variables.

$$\text{Percent bias (PBIAS)} = \frac{\sum_{i=1}^{n}[s_i - o_i]}{\sum_{i=1}^{n} o_i} * 100 \qquad \text{(i)}$$

Root means square error (RMSE) in Eq. (ii) is used to shows the differences between observed and model outputs. RMSE value close to 0 indicates a very good agreement between studied variables.

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{[s_i - o_i]^2}{n}} \qquad \text{.....(ii)}$$

Where i run from 1 to n (total number of data points).

MAE of the models has to be determined with respect to observation (MAE) on Eq. (iii) and the hypothetical model (MAE_{ref}) to determine the skill score of the models as shown in Eq.

$$MAE = \sum \frac{|M - O|}{N} \quad \text{(iii)}$$

and

$$MAE_{ref} \sum \frac{|\overline{O} - O|}{N} \quad \text{(iv)}$$

Where M stands for model, $\bar{0}$is assumed as if it is obtained from the perfect hypothetical model that accurately predicts seasonal or annual mean variable (Reanalysis data), and O is observed variable. Once the two MAEs are determined, the skill score (SS) is evaluated based on Eq. (v).

$$SS = 1 - \frac{MAE}{MAE_{ref}} \quad \text{(v)}$$

Meteorological reanalysis data provide an accurate description of the past weather by assimilating land surface and atmospheric observations from several sources into the most advanced numerical weather prediction models that obey physical laws, in order to create a complete and consistent climate dataset that covers several decades back in time and that is coherent both from physical and dynamic perspectives (Soci *et al.,* 2016). ERA5 is the fifth generation of European Centre for Medium-Range Weather Forecasts (ECMWF) global reanalysis, succeeding ERA-Interim and covering the entire globe from 1979 at a spatial resolution of about 31 km (Hersbach *et al*., 2020). According to Chen *et al.* (2018), the Reanalysis dataset have increasingly been used in various environment and hydrological applications. They are also commonly used in regional climate modelling, weather forecasting and more recently as substitute for surface precipitation and temperature in various hydrological modelling studies (Beck *et al.,* 2017). These data have shown to provide good proxies to observations and even to be superior to interpolated (from surface stations) datasets in regions with sparse network surface coverage (Essou *et al*., 2017).

A superior model over the hypothetical model will have lower MAE than the reference (hypothetical) model which implies that SS is positive for a model that is better than the reference model. In contrast, a negative SS implies inferior CORDEX model compared with the reference model. RACMO22T generated by ICHEC-EC-EARTH was chosen to be used in this study due to its higher SS. RACMO22T-ICHEC-EC-EARTH was then used to download future climatic data in 24 sites that were chosen randomly in the study area using historical data (observed) from the reanalysis data (ERA5 data) for the period of 30 years (1981- 2011) (Table 5.2, 5.3 and 5.4).

Table 5.2: Statistical analysis between the simulated RCMs and observation rainfall

No.	RCMs	GCMs	PBIAS (%)	RMSE	SS
1	REMO2009	MPI-M-MPI-ESM-LR	- 8.3	22.34	-0.34
2	RCA4	CCCma-CanESM2	-16	20.77	-0.41
3	RACMO22T	ICHEC-EC-EARTH	-3.2	15.07	-0.25

Table 5.3: Statistical analysis between the simulated RCMs and observation maximum temperature

No.	RCMs	GCMs	PBIAS (%)	RMSE	SS
1	REMO2009	MPI-M-MPI-ESM-LR	1.58	3.25	-0.5
2	RCA4	CCCma-CanESM2	1.54	3.17	-0.46
3	RACMO22T	ICHEC-EC-EARTH	1.45	3.02	-0.4

Table 5.4: Statistical analysis between the simulated RCMs and observation minimum temperature

No.	RCMs	GCMs	PBIAS (%)	RMSE	SS
1	REMO2009	MPI-M-MPI-ESM-LR	1.76	2.74	-0.6
2	RCA4	CCCma-CanESM2	1.55	2.62	-0.6
3	RACMO22T	ICHEC-EC-EARTH	1.43	2.40	-0.4

5.3.2.2 Historical climate

30-year daily historical weather data were obtained from Lyamungu, Tanzania Metrological Office (TMA) (Hai district), other weather data were obtained from Arusha TMA office and from a private company, Burka Coffee estate both located in Arusha town. Weather variables

included minimum and maximum temperature, solar radiation, wind speed, relative humidity and rainfall. These data were used in calibrating the Model.

5.3.2.3 Data for Soil profiles

Field sampling was done prior and after trial establishment. Bulk soil samples for the determination of organic carbon and texture were collected with hand-auger from the depths of 0-30 cm and 0-60 cm at Lyamungu and Burka sites. A total of 24 soil profiles data are also retrieved from Africa soil profiles database (Leenaars *et al.,* 2013) to be used in the 22 simulated locations and the other two profiles were used to add data at Burka and Lyamungu sites. The hydrological characteristics of layers for each soil sample were estimated using soil water characteristic calculator (Saxton & Rawls, 2009). The input variables in this calculator are soil type (sand, silt or clay) and organic matter and the output parameters are minimum water content and water content at Field capacity. Pore fraction for different soil types were estimated according to (Saxton and Rawls, 2006). Roots were obtained by excavating the entire root system and roots fraction distribution in three layers, 0-1.25 m, 1.25 -1.75m, 1.75-to 3.75 m (Defrenet *et al.,* 2016) were determined according to Vezy *et al.* (2020).

5.3.2.4 Crop model

Dynamic Agroforestry Coffee model (DynACof) use plot scale to simulate the daily growth and yield of coffee plants under different species of shade tree and management options (Murthy, 2004). The coffee layer can be simulated either in monoculture or in agroforestry systems. Each layer is simulated sequentially at a daily time step. The model accounts for potential competition for light acquisition and water availability between plant and soil layers (Vezy *et al.,* 2020). Light interception and photosynthesis, Carbon supply, maintenance respiration, carbon allocation to organs, growth respiration and net primary productivity were calculated as described in Vezy *et al*. (2020).

5.3.2.5 Model input files

All parameters needed for a DynACof simulation are stored in specific input files for the shade tree, the coffee, the soil, the site and the meteorology. However, since this study is not evaluating shade management, only four files for each of the 24 sites were prepared. Nevertheless, the default shade file remained in the model but not selected as the management option. The meteorology file involves maximum and minimum temperature of the day (°C), the RAD or PAR (MJ m-2 d -1) and the relative humidity. The soil file on the other hand includes the total soil depth occupied by the roots of the coffee plants, water at wilting point, water at field capacity, water content within the three layers of the soil root depth. The pore fraction of the soil and the fraction of the roots within each layer are also part of the soil file. Furthermore, the site file includes latitude, longitude, elevation and location. The coffee file involves the vegetative and reproductive characteristics of coffee plant.

5.3.2.6 Model calibration and Validation

Before running the model, adjustments were necessary (calibration) to reflect local crop cultivars and site conditions. The model was then run for about 2 years (April, 2020 – July, 2022) corresponding to the length of the experimental data. The experimental data were obtained from two experimental fields that were established in two areas with distinct climate conditions. There were 9 simulations which correspond to the combination of 3 main factor and 3 sub factor treatments. The choice of parameters to calibrate was based mainly on observed available data and also on suggestions from DyACof developers (Vezy *et al*., 2020). Adapting the model to other sites require mainly updating the site parameters (e.g., latitude, longitude, elevation), the soil properties (e.g., field capacity, pore fraction) and the meteorology. Therefore, since the model was adapted to other sites, all parameters related to sites were adjusted. Soil properties including field capacity, pore fraction and the proportion of roots to the total root biomass were also adjusted. Meteorological data were also adjusted accordingly. Parameters related to the type of seedlings were also adjusted accordingly; this includes the specific leaf area (SLA), leaf width, plant height and maximum number of buds that can break dormancy per day. All these data were measured in the field

experiment located at Lyamungu with exception of maximum number of buds that can break dormancy per day which was just calibrated in the model. The adjusted parameters are shown in Table A.5 and B.5. To evaluate model efficiency in predicting observed yields the Root-mean-square error (RMSE) was used.

5.3.2.7 Simulation of Coffee yield

Using the calibrated DynACof model, coffee yield simulation was carried out with historical climate data from the Reanalysis data from ERA 5 data for the base period of 1981-2011. Yield simulation for the near-term period (2026-2056) was done using climatic data from RACMO22T RCM downscaled from ICHEC-EC-EARTH GCM under RCP 4.5. The simulation was done to mimic the Split–plot design of the experimental fields (three main -factor and three sub-factors), and this resulted into 9 simulations per one site. Friedman two—way analysis of variance by ranks was used to determine if the treatments means are significant (Friedman, 1937).

5.4 Results

5.4.1 Model Calibration and Performance

The adjusted values of coffee plants and sources of the parameters used in the model are listed in Table B.5. As shown in Table 5.5 and 5.6 simulated green coffee yield closely matched with their observed values, indicating that cultivar specific parameters within the model were reasonably adjusted. Also, there were good relationship between observed and simulated variables (r^2 values were 0.997 and 0.985 respectively) for Kg ha^{-1} green coffee at Lyamungu and Burka respectively. Cuttings propagated plants combined with 75 g NPK showed high RMSE and MAE both at Lyamungu and Burka than other treatments. Seed propagated plants combined with 37.5 g NPK + 10 Kg FYM had lowest RMSE and MAE both at Lyamungu and Burka. Cuttings propagated plants resulted into higher green coffee yield (Kg/ha), followed by seed and grafted propagated plants. Similarly, plants applied with organic fertilizer resulted into higher green coffee yield (Kg/ha) as compared to plants applied with inorganic fertilizer alone.

Table 5.5: Comparison of observed and simulated green coffee yield at Lyamungu (2020-2022)

Treatments		Green coffee yield (Kg/ha)		RMSE (Kg/ha)
Type of seedling	Fertilizer options	Observed	Simulated	
Cuttings	75 g NPK	3502.56	3649	48.81
Seed	75 g NPK	2090.16	2208	39.28
Grafting	75 g NPK	1333.05	1462	42.98
Cuttings	37.5g NPK +10 Kg FYM	3214.21	3339	41.60
Seed	37.5 g NPK +10Kg FYM	1944.22	1945	0.26
Grafting	37.5 g NPK +10Kg FYM	1513.28	1543	9.91
Cuttings	37.5 g NPK +20Kg FYM	3603.06	3704	33.65
Seed	37.5 g NPK +20Kg FYM	2224.98	2261	12.01
Grafting	37.5 g NPK +20Kg FYM	1437.8	1543	35.07

Note: The ratio of N: P: K = 20:10:10

Table 5.6: Comparison of observed and simulated green coffee yield at Burka (2020-2022)

Treatments		Green coffee yield (Kg/ha)		RMSE (Kg/ha)
Type of seedling	Fertilizer options	Observed	Simulated	
Cuttings	75 g NPK	2296.75	2069	75.92
Seed	75 g NPK	1468.96	1319	49.99
Grafting	75 g NPK	771.22	822	16.93
Cuttings	37.5 g NPK +10 Kg FYM	2095.62	1872	74.54
Seed	37.5 g NPK +10Kg FYM	1050.42	1059	2.86
Grafting	37.5 g NPK +10Kg FYM	690.44	844	51.19
Cuttings	37.5 g NPK +20Kg FYM	2194.72	2026	56.24
Seed	37.5 g NPK +20Kg FYM	1528.45	1311	72.48
Grafting	37.5 g NPK +20Kg FYM	804.47	855	16.84

Note: The ratio of N: P: K = 20:10:10

5.4.2 Historical rainfall (1981–2011) and projected rainfall (2026-2056) in the Northern Highlands zone of Tanzania

Over 30-year baseline period (1981–2011), average rainfall for Lyamungu and simulated areas in the Northern Highlands zone ranged between 512.47-3379.7 mm per annum. The lowest amount of rainfall being observed in Arusha region and highest amount in Kilimanjaro region. The projected rainfall ranged between 512- 3732 mm per annum. An increase in the amount of rainfall across all the 24 study areas of the Northern Highlands zone during the Near-term

period (2026-2056). This increase varies from 0.2-13 % in Kilimanjaro region and 6.05 -13 % in Arusha region (Fig.5.1).

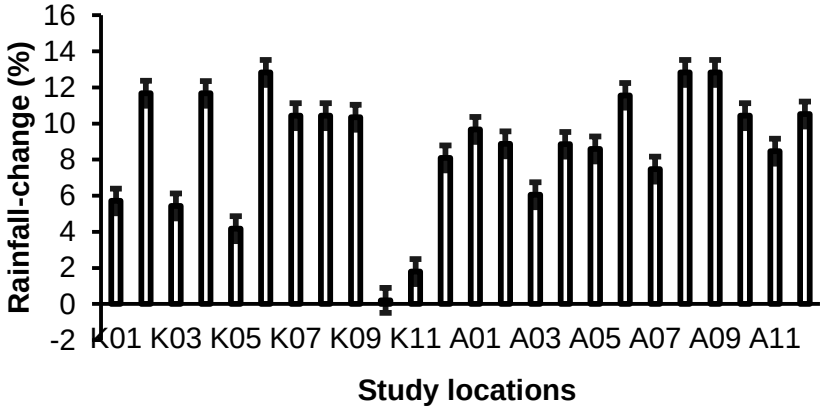

Figure 5.1: Relative change in rainfall in Near-Term period (2026-2056); (K01-K12 study sites in Kilimanjaro region and A0-A12 study sites in Arusha region (Table A.5) Error bars represent ±5% standard error of the mean.

Temperature results indicate that, highest Tmin greater than 19 °C and T_{max} greater than 29 °C were observed at Kilimanjaro region during the baseline period. There was also an increase in T_{min} during the Near-term period (2026-2056) which varies between 1.4-1.48 °C in Kilimanjaro region and 1.36-1.64 °C in Arusha region. Moreover, projections indicate an increase in T_{max} within the Northern Highlands zone which also varies between 1.07-1.20 °C in Kilimanjaro region and 1.01-1.15 °C in Arusha region (Fig.5.2).

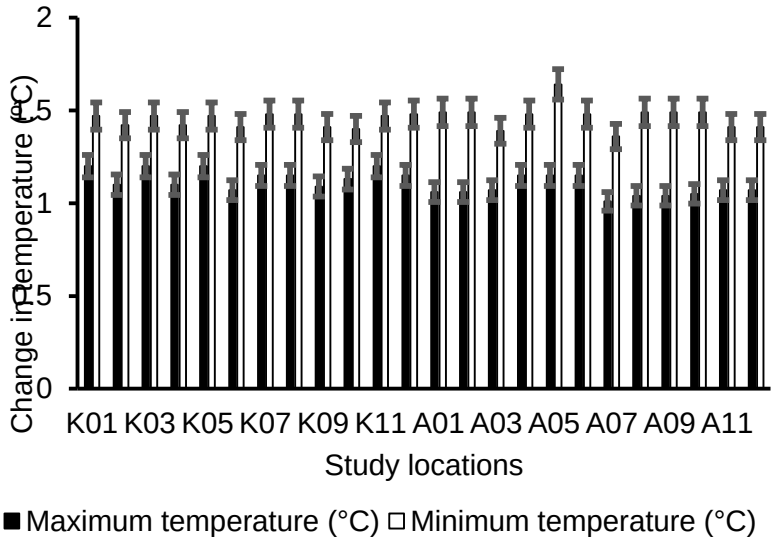

Figure 5.2: Absolute change in temperature in Near-Term period (2026-2056 (K01-K12 study sites in Kilimanjaro region and A0-A12 study sites in Arusha region (Table A.5) Error bars represent ±5% standard error of the mean.

5.4.3 Projections of coffee yields under climate change

Highest green coffee (2 828.8) Kg ha^{-1}has been observed at Kilimanjaro region during the historical period (1981-2011) while during the Near-term period (2026-2056) the highest amount of green coffee (2 559) Kg ha^{-1} is projected to be produced at Arusha region. The percentage change in coffee yield relative to the baseline in the Northern Highlands zone during the Near-term period (2026-2055) under RCP 4.5 are presented in Fig. 5.3 for the percentage change per year. The findings indicate that the downscaled climatic data from RACMO22T- ICHEC-EC-EARTH decrease annual green coffee yield at varying percentage in the Northern Highlands zone. The projected negative changes are in the range of 2-40 % Kg ha^{-1} in the Kilimanjaro region and 4-51% Kg ha^{-1} in Arusha region. Furthermore, the projections indicate that climatic data from RACMO22T- ICHEC-EC-EARTH will increase coffee yield in some areas of the Northern Highlands zone. In Kilimanjaro region the increase will range between 8- 100 % Kg ha^{-1} while in the Arusha region the increase will range from 0.5-20 % Kg ha^{-1}.

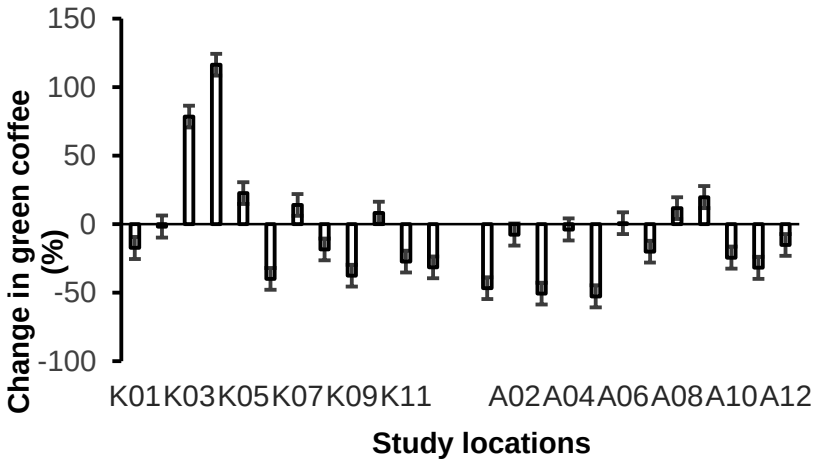

Figure 5.3: Relative change in green coffee yield in Near-Term period (2026-2056) (K01-K12 study sites in Kilimanjaro region and A0-A12 study sites in Arusha region (Table A.5)). Error bars represent ±5% standard error of the mean.

5.4.4 Specific Leaf Area (SLA)

Specific Leaf Area for coffee plants varied among the treatments tested in this study. Higher SLA was produced by cutting- propagated plants ranging from 25-30. Seed- propagated plants ranked the second with a range of 13-25 and Grafted plants ranked the last with the SLA from 8-10.

Fig. 5.4 below depicts difference in the percentage change of green coffee yield according to the type of management options. During the Near-term period (2026-2056), cutting and seed-propagated plants combined with FYM will result into yield reduction of about 25 %, however when inorganic fertilizer is used alone yield reduction will be 45 %. On the other hand, grafted propagated plants combined with FYM will cause yield reduction of about 10 % while when grafted – propagated plants are combined with inorganic fertilizer alone yield reduction will be 30 %. The study revealed further that, during the Near-term period (2026-2056), majority of cuttings and seed propagated plants will cause yield increase of about 10 % while grafted –propagated plants will cause yield increase up to 40 %.

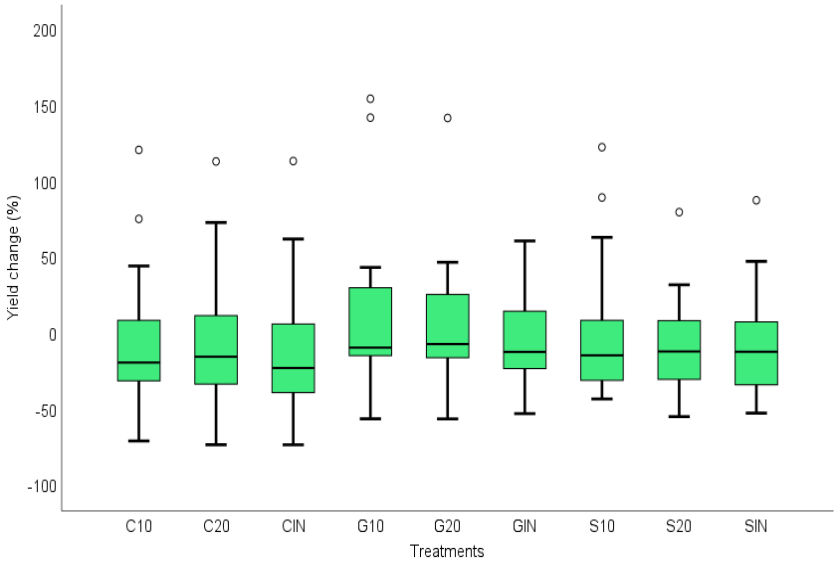

Figure 5.4: Effect of type of coffee seedling and different fertilizer options on relative coffee yield change with respect to historic climate over the Northern Highlands zone of Tanzania

Note:

C10 = Cutting seedlings * 37.5 g NPK +10Kg FYM
C20 = Cutting seedlings*37.5 g NPK +20Kg FYM
Cinor = Cutting seedlings * 75 g NPK
G10 = Grafting seedling *37.5 g NPK +10Kg FYM
G20 = Grafting seedling *37.5 g NPK +20Kg FYM
Ginor = Grafting seedling * 75 g NPK
S10 = Seed seedling* 37.5 g NPK +10Kg FY
S20 = Seed seedling* 37.5 g NPK +20Kg FY
Sinor =Seed seedling * 75 g NPK

Friedman two—way analysis of variance by ranks indicates that there is indeed difference in percentage change between the nine treatments above. At 95 % confidence interval found a significant difference between 9 treatments with Chi- square = 36.44and p=0.001.

Table 5.7: Multiple Comparisons Test

		C10	C20	Cinor	G10	G20	Ginor
	Mean rank	4.46	3.92	3.58	6.79	6.75	5.83
C10	4.46	-					
C20	3.92	0.69	-				
Cinor	3.58	1.11	0.42	-			
G10	6.79	2.95*	3.63*	4.06*	-		
G20	6.75	2.89*	3.58*	4.01*	0.05	-	
Ginor	5.83	1.7	2.42*	2.85*	1.21	1.16	-
S10	5.04	0.73	1.43	1.86	2.21*	2.16*	1.00
S20	4.33	0.16	0.53	0.95	3.11*	3.06*	1.90
Sinor	4.29	0.21	0.47	0.86	3.16*	3.11*	1.95*

Note * = difference between means is significant at 0.05

Note:

C10 = Cutting seedlings * 37.5 g NPK +10Kg FYM
C20 = Cutting seedlings*37.5 g NPK +20Kg FYM
Cinor = Cutting seedlings * 75 g NPK
G10 = Grafting seedling *37.5 g NPK +10Kg FYM
G20 = Grafting seedling *37.5 g NPK +20Kg FYM
Ginor = Grafting seedling* 75 g NPK
S10 = Seed seedling * 37.5 g NPK +10Kg FY
S20 = Seed seedling * 37.5 g NPK +20Kg FY
Sinor = Seed seedling * 75 g NPK

5.5 Discussions

In this paper high resolution climate change information derived from RACMO22T Regional Climate Model (RCM) and driven by ICHEC-EARTH Global Circulation Model (GCM) are used to simulate coffee yield over the Northern Highlands zone during the Mid-century (2026-2056) under RCP 4.5. The primary aim was to assess how climate change will affect coffee yield from the coffee plants propagate through seeds, cuttings and grafting while at the same time being integrated with different fertilizer material.

5.5.1 Future trends of temperature and rainfall over the northern highlands zone

Temperatures are projected to increase in the Northern Highlands zone with T_{min} increasing at the higher rate than T_{max}. However, according to the projection made by RACMO22T- ICHEC-EARTH,

T_{min} will increase at higher rate in Arusha region as compared to Kilimanjaro region under RCP 4.5. Changa *et al*. (2017), in their study conducted in the Northern Highlands zone observed that the number of cold days and cold nights over Arusha and Kilimanjaro region exhibit a decreasing trend. Their study also found that the percentage number of warm night and warm days has been increasing, and the trend is more pronounced in Arusha region. These findings concur with the findings in this study in the sense that they both indicate that the nights are warming faster in Arusha region as compared to Kilimanjaro region. Mbwambo *et al.* (2022), using observed data (1979-22018) from Tanzania Meteorological Agency (TMA) observed significant increase of T_{min} at Lyamungu Hai district. Similarly, the observed findings also compliant with the observed temperature extremes trends in different parts of the world as depicted in the IPCC Assessment reports (Changa *et al*., 2017; Shukla *et al.,* 2019) which indicate that the number of cold days and night have been decreasing, while the number of warm days and night have been increasing. The projected change in rainfall during the Near-term period (2026 – 2056) indicates increase in rainfall in the Northern Highlands zone, with higher percentage changes expected to occur in Arusha region as compared to Kilimanjaro region. The findings of this study agree with the observation made by Ongoma *et al.* (2020), showing that most studies agree that the rainfall over the larger part of the Great Horn of Africa (Kenya, Uganda, Tanzania, Ethiopia, Rwanda, Burundi, Sudan, South Sudan, Eritrea, Djibouti, Somali) is likely to increase in the 21st century. Nevertheless, our findings differ from that of Mbwambo *et al.* (2022), which indicated decline, in annual rainfall (not significant) over the coffee -growing areas of the Northern Highlands zone of Tanzania for the four past decades (1979-2018).

5.5.2 Projections of coffee yields

It is clear that the impacts of climate change on future coffee yields are considerably big in comparison with the simulated baseline yields in the Northern Highlands zone. These projected changes are mainly attributed to increase in maximum and minimum temperatures. T_{min} is increasing at the higher rate than T_{max} and so the former is more attributed to the reduction of coffee in the area. Hence, despite the

fact that, T_{mean} in the Northern Highlands zone of Tanzania seems to have reached the upper limit of the mean temperature bracket (18-21°C) suitable for coffee cultivation (Wrigley (1988), it is the T_{min} that is warming the average temperature. Jaramillo *et al*. (2011) stated that, even the smallest increase in temperature could cause extensive damage in coffee production. Bapuji Rao *et al.* (2014) and Nagarajan *et al.* (2010) indicate that high night temperatures increase the rate of respiration so the assimilates which could be used for growth and yield are reduced. Drought and high temperatures cause fruit abortions, increased bean defects, reduced berry growth, and acceleration of ripening, leading to a reduction in coffee yield and quality (Craparo *et al.,* 2020). Davis *et al. (*2012) on the other hand, point out that lower mean annual air temperatures cause growth to be depressed.

Moreover, climate change information generated by RACMO22T–ICHEC-EARTH model indicates that both higher altitude and lower altitude areas are expected to be suitable for growing coffee in the Near-term period (2026-2056). Areas located at high altitude (> 1500 m.a.s.l) are expected to have an increase in coffee yield due to the increase in temperature (T_{min}). These findings are in consistency with that of Ovalle-Rivera *et al.* (2015) which indicate that, Tanzania and Uganda would lose suitable area at elevations below 1400 m.a.s.l. According to Ovalle-Rivera *et al*. (2015), climate suitable for Arabica coffee in East Africa are predicted to shift from 400-2000 m.a.s.l to 800-2500 m.a.s.l. Nevertheless, despite projections in this study and other study suggesting that suitable coffee growing areas will shift to the higher altitude, this will coincide with the protected forests which start around 2200 m.a.s.l. (Ovalle-Rivera *et al.,* 2015), hence agricultural expansion to these higher altitudes is not permitted. On the other hand, the projected increase in yield at the lower altitude could be the results of [CO2] fertilization effect and the increase in rainfall which is projected by the RACMO22T– ICHEC-EARTH model in the Near-term period (2026-2056). Elevated [CO2] might mitigate the negative effects of predicted climate change at low altitude if no physiological and/or morphological acclimation processes take place.

5.5.3 Effect of type of coffee seedling and fertilizer management on coffee yield

This study indicates that plants propagated through cuttings and seeds are not significantly different when combined with either of the fertilizer management practices. However, minimum change in coffee yield was observed when these types of seedlings were combined with integrated nutrient source than when it was inorganic fertilizer alone. Firstly, the study shows the comparative advantage of combining organic and inorganic sources of nutrients. That is apart from providing plants nutrients the integration also improves water holding capacity of the soil through additions of organic matter in the soil. Similar finding has been reported by Chemura *et al*. (2013) and Maro and Mbwambo (2020). Secondly the study reveals that, integrated nutrient source may help to attenuate the impact of climate change and enable coffee to be grown sustainably in the context of climate change without jeopardizing the coffee yield.

The study reveals further that, grafted –propagated plants will be the least in reducing coffee yield in the Near-term period (2026-2056) than cuttings and seed-propagated plants. According to the projections made by RACMO22T-ICHEC-EARTH model, the Near-term period (2026-2056) will experience high T_{min} and T_{max} and this may accelerate drought despite the fact that the projections indicate an increase in rainfall. Drought will accelerate evapo-transpiration due to the increase in temperature and this may result into crop failure. Therefore, the reason why the grafted plants outweighed the other two types of seedlings (cutting and seed) could be due to its characteristics of having small specific Leaf area (SLA). Among the three types of seedlings, it was grafted-propagated plants that had small SLA (8.7) than cuttings (28.3) and seed (19.3) propagated plants. According to Grace (1990), Specific Leaf Area (SLA) is the amount of leaf surface area per unit of leaf mass that is available for water loss). Therefore, the larger negative change that have been observed in cuttings propagated plants could have been due to its higher SLA which resulted into loss of water among the cuttings propagated plants. According to Bragança *et al.* (2010) few cuttings propagated plants tend to exhibit irregular relationships between their above ground parts and below ground parts resulting in plants death

in many cases. On the other hand, Oliveira *et al.* (2004), have indicated that grafting enables even plant's biomass contributing to increased coffee productivity.

Crop modelling was also associated with uncertainties due to lack of observations data such as soil, climate and crop in many points where the study was conducted. During modelling a lot of coffee crop data were required, yet in the country only few compact coffee variety data have been documented to date, this caused a lot of data from literature to be used and only a few from field experiments conducted within the area. Daily climatic data and soil characteristics were also not available in many points used for simulation. Data on the rooting characteristics of cutting, seeds and grafted propagated coffee plants is also missing. Nevertheless, despite these limitations, results show that parameters within the model were well adjusted since there was good association between the simulated results and observed.

5.6 Conclusion

Projections indicate that during the Near-term period (2026-2056) rainfall will increase in Kilimanjaro region at the range of 0.2-13 % while in Arusha region the increase will be 6.05-13 %. Tmin is expected to increase at the higher rate than Tmax at the range of 1.4-1.48 °C in Kilimanjaro region and in Arusha region at the range of 1.36-1.64 °C. The zone will also experience an increase in Tmax at a range of 1.01-1.15 °C and 1.07-1.20 °C in Arusha and Kilimanjaro regions respectively. The change in temperature will cause some areas in higher elevation to be warm especially due to increase in Tmin. Projections indicate reduction of annual green coffee (Kg ha^{-1}) of 2-40 % in Kilimanjaro region and 4-51 % in Arusha regions. The use of cuttings, seeds and grafted propagated coffee plants will reduce green coffee (Kg ha^{-1}) by 40 %, 40 % and 10 % respectively. High reduction of yield observed under cuttings propagated plants is probably due to their characteristics of high Specific Leaf Area (SLA) which could result into high loss of water against small SLA observed in grafted propagated plants. Coffee yield obtained from using half rates of recommended inorganic fertilizer with either 10 Kg FYM or 20 Kg FYM has no significant difference. It is therefore recommended to distribute types of coffee seedlings to farmers based on the amount of

rainfall and temperature of the area. Integrated soil fertility management (37.5 g N.P.K +10 Kg FYM) tree^{-1} may be used as one of the adaptation strategies because apart from providing nutrients to the coffee plants the package also helps in improving water retention properties of the soil. Furthermore, considering uncertainties which are associated with crop modelling further improvement to the model is recommended for DynACof model to be able to deal with coffee tree from various propagation techniques.

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CHAPTER SIX

6.0 GENERAL DISCUSSION

6.1 Coffee adaptation strategies for climate change in Tanzania

Climate change (increase in temperature and decrease in rainfall) is hypothesized to be the reasons for coffee decline in Tanzania. Therefore, an overall objective of this work was to develop agronomic techniques for adapting coffee (*Coffea arabica.* L*)* to climate change. Its conceptual framework was based on the assumption that effective research into an environmental problem facing farmers should start with the farmers themselves.

6.1.1 Farmers perceptions of climate change

The findings of this study indicate that climate change is already being experienced by coffee farmers form the Northern and Southern Highlands zone of Tanzania. Among the 242 respondents, 163 67%) farmers perceived climate change by a way of change in intensity of the climate variables (increase in temperature and decrease in rainfall). Bharat *et al.* (2022) in their study also indicated that communities in India have already experienced climate change in the form of irregular and snowfall, increasing temperature and decreasing moisture content. In their study, Reddy *et al*. (2022) indicated that 62% of the sampled perceived climate change in various meteorological indicators. Farmers are the ones to undertake the adaptive action (Berry *et al*, 2006), If farmers are not aware, they will be reluctant for adaptation. As reported by Bharat *et al.* (2022), several factors such as education, experience in farming and extension Services have been influencing farmer's perceptions to climate change in the two major Arabica coffee growing zones. Farmers' perceptions were compared with the results of the historical trends from meteorological data and the results indicate that the two are in agreement.

6.1.1.1 Perceived Impacts of Climate Change on Coffee Farming by farming households

Farming households in the Northern and Southern Highlands zones noted decrease in crop productivity because of increase in temperature and decrease in rainfall. The decrease in crop

productivity was mainly due to increase in crop insect pest (79 %), increase in crop diseases (63%), late flowering (63 %) and crop failure due to water shortage (59%). According to Agegnehu *et al.* (2015) climate variations is the most favourable for increase of coffee pest and disease and the loss estimate is 13 % globally. In their study Laderach *et al*. (2010) found that climate variation during coffee growing will increase pest and disease prevalence, expanding the altitudinal range in which the fungal disease coffee rust (CLR) and coffee berry borer (CBB) can survive. Rising temperature will increase the infestation by CBB particularly in places where coffee is grown un shaded (Walyaro, 2010). Late flowering as observed by coffee farming households could be the results of unpredictable rainfall patterns. The unpredictable rains or uncertain rains will make the coffee plants to flower at various times throughout the year this phenomenon is known as running blossom or off-season flowering or continuous flowering in coffee. This condition ultimately making the farmers to harvest small quantities continuously this will affect the physiology of coffee crop.

6.1.1.2 Farmers' Responses to Climate Change

The findings of this study reveal that some coffee farmers have adapted agronomic practices relevant to climate change. Response actions include planting shade trees, the use of disease-tolerant varieties, soil fertility management, soil and water conservation practices (the use of terraces, cut-off drains, and mulching), and irrigation practices. According to Jassogne *et al*. (2013), good management practices that reduce soil erosion (e.g., cover crops and contour bunds) increase water retention (mulching, shade) will further help farmers adapt to climate change and retain the more fertile topsoil.

Scientists seem to agree that the best way to preserve coffee is with shade trees (Jaramillo *et al*., 2009). Shade trees planted near coffee plants have the ability to block out the sun's impact on the plants. They create lower temperature; reduce up to 4°C better suited for Arabica coffee plants (Jassogne *et al*., 2013). On the other hand, Craparo *et al.* (2015) queries the popular belief that shade trees are required for climate change adaptation in warmer areas due the role

of minimum temperature and diurnal temperature variation. Furthermore, other studies have reported that many farmers are continuing intensify the management of existing Arabica coffee field in an effort to obtain higher yields, reduce labour cost and control pest and disease outbreak (Harvey *et al*., 2021). The conventional intensification of coffee production involves reducing, simplifying or eliminating shade and increasing planting density of coffee plants (Perfecto *et al.,* 2019).

The use of disease-tolerant varieties as a way to adapt to climate change impact have also been reported by Gay *et al.* (2006) and Avelino and Anzueto (2020), who demonstrate that coffee farmers are actively changing the coffee varieties they grow, replacing traditional variety they grow to high yielding coffee varieties that have been bred to be resistant to coffee diseases. According to Kilambo *et al.* (2013), the use of resistant Arabica coffee (*Coffee arabica*) varieties is considered as the most economical control for coffee beery disease (CBD) and coffee leaf rust (CLR) in Tanzania. Currently the improved coffee varieties in Tanzania are propagated through the use of hybrid seeds, grafting and clones (cuttings) (TaCRI, 2011). Plants derived from hybrid seeds and grafting are characterised by deep and vigorous root systems on one hand while on the other hand plants derived from cuttings lack tap root (Partelli *et al.,* 2014). Therefore, despite the fact that the three methods are used for mass multiplication of improved coffee varieties, the observed difference in these types of seedlings may result into different response towards adverse environmental conditions.

The paper by Adjei-Nsiah *et al*. (2022) address Integrated soil fertility management as a credible pathway for building resilient systems to mitigate the adverse effect of climate change and boost agricultural productivity. Yet the results of this finding indicate that, organic manure was the most widely applied nutrient source. Moreover, soil fertility amendment practices in Tanzania involves application of 75-215 g of N.P.K (20:10:10), 60-175 g of Calcium Ammonium Nitrate (CAN)/ Ammonium Sulphate Nitrate (ASN) or 30-100g of urea per tree depending on production level of coffee tree and season of the year (short rain/long rain). Phosphates fertilizer (Triple

Superphosphate (TSP), Di ammonium Phosphate (DAP) or Single Superphosphate (SSP) in combination with 10 kg of farm yard manure (FYM) are used as planting fertilizer. Therefore, it is only at planting time that inorganic fertilizer is integrated with FYM. According to Stockdale *et al*. (2002) the use of inorganic fertilizers has significantly contributed to increased crop productivity while manure on the other hand, plays an important role in the soil by adding organic carbon and improving water holding capacity. For the case of irrigation practices, only about 17% of coffee farmers in the Northern and 5% in the Southern Highlands zone used irrigation practices in their coffee fields.

Therefore, this thesis establishes that, climate change has already impacted coffee production according to farmer's perception. Additionally, coffee growers in the Northern and Southern Highlands zones are willing and have the ability to adapt to climate change practices. Nevertheless, there is still a limited knowledge on the extent to which the current agronomic practices can bring about resilience of coffee cropping systems. It was therefore, important to quantify the perceptions of farmers with regards to the impact of climate change on coffee production using meteorological data from Tanzania Meteorological Agency (TMA) and official historical data from Tanzania Coffee Board.

6.1.2 Relationship between scientific climate change record and production records in the coffee growing area of Tanzania

6.1.2.1 Climate Variability

6.1.2.1.1 Rainfall

In chapter three of this thesis, it was established that the Northern Highlands zone of Tanzania was characterized by decline in long rains over the past 40 years. Shortening of rainy season caused by earlier cessation of rainfall in April and May was found to be the reasons for the decline in long rainfall. These findings correspond to previous studies on climate change in East Africa (Rowell *et al*., 2015; Wainwright *et al*., 2019). According to Liebmann *et al*. (2014) "long rains" season [March-May (MAM)] is a manifestation of a long-term decline in rainfall totals. Therefore, the decrease of long rains in the Northern Highlands zone has a direct link with the decline in annual

rainfall over the area The rapid warming of the Indian Ocean which causes an increase in convection and precipitation over the tropical Indian Ocean is suggested to be the link to the decrease in rainfall in this area (Lemma & Megersa, 2021). On the other hand, Arusha region has been experiencing an increase in rainfall during the short rain season. Extreme Indian Ocean Dipole (IOD) events which affect the short rainy season from October to December could be the reasons for the increase in rainfall during this short rain period (Limbu *et al*., 2019). Despite the fact that there has been no downward trend in the "short rains" [October-December (OND)], this season has continued to exhibit large year-to-year variability, which at times has exacerbated the impact of the long rains decline. This is where successful adaptation measures are critical (Wagner *et al.,* 2019). Furthermore, coffee-growing farmers, in the Southern Highlands zone are also confronted with reduced rainfall which occurs during the growing season and annually. However, as in Craparo *et al*. (2015), the decrease in rainfall in the Southern Highlands zone was not statistically significant.

6.1.2.1.2 Temperature

The findings of this thesis reveal further that, there have been increasing trends in monthly, seasonal, and annual temperature in the two zones with T_{min} increasing at a higher rate than T_{max}. These findings are in agreement with those from the Northern part of Tanzania (Craparo *et al.,* 2015), Ethiopia (Mekasha *et al.,* 2014), Kenya (Omondi *et al.,* 2014), and Uganda (Nsubuga *et al*., 2014) which reported that mean warming is primarily driven by substantial increases in the daily minima composition compared with daily maxima. Additionally, according to the observed results, the T_{mean} in the Northern and Southern Highlands zone of Tanzania seems to have reached the upper limit of the mean temperature bracket (18-21°C) suitable for coffee cultivation (Wrigley,1988).

6.1.2.2 Effect of Climate Change on Coffee Production

Results in chapter three of this thesis indicate that, the decline of coffee production in the Northern Highlands zone is linked to the decrease in long rains and the increase of T_{min}. Long rains are very important in reproductive phase of the coffee plant as it is during this period that the coffee berries need to expand and so rainfall is required to sustain berry development (Jassogne *et al.,* 2013). Therefore, the decline in long rains in the Northern Highland zone negatively affected coffee berries development. Furthermore, in the

Northern Highlands zone coffee crop enters the reproductive phase during the short rain season (October-December) and so the crop becomes more sensitive to temperature during this period. Generally, high night temperatures increase the rate of respiration so the assimilates which could be used for growth and yield are reduced (Bapuji Rao *et al*., 2014; Nagarajan *et al.,* 2010).

Drought and high temperatures during long rains period in the Kilimanjaro region will cause fruit abortions, increased bean defects, reduced berry growth, and acceleration of ripening, leading to a reduction in coffee yield and quality (Wagner *et al.,* 2021). The study of Craparo *et al.* (2015), reported similar findings that yield in the Northern Highlands zone is decreasing as the results of the increase in T_{min}, however, in their study, there was no relationship between yield decrease and decrease in long rains as observed in this study. According to the results of this thesis it was also established that coffee production in the Southern Highlands zone has not yet been affected by climate change impacts due to its positive correlation with temperature. Southern Highlands zone is characterized by low minimum temperature and maximum temperature during the months of June, July and August which could have reduced the negative impact of high temperature during the growing seasons. Despite the fact that increase in temperature did not affect coffee production in the Southern Highlands zone, continue increase in minimum temperature may cause coffee production to be affected in the future.

Generally, the results have conformed to the perceptions of farmers in the Northern and Southern Highlands zone reported in the second chapter of this thesis, that reduced rainfall and/or increase in temperature have resulted in coffee production decline. Therefore, this call for adaptation practices especially in the Northern Highlands zone where the impacts of climate change are significantly evident. The inclusion of more shade trees might help to reduce heat stress (Kajembe *et al.,* 2016), however, as already stated above conservation of heat during the night challenges the common notion that shade trees are always a beneficial aspect of climate change adaptation (Craparo *et al*., 2015). Other strategies may include, re-adapting the coffee agronomic practices to climate change, use of

technologies that will improve water and nutrient use efficiency in coffee trees, and developing genetically improved coffee varieties that will tolerate the impact of climate change. Limited knowledge on the extent to which the current agronomic practices can bring about resilience of coffee cropping systems reported in chapter 2 of this thesis made it important for another study to be conducted so as to evaluate the performance of some agronomic practices used by coffee farmers.

6.1.3 Field performance of compact coffee variety under selected propagation methods and soil fertility amendment practices in the Northern Zone, Tanzania

The use of vegetative propagules of *Coffeea arabica* has been an important tool for the large scale deployment of improved coffee varieties in Tanzania, following major achievements made by TaCRI in the development of improved coffee varieties that are resistant to coffee berry disease (CBD) and coffee leaf rust (CLR) for Arabica and coffee wilt disease (CWD) for Robusta (Teri *et al*., 2011). However, the field performance of cuttings and grafted propagated compact coffee variety have not been studied in details to guarantee their long term adoption.

6.1.3.1 Effects of Type of Seedling on Growth characteristics and Yield

Chapter 4 of this thesis have indicated cuttings propagated plants under the age of 4 years to be superior in terms of plants characteristics and yield compared to the grafted and seeds propagated plants. Plants propagated by cuttings were taller with the wider plant canopy and a greater number of primary branches than their counterparts. They also had a greater number of berry cluster and internodes. The superiority of cuttings propagated plants could be due to greater physiological maturity attained in these plants as compared to the other two types of seedlings. In an attempt to ensure that these types of seedling posses' roots of the same age cuttings propagated plants had more time to grow and accumulate biomass than grafted propagated plants which had to slow down during grafting process before it takes over again. Partelli*et al*. (2014), demonstrate similar findings when cuttings propagated plants were

compared with seed propagated plants. In their study they reported that, it is possible that at the time when the seedlings were established in the field, cuttings –propagated seedlings had enough reserve which was directed to produce biomass for the aerial pats, allowing cutting-propagated plants to excelled in all growth characteristics against the same grafted material. The superiority of cuttings propagated plants have also been reported by Weigel and Jurgens (2002). This paper demontrated that, cutting-propagation is physiologically viable and ensures maximum crop homogeneity, besides other desirable traits, especially grain maturation, fruit yield and size, and plant vigor. Contraly to what has been observed in this thesis, Andrade Junior *et al.*(2013) found conilon grafted plants to be superior to cuttings propagated plants. The difference in results between these two studies could be due to the methodolody taken to develop the seedlings, since according to Andrade Junior *et al.,* (2013), cuttings seedlings were established 90 days after the establishment of the rootstock. Therefore, at the moment of grafting on day 90, there was already a rootstock radicular system that have exhibited satisfactory growth, ensuring their expressive growth against the same clone materials.

The results of this thesis have also demonstrated that,cuttings propagated plants are characterised by un balanced plants growth biomass between the above ground parts and below ground parts (roots). For the case of cutings propagated plants the top is havier than the roots. Bragança *et al.* (2010) have also indicated that, few cuttings in the field have shown allometric growth, exhibiting uneven relationships between their aerial parts and radicular systems and in many cases resulting in the death of the plants. observed sigmoidal growth for conilon coffee where there is no balance between the foliar area and the total biomass of the plant have also been reported by Partelli*et al*. (2014). On the other hand, plants propagated through grafting and seeds propagation method resulted into a balanced plant biomass. According to Oliveira *et al*. (2004), grafting effectively enables a new balancing of the plant’s biomass with quick results in arabian coffee beans contributing to increased productivity.

6.1.3.2 Effects of Soil Fertility management practices on growth characteristics and Yield

The findings of this thesis have established that, 10 Kg of FYM when combined with half dose of inorganic fertilizer (37.5 g NPK) produced growth and yield characteristics that are comparable with the recommended inorganic fertilizer rates (75 g NPK). Chemura *et al*. (2014) and Nyalemegbe *et al*. (2009) observed similar findings when combined inorganic fertilizer and organic manure.

Despite the fact that chapter 4 of this thesis have demonstrated the superiority of cuttings propagated plants under current climatic conditions, their reciliancy to future climate change impacts have not yet been demonstrated. Using field experiment to predict such outcome is costfuly and time consuming especially for perennial crops like coffee. Moreover, yield stability cannot directly be measured in a single field experiment in a single year—it must be assessed based on measurements of yield over years and locations (Recklin*et al*., 2021). Crop growth models may be used to study the potential impacts of climate change on coffee productivity (Kasampalis *et al.*, 2018). Therefore another study which used crop growth model and future climatic data was done so as to determine the ability of type of seedlings and soil fertility managent practices in adapting arabica coffee to climate change.

6.1.4 The role of type of seedling and fertilizer management practices in adapting Arabica coffee to climate change in Tanzania.

6.1.4.1 Future climatic trends

The results of future (2025-2056) projections of temperature and rainfall over the Northern Highlands zone of Tanzania are presented under chapter 5 of this thesis. Projections made by RACMO22T-ICHEC-EARTH demonstrate an increase in temperature during the Near-term period (2026-2056) over the Northern Highlands zone. Furthermore, projections indicate that there will be higher increase of Tmin (1.36-1.64 °C) as compared to Tmax (1.01-1.20 °C) over the Northern highlands zone under Representative Concentration Pathway (RCP) 4.5. These results support the findings from other studies such as Chang'a *et al*. (2017); Craparo *et al*. (2015), (2021);

Luhanga *et al.* (2022) who indicated warming of nighttime temperature is higher compared to daytime temperature across several regions of Tanzania.

On the other hand, projections made by RACMO22T- ICHEC-EARTH indicate that during the Near-term period rainfall will be increasing by 13 % over the Northern Highlands zone. This is contrary to what have been observed in chapter 3 of this thesis, where a decline in annual rainfall (not significant) over the coffee -growing areas of the Northern Highlands zone of Tanzania for the four past decades (1979-2018) was observed. Nevertheless, the findings of this thesis support the findings by Omondi *et al.* (2014), which indicated general decrease in historical precipitation trends over East Africa.

6.1.4.2 Projections of Coffee Yields

Simulation results under RACMO22T- ICHEC-EARTH by 2056 under RCP 4.5 are presented in chapter 5 of this thesis**.** It is clear that the impacts of climate change on future coffee yields are considerably big in comparison with the simulated baseline yields in the Northern Highlands zone of Tanzania. Minimum temperature is attributed to the reduction of coffee yield in the Northern Highlands zone due to its high percentage increase. A previous study by Craparo *et al.* (2015) similarly observed that it is minimum temperature which determines the productivity and yield of coffee in the Northern Highlands zone of Tanzania. The findings in chapter 3 of this thesis indicate that 1 °C increase in minimum temperature significantly reduce coffee yield by 6,041 tonnes, so the projected increase in minimum temperature (1.36-1.64 °C) in the Near-term period (2026-2056) will obviously result into coffee yield reduction in the area. Results from the current study are in agreement with previous studies e.g., Bapuji Rao *et al.* (2014) and Nagarajan *et al.* (2010) which indicate that high increase in minimum temperature is detrimental in coffee production in the sense that; high night temperatures increase the rate of respiration so the assimilates which could be used for growth and yield are reduced. Moreover, Areas located at high altitude (>1500 m.a.s.l) are expected to have an increase in coffee yield due to the increase in minimum temperature. These findings are in consistency with that of Ovalle-Rivera *et al.* (2015) which indicate that, Tanzania and Uganda would

lose suitable area at elevations below 1400 m.a.s.l. Given that coffee production is generally affected by climate change, the presented results are important for the preparation of adaptation strategies from the projected climate change.

6.1.4.3 Adaptability to climate change through types of Seedling and Fertilizer Management practices

The findings from this thesis reveal that, plants propagated through cuttings, seeds and grafting respond differently to climate change. Cuttings and seeds propagated plants being more vulnerable to climate change (increase in temperature) than the grafted propagated plants. High vulnerability to climate change in these plants could be due to high Specific Leaf Area (SLA) which was observed in these plants. According to Grace (1990), SLA represents the amount of leaf surface area per unit of leaf mass that is available for water loss. Additionally, IPCC (2014), indicate that a first step towards adaptation to future climate change is reducing vulnerability and exposure to present climate variability. These findings are supported by the findings observed in chapter 4 of this thesis in which cuttings propagated plants showed un balanced plants biomass meaning the top was much heavier than the roots. These results are also supported by Bragança *et al.* (2010) and Partelli *et al*. (2014) who indicated that cuttings plants may fail to grow well in the field and even die due to uneven relationships between their aerial parts and radicular systems. Balanced plant biomass observed in grafted propagated plants agrees with the findings of Oliveira *et al*. (2004), which indicated that grafting propagation method effectively enables a new balancing of the plant's biomass with quick results in Arabian coffee beans contributing to increased productivity.

The finding from this thesis has indicated the comparative advantage of combining organic and inorganic sources of nutrients in attenuating the impact of climate change without jeopardizing the coffee yield. According to Chemura *et al.* (2013), apart from providing plants nutrients the integration also improves soil properties such as water holding capacity through additions of organic matter in the soil. Similar findings have also been reported by Maro and Mbwambo (2020). It was concluded that, climate change has had substantial

effect on cuttings and seeds propagated plants while grafted propagated plants are more resilient. Additionally, combined effect of organic and inorganic fertilizer can attenuate climate change effect.

CHAPTER SEVEN

7.0 GENERAL CONCLUSION AND RECOMMENDATIONS

7.1 Summary and General Conclusion

This work aimed at increasing coffee production sustainably through improved agronomic practices for adaptation to climate change in the Northern and Southern Highlands zones of Tanzania. The work was conceived in response to the decrease of coffee production and the climate change being hypothesized to be among the reasons for the decline in coffee production. Its conceptual framework was based on the assumption that effective research into an environmental problem facing farmers should start with the farmers themselves followed by verification by actual data. Once the concern is verified, approaches to address it are devised, tested and recommended as feedback to the community.

A series of activities was conducted in the two major Arabica coffee growing zones; northern highland zone (Kilimanjaro and Arusha regions) and southern highland zone (Songwe, Mbeya and Ruvuma regions). In these zones, coffee production is exclusively rainfed, whereas the Northern Highland zone is characterized by bimodal rainfall pattern while the southern highland zone experiences the uni-modal rainfall pattern. The perception of farmers as regards to climate change was assessed in order to verify if farmers have the feelings that there is a change in climate. Significant positive perception in terms of decrease in rainfall and increase in temperature was observed among the two zones' farmers; and that factor such as level of education, farming experience and access to climate information influenced farmers on how they perceive climate change. Additionally, farmers' perceptions were consistent with meteorological data both pointing to significant decline in rainfall and increase in temperature since 1979.

The impacts of current climate change on Tanzania's Arabica coffee production were then evaluated and most significant climatic variables, which influence coffee production in the respective regions, were determined. The findings established that, minimum temperature has been increasing at a higher rate than the maximum

temperature in the Northern and Southern Highlands zones. Therefore, the warming which has been observed in the two zones is caused by high rates of minimum temperature. Over the 40-year period (1979-2018), the Northern Highlands zone has experienced significant reduction in coffee yield as the result of climate change. In Kilimanjaro region, 1°C increase in minimum temperature during short rains significantly reduced coffee production by 6,041tons. The increase of mean temperature by 1 °C in Arusha region also reduced coffee production by 4 450 tons. The decline in the long rains in Kilimanjaro region has also caused significant reduction in coffee yield. In the Southern Highlands zone coffee production positively correlated with temperature over the 40-year period (1979-2018).

Field performance of cutting, seed and grafted propagated plants when combined with inorganic fertilizer alone or with integration of farmyard manure was done for 2.5 years in the Northern Highlands zone. Cuttings-propagated plants outperformed seed and grafted–propagated counterparts in all aspects (growth characteristics and yield). Cuttings-propagated plants had the highest yield during the study period ranging between 1800 -2800 green coffee $Kgha^{-1}$ at Burka site and 3 000-3 600 green coffee $Kgha^{-1}$ at Lyamungu site. The grafted-propagated plants had the lowest green coffee yield which ranged between 600-800 green coffee $Kgha^{-1}$ at Burka site and 700-1700 $Kgha^{-1}$at Lyamungu. Soil fertility management practices did not significantly affect growth characteristics, yield components and coffee yield between cuttings, seed and grafted –propagated plants. Generally, it is known that positive impacts of FYM application on crop yield and soil properties can be realized after a long-term application. The current finding from a single application of FYM in a 2.5 years' coffee crop has highlighted the potential of FYM in improving productivity of coffee

Identification of the best type of coffee seedling in adapting Arabica coffee to adverse conditions caused by climate change was done using DynACof model. The study made use of high-resolution climate simulation from Coordinated Regional Climate Downscaling Experiment program regional climate models (CORDEX-RCMs). Three CORDEX-Africa RCMs (SMHI-RCA4, KNMI- RACMO22T and

MPI-CSC-REMO2009) were downscaled dynamically from three GCMs; RCA4/CCCma-CanESM2, RACMO22T/ICHEC-EC-EARTH and REMO2009/MPI-M-MPI-ESM-LR RCM simulated daily rainfall, maximum and minimum temperature data were obtained from the CORDEX project. Projections indicate that during the Near-term period (2026-2056) rainfall will increase in Kilimanjaro region at the range of 0.2-13 % while in Arusha region the increase will be 6.05-13 %. T_{min} is expected to increase at the higher rate than T_{max} at the range of 1.4-1.48 °C in Kilimanjaro region and in Arusha region at the range of 1.36-1.64 ºC. The zone will also experience an increase in T_{max} at a range of 1.01-1.15 °C and 1.07-1.20 °C in Arusha and Kilimanjaro regions respectively.

The change in temperature will cause some areas in higher elevation to be warm especially due to increase in T_{min}. There will be reduction in coffee yield in Kilimanjaro and Arusha regions at the range of 2-40 % green coffee $Kgha^{-1}$ and 4-51 % $Kgha^{-1}$ respectively. The use of Cuttings and seed propagated coffee plants when combined with farmyard manure will result into 35 % yield reduction probably due to their characteristics of high Specific Leaf Area. On the other hand, projections indicate that, the use of grafted-propagated plants will cause 10 % yield reduction. Moreover, the use of half rates of recommended inorganic fertilizer with either 10 Kg FYM or 20 Kg FYM has no significant difference in attenuating the impact of climate change.

Based on the above summary of results, the following conclusions were made:

i. During the last 40 years, coffee farmers from the Northern and Southern Highlands zone of Tanzania have experienced changes in climate i.e., increase in temperature and decrease in rainfall.

ii. The rise in minimum temperature and decline in long rains has significantly affected coffee production in the Northern Highlands zone.

iii. The Southern Highlands zone, on the other hand, has not yet suffered from the impact of climate change. Nevertheless,

minimum temperature is increasing at a higher rate in the area and it may affect the production of coffee shortly.

iv. Smallholder farmers have been responding to un-predictable weather patterns in different ways with their level of response being influenced by the, education level, farming experience, access to extension services, and time aware of climate change information.

v. Tmin is expected to increase in the Near-term period (2026-2056) at the range of 1.4-1.48 °C in Kilimanjaro region and in Arusha region at the range of 1.36-1.64 °C.

vi. Integrated nutrients sources are able to provide sufficient nutrients to the three types of seedlings (cuttings, grafting and seed) for healthy coffee growth just as the recommended rates of inorganic fertilizer.

vii. Cuttings-propagated plants under the age of four years with the same rooting age as seed and grafted plants perform better in the field than seeds and grafted propagated plants by producing plants with better characteristics in terms of; plant height, plant vigour, canopy width, number of berry cluster, number of internodes and number of primary branches.

viii. The yield of cutting propagated plants under the age of four years if established at the same time with seeds and grafted propagated plants is significantly higher than that of seed and grafted-propagated coffee plants.

ix. The presence of tap-root (seeds and grafts) or lack thereof (cuttings) has little effect if any on growth and yield of Arabica coffee under the age of 4 years.

x. Grafted propagated plants are more resilient to climate change.

xi. Combined effect of organic and inorganic fertilizer attenuate climate change effect.

7.2 Recommendations

From the findings of this work, the following recommendations were made:

i. Integrated soil fertility management (37.5 g N.P.K +10 Kg FYM) tree^{-1}to be used as one of the adaptation strategies because apart from providing nutrients to the coffee plants the package also helps in improving water retention properties of the soil.

ii. Seedling distribution should be location specific, with cuttings-propagated plants being distributed in areas with rainfall above 1200 mm year^{-1}.

iii. A longer experimental period to be conducted to satisfactorily monitor the response of the types of seedlings propagated through seed, grafting and cuttings above the age of four years assuming that at a later age the coffee tree will have reached its maximum production and so more nutrients and water will be required.

iv. Considering uncertainties which are associated with crop modeling further improvement to the model is recommended for DynACof model to be able to deal with coffee tree from various propagation techniques.

v. The findings hold significant policy implications for enhancing coffee production in regions affected by climate change. Policymakers should enhance timely and accurate weather information delivery along with developing institutions responsible for education and extension services provision. Multiplication and adoption of improved coffee varieties has to be enhanced and promoted by the policymaker. By promoting adoption of improved coffee varieties policymakers can enhance farmers' adaptive capacity and reduce the vulnerability of coffee production to climate-related risks.

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APPENDECES

Appendix A2. 1. Demographic characteristics of farmers from two major coffee-growing zones (%)

	Northern Highlands zone					Southern Highlands zone	
	Arumeru (n= 34)	Hai (n =27)	Moshi (n =41)	Rombo (n=30)	Siha (n=29)	Mbinga (n =41)	Mbozi (n =40)
Age (years)							
41–50	44	15	24	13	34	39	45
51–60	32	33	12	37	28	49	42.5
61–70	15	41	29	23	21	5	12.5
70–80	9	7	24	20	7	7	0
> 80	0	4	10	7	10	0	0
Farm size (ha)							
<0.5	59	24	53	41	29	15	18
0.5–1	26	38	41	29	44	47	29
1.2–1.4	3	6	15	18	6	18	38
1.5–2	6	12	9	0	3	15	32
>2	6	0	3	0	3	26	0
Education level							
No formal education	18	4	7	13	14	2	0
STD 1-VII	62	59	73	60	76	78	77.5
Form I-IV	0	26	12	7	7	7	20
Form V-VI	6	4	0	0	0	0	0
College	9	4	2	0	0	0	0
University	0	0	2	3	0	0	0
Farming experience (Years)							
10–19	21	15	10	13	21	12	18
20–29	32	30	22	33	34	44	43
30–39	29	11	32	20	21	37	25
40–49	12	33	24	20	17	0	15
>50	6	11	12	13	7	7	0
Sex of the respondent							
Male	88	78	73	77	79	71	78
Female	12	22	24	23	21	29	22

n = Number of households

Appendix A3.1: Summary of seasonal and annual rainfall and temperature statistics for study regions

		Regions			
		Kilimanjaro	**Arusha**	**Mbeya/ Songwe**	**Ruvuma**
Rainfall (mm)	Mean	1435.77	733.4	1306.09	1203.74
	STD	333.93	171.55	203.79	166.2
Temperature (^{o} C)	Mean	19.67	20.3	19.44	21.44
	STD	0.329	0.285	0.301	0.319
	Tmax	24.78	26.04	25.25	26.62
	STD	0.346	0.442	0.442	0.414
	Tmin	14.56	14.73	13.04	16.00
	STD	0.36	0.362	0.292	0.32

Note. STD = Standard deviation, T_{MIN} = Minimum temperature, T_{MAX}= Maximum temperature.

Appe ndix A5.1: Soil data

Study sites	Lat.	Long.	Elev.	Soil depth (mm)	% SAND	% CLAY	% OC	Texture	Pore fraction
K01	3.2	37.23	1623	0-1.25	42	15.8	2.7	Loam	0.47
				1.25-1.75	24	35.2	1.4	clay loam	0.46
KO2	3.3	37.30	1167	0-1.25	35.1	32.9	2.9	clay loam	0.46
				1.25-1.75	31.7	31.7	1.7	clay loam	0.46
K03	3.014	37.56	1731	0-1.25	33.3	31.5	3.4	Clay loam	0.46
				1.25-1.75	39.3	31.8	2	Clay loam	0.46
K04	3.38	37.53	1037	0-1.25	31.3	21.9	1.9	loam	0.47
				1.25-1.75	35.7	20.3	0.9	loam	0.47
K05	3.24	37.25	1296	0-1.25	43	18	3.17	loam	0.47
				1.25-1.75	48	19.9	1.99	loam	0.47
KO6	3.16	37.05	1355	0-1.25	58	12	2.3	Sandy loam	0.45
				1.25-1.75	56	8	3.3	Sandy loam	0.45
KO7	3.21	37.07	1245	0-1.25	31.3	21.9	1.9	loam	0.47
				1.25-1.75	35.7	20.3	0.9	loam	0.47
KO8	3.33	37.42	1075	0-1.25	31.3	21.9	1.9	loam	0.47
				1.25-1.75	35.7	20.3	0.9	loam	0.47
KO9	3.3	37.65	1019	0-1.25	27.2	37.4	6	Clay loam	0.47
				1.25-1.75	23.9	44.5	5	Clay	0.47
				1.75-3.75	20.7	47.3	4	Clay	0.47
K10	3.3	37.69	1003	0-1.25	50	23	0.8	Sandy clay loam	0.4
				1.25-1.75	55	23	1.9	Sandy clay loam	0.4
K11	3.25	37.26	1309	0-1.25	43	18	3.17	loam	0.47
				1.25-1.75	48	19.9	1.99	loam	0.47
				1.75-3.75	35	44	0.98	clay	0.47
K12	3.06	36.99	2100	0-1.25	47.4	24.3	5.68	loam	0.47
				1.25-1.75	44	28.5	4.65	Clay loam	0.46

A01	3.4	35.47	1660	0-1.25	20	46	1.6	Clay	0.47
				1.25-1.75	20	46	1.2	Clay	0.47
A02	3.35	35.60	1595	0-1.25	6	72	1.6	Clay	0.47
				1.25-1.75	4	75	1.2	Clay	0.47
A03	3.369	36.64	1437	0-1.25	58	12	2.3	Sandy loam	0.45
				1.25-1.75	56	8	3.3	Sandy loam	0.45
A04	2.96	37.00	1321	0-1.25	38	40	6	Clay	0.47
				1.25-1.75	40	32	5	Clay	0.47
AO5	2.96	36.84	1185	0-1.25	38	40	6	clay	0.47
				1.25-1.75	40	32	5	clay	0.47
AO6	3.05	36.85	1337	0-1.25	47.4	24.3	5.68	loam	0.47
				1.25-1.75	44	28.5	4.65	Clay loam	0.46
AO7	3.33	35.65	1535	0-1.25	70	10	2.3	Sandy loam	0.45
				1.25-1.75	77	11	3.3	Sandy loam	0.45
AO8	3.34	35.68	1537	0-1.25	8	60	6	Clay	0.47
				1.25-1.75	7	53	5	Clay	0.47
AO9	3.31	35.67	1618	0-1.25	8	60	6	Clay	0.47
				1.25-1.75	7	53	5	Clay	0.47
				1.75-3.75	30	46	4	Clay	0.47
A10	3.41	36.77	1388	0-1.25	44	38	2.3	Clay loam	0.46
				1.25-1.75	43	24	3.3	loam	0.47
				1.75-3.75	35	35	2.8	Clay loam	0.46
A11	3.4	36.85	1150	0-1.25	54.8	9.2	2.3	Sandy loam	0.45
				1.25-1.75	54.8	9.2	3.3	Sandy loam	0.45
A12	3.43	36.78	1216	0-1.25	58	12	2.3	Sandy loam	0.45
				1.25-1.75	56	8	3.3	Sandy loam	0.45

Appendix B5. 1: Coffee data

Parameter	Unit	Value	Description	Source
Stocking Coffee	Plat /ha	3333	Coffee initial planting density	This study
AgeCoffeeMin	Year	1	Minimum age of coffee plants	Vezy *et al*., 2020
Agecof Max	Year	40	Maximum length of plantation cycle	Vezy *et al*., 2020
Specific Leaf Area		30	Cuttings plants + Inorganic fertilizer	This study
		25	Cuttings plants + Half inor+10Kg FYM	
		30	Cuttings plants + Half inor+20Kg FYM	
		10	Grafting + Inorganic fertilizer	
		8	Grafting + 10 Kg FYM	
		8	Grafting +20 Kg of manure	
		20	Seed plants +Inorganic fertilizer	
		13	Seed plants + Half inor+10Kg FYM	
		25	Seed plants + Half inor+20Kg FYM	
Leaf Width		0.062	Grafting	
		0.057	Cutting	
		0.059	Seed	This study
DVG1	DOY	109	Beginning of vegetative growth	This study
DVG2	DOY	351	End of vegetative growth	This study
Max-Bud Break		35	Cuttings plants + Inorganic fertilizer	
		35	Cuttings plants + Half inor+10Kg FYM	
		35	Cuttings plants + Half inor+20Kg FYM	
		16	Grafting + Inorganic fertilizer	
		16	Grafting + 10 Kg FYM	
		16	Grafting +20 Kg of manure	
		16	Seed plants +Inorganic fertilizer	
		16	Seed plants + Half inor+10Kg FYM	
		16	Seed plants + Half inor+20Kg FYM	
Age Maturity		3	First age of flowering after planting	This study