# PERFORMANCE AND WATER PRODUCTIVITY OF SELECTED SWEET POTATO (*Ipomoea batatas L*) VARIETIES INTERCROPPED WITH COMMON BEANS IN KATUMANI - KENYA

**BY**

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**2021**

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This thesis is my original work and has not been presented for the award of a degree in any other university.

Signature ____________ Date 13$^{TH}$ November 2021

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This thesis has been submitted for examination with our approval as university supervisors.

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**Performance and water productivity of selected sweet potato (*Ipomoea batatas L.*) varieties intercropped with common beans in Katumani - Kenya**

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# DEDICATION

To my father and mother, Mr. and Mrs. Mbayaki, Melvin, and Joshua, for their unwavering support and motivation throughout the entire study.

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## ABBREVIATIONS AND ACRONYMS

AI- Aridity Index

APSIM- Agricultural production systems simulator

ASALS- Arid and Semi-Arid Lands

CROPWAT- Crop Water Allocator model

CWP- Crop Water Productivity

CWR- Crop Water Requirements

DSSAT-Decision Support Tool for Agrotechnology Transfer

DST-Decision Support Tool

ET-Evapotranspiration

FAO- Food and Agriculture Organisation of the United Nations

GCM- Global Circulation Model

GDP -Gross Domestic Product

HI- Harvest Index

ISAREG-Irrigation Scheduling model

KALRO – Kenya Agricultural and Livestock Research Organisation

LAI- Leaf Area Index

LER- Land Equivalent Ratio

RCP - Relative Concentration Pathway

SPAC- Soil plant atmosphere continuum

SWB- Soil Water Balance

WU- Water Use

WUE - water use efficiency

# GENERAL ABSTRACT

The main deterrent factors for achieving sustainable agricultural production in Eastern Kenya are irregular rainfall and low available water capacity. Knowledge on crop performance, water needs and optimization of deficit irrigation schedules would therefore help to minimize water stress and thus increase ASALs' achievable yields. The study was undertaken for two short rainy seasons of S(i); 2018 and S(ii) 2019, respectively at KALRO-research station in Katumani, Machakos County. The objectives were; to assess the performance, growth, yield and water use efficiencies of two sweet potato varieties in sole and intercrop systems as well as to predict the implications of climate change on sweet potato water needs and scheduling irrigation water using CROPWAT model version 8.0 from 2019 to 2039 based on a rainwater discrepancy. The trials were established as a Randomised Complete Block Design with three replications acting as blocks and five treatments comprising of: (i) V1; Kabode (orange-fleshed), (ii) V2; Bungoma (white-fleshed), (iii) B1; Sole common beans (*Miezi miwili*), (iv) V1M; Kabode + common beans and (v) V2M; Bungoma + common beans. Sweet potato was the main crop of interest. Intercropping with common beans significantly ($p < 0.05$) reduced the yields of Kabode and Bungoma varieties by 18.4 and 32.0 %, respectively. Sole cropping of Kabode variety yielded 31.4 t ha$^{-1}$ significantly ($p < 0.05$) higher than monocropped Bungoma with 23.9 t ha$^{-1}$ whereas, ones intercropped with common bean yielded 26.2 and 18.1 t ha$^{-1}$ respectively. Similarly, the percentage of land saved by intercropping varied from 8 to 33%. Aridity Indices (AI) in seasons (i) and (ii) were 0.4 and 1.2, respectively and contributed to shortening and lengthening of the humid periods. The total and readily available water within the soil profile were 330.4 and 214.7 mm, respectively. In addition, data from the test crops showed water use efficiency values of 39.8 and 30.0 kg ha$^{-1}$ mm$^{-1}$ and rain water productivity indices of 1.11 and 0.95 kg m$^{-3}$ for Kabode and Bungoma varieties, respectively. The baseline climate 1991-2016, current and the projected climate scenario for 2020-2039 water requirements were modelled at 579.9 and 634.1 mm, respectively thus generating a 10.2% increase in the overall sweet potato water requirement. A 0.9 yield response (Ky) was modelled to be experienced on the baseline and projected scenarios, thus 452.3 and 500.4mm supplemental irrigation water requirement for optimal yields. Variety adaptability among the test crops instituted Kabode’s acceptability within the warm-dry and warm-wet climates of the study area.

Keywords: Sweet potato, intercropping, water use efficiency, crop water requirements, climate change

# CHAPTER ONE

# GENERAL INTRODUCTION

## 1.1 Background information

The world's most critical problems are chronic food shortages and water scarcity (Brown, 2012). This are expected to worsen in the future as population increase, agricultural intensification, and industrialization put additional pressure on land and water supplies, contributing to climate change (Smith et al., 2014; Mancosu et al., 2015). Thus, the challenge in food production for the population has necessitated the development of precise methods to curb such demand (Cosgrove and Loucks, 2015).

In regions where rainfall is inadequate, water stress is one of the most significant constraints to crop production aggravated by climate change (Hsiao et al., 2009). Climate change affects crop growth and yields, as well as the soil water balance, primarily by changing soil evaporation and transpiration rates in plants (Kang et al., 2009; Rockström, 2003). Irrigation is the primary user of water resources in Kenya (Campbell et al., 2000; Nyika et al., 2016; Chuchird et al., 2017). Climate change seems to have altered hydrological cycles and water resources, resulting in lower agricultural productivity (Simonovic, 2017). Crop growing cycles differ as a result of the intensity and distribution of rainfall events (Iizumi and Ramankuty, 2015). Water shortage reduces crop water consumption (ETcrop), resulting in low photosynthetic activity and consequently, low yields in rain-fed agriculture. The actual crop evapotranspiration (ETa) is the amount of water required to meet the on lost via evapotranspiration. As a result, determining the plants' ability to respond to climate change is important (Amedie, 2013; Iizumi and Ramankuty, 2015).

Water Use Efficiency is described as the amount of plant biomass generated per unit of water consumed (De Pascale et al., 2011). Equally, Karuku et al. (2014) and Koech et al. (2015) defined WUE as the highest yield obtained in relation to the amount of water used, expressed as the amount of evapotranspiration (ET) or transpiration. Fischer et al. (2019) define ET as an estimate of the amount of water used in the Soil-Plant-Atmosphere Continuum (SPAC). Johnson et al. (2018) also listed the difficulties in obtaining transpiration (T) under standard operating conditions. Because not all of the rainfall received is used to create biomass, transpiration can be determined by subtracting evaporation (E) from the water balance and measuring E with a microlysimeter (Kinama et al., 2005). Evaporation is a component of ET that is not used in the creation of biomass. On the contrary, Kinama et al. (2007) indicated that T can be influenced by daily atmospheric conditions, rainfall and drainage quantity, and soil E. Crop water use (CWU) studies can be performed using the energy balance and the soil water balance (SWB). The SWB is dependent on rainfall, drainage, and the capacity of the soil to retain water. Further, its reliant on runoff, irrigation, and the soil's ability to absorb water. Improving crop water productivity is dependent on conserving soil water and maximizing its use efficiency (WUE), all of which contribute to crop productivity (De Pascale et al., 2011; Masango, 2014; Gitari et al., 2018). Similarly, Karuku et al. (2014) reported high WUE by using crop management strategies including mulching, intercropping, and surplus irrigation.

Sweet potato (*Ipomoea batatas L*) is a starchy and tuberous dicotyledonous crop originating from South America and has since rapidly spread to other parts of the world (Lusweti, 1994). It is grown in the tropics and subtropics, and its annual production is estimated to be about 123 million tonnes. Sweet potato is the 7th most important crop in the world, preceding maize, soybeans, wheat, cassava, potato and rice (FAO, 2006). After maize, potato, and cassava, it ranks third in Eastern and Southern Africa (Prabawardani and Suparno, 2015). Busia, Kakamega, Homabay, Kisii and sections of the Central and Coastal counties of Kenya grow it. (Kundu et al., 2013). Sweet potato is a C3 plant having considerable phenotypic plasticity that has adapted to drought-prone environments. The tendency of sweet potatoes to adapt their systems in response to environmental changes is referred to as phenotypic plasticity (Motsa et al., 2015).

Intercropping is a traditional cropping pattern used by smallholder farmers in Sub-Saharan Africa to increase productivity over a small field (Sitienei et al., 2017; Kwena et al., 2018). In Kenya, common beans are essential crops with the potential to improve productivity in a variety of cropping patterns (Biamah, 2005). Several experiments have shown the advantages of intercropping crops with legumes (Kiseve, 2012; Gitari et al., 2018). The biggest advantage is that it allows the best use of finite resources while yielding high returns (Mobasser et al., 2014). The purpose of this research is to evaluate water productivity and relative performance of two sweet potato varieties intercropped with common beans in the ASALs of Eastern Kenya.

## 1.2 Statement of the problem

Agriculture accounts for more than half of Kenyan families with their primary source of revenue, accounting for roughly 30% of the country's Gross Domestic Product (GDP) and is thus referred to as the country's backbone (Salami et al., 2010). Crop production, on the other hand, is inextricably tied to climatic conditions, making it the most vulnerable economic sector to weather and climate change (Chukaliev, 2016). Rain-fed agriculture crops experience water stress during development given the uncertainty of rainfall, reducing their growth activity and yield potential (Mgcibelo, 2014). Water shortages, irregular rainfall, and a lack of sufficient water capacity are major impediments to achieving long-term agricultural production in Eastern Kenya. As a result, smallholder farmers in Kenya's ASALs face seasonal lotteries when it comes to timing their crops for short rainy periods, and crop failures and famines are not uncommon. This means that crop yield in the semi-arid areas of Eastern Kenya is largely water-limited.

Legumes have the ability to increase soil fertility in a number of cropping systems, including sweet potato intercropping, when used as a companion crop (Jalilian et al., 2017; Stagnari et al., 2017). Nonetheless, intercropping sweet potato with legume crops is not popular in the semiarid regions of Eastern Kenya. Preceding research hasn't gone into great detail about the benefits of intercropping sweet potatoes with legumes. Ossom and Rhykerd (2007) observed no major variations in yields when sweet potato was intercropped with maize, but there is still lack of knowledge on sweet potato water use under various cropping systems. More data on productivity, water use efficiency, yields, and economic returns from intercropping are needed. When compared to yellow fleshed sweet potato in the ASALs, orange fleshed sweet potato provides a higher supply of dietary carotenoids; however, its drought weakness is a significant obstacle to its growth and acceptance (Tumwegamire, 2004).

Soil water stress is a major hindrance in crop production especially in the ASALs whereas its effects are envisaged on the physiological and biochemical processes of plants (Muli, 2015). Plant quality and yields could be hampered by poor crop and water management (Fan et al., 2012). CWR are a vital constituent to warrant better scheduling of irrigation a factor that has been researched on different crops all over the world. However, changes in temperature, crop varieties, and crop growth conditions have made it difficult to extend the numerous research findings from beyond Katumani and other ASALs in Kenya. There is a scarcity of knowledge on sweet potato water requirements and soil hydraulic properties, especially in the semi-arid region of Machakos. Modelling is thus needed for estimating sweet potato water requirements, predicting and analysing yield capacity, and scheduling irrigation.

## 1.3 Justification

Sweet potatoes lead to the realization of the Ministries of Agriculture and Health's Agri-nutrition agenda through meeting dietary criteria targeted at decreasing the degree of malnutrition among households. Because of its low sodium and cholesterol content, the crop has a high nutritional value. It also contains dietary fibre, beta carotene, vitamin B6, potassium and vitamins; A, C and Manganese.

As the world's population grows, soil quality remains a major problem in agriculture and indeed the findings of this study were meant to assist smallholder farmers in managing water and maximizing crop yields. Understanding the use of agricultural irrigation is also a crucial choice factor in drought-prone regions. Crop water productivity is a crucial requirement for increased agricultural production because crop water is needed to substitute for water loss by transpiration and soil evaporation. The quantification of sweet potato water use generated site-specific data that will facilitate land use planning to conserve water required to fulfil crop water needs. Improving awareness of the criteria for sweet potato water needs is a critical feature of maximizing irrigation schedules and thereby allowing smallholder farmers to raise crop yields under varied water supply. Using the CROPWAT model, supplementary irrigation and irrigation schedules were established to mitigate water stress based on a rainwater deficit analysis. The model was critical in predicting crop water needs, which aided in the collection of data for policy formulation, particularly in locations where water scarcity is a concern. Understanding the degree to which water is consumed by crops at different growth phases is necessary for improving water use efficiency, which entails the creation of a practical and simplified irrigation schedule for the irrigated area. The use of a crop simulation model allowed smallholder farmers to broaden their approaches for reducing the hazards and risks associated with rainfall fluctuations. As a result, smallholder farmers require knowledge to assist them in making better use of available rainwater, such as coordinating crop growth phases with rainy season timings. This aided in the productive usage of this limited resource and increased the yields achievable in Katumani, Kenya. Sweet potato cropping systems were crucial in resolving the lack of arable land, improving farmer earnings, and encouraging sustainable natural resource use.

## 1.4 Objectives

### 1.4.1 Overall objective

Contribute to the long-term production of sweet potatoes and the overall food situation in Kenya by implementing cropping patterns that minimize soil water loss, maximize water consumption, and ensure optimum yields.

### 1.4.2 Specific objectives

1. To compare the growth, yields and competitiveness of orange (Kabode) and white fleshed (Bungoma) sweet potato varieties in sole and intercrop systems.
2. To examine the effect of soil hydraulic properties on crop water productivity in orange and white fleshed sweet potato varieties intercropped with common beans in rain-fed conditions.
3. To use the CROPWAT model to predict the effect of climate change on crop water requirements and irrigation scheduling for direct sown rain-fed sweet potato (Ipomoea batatas L.) in Katumani, Kenya for the next 20 years.

## 1.5 Hypotheses

1. The kind of cropping system has little impact on the growth and yields of orange and white-fleshed sweet potato varieties.
2. All orange and white-fleshed sweet potatoes require the same amount of water.
3. Sweet potato yields and water needs will not vary in the near future under rainfed conditions.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Drought in terms of crop production: growth and yields

Biological and ecological stress have overt and indirect effect on crop production (Oshunsanya et al., 2019). Insect pests, weeds and viruses are examples of biotic factors, while abiotic factors include low soil fertility, salinity and sodocity, droughts, soil contamination high temperatures and floods. Drought is mainly classified based on meteorological, hydrological, agricultural, and socioeconomic factors (Wilhite and Glantz, 1985). The first three techniques are concerned with determining how to quantify drought as a physical event. The latter examines drought in terms of supply and demand, tracing the consequences of water scarcity and its ramifications across socioeconomic systems. Agricultural drought is a common occurrence in most Sub-Saharan African (SSA) countries, and it is caused by a lack of water during agricultural production periods, leading to water stress (Heisey and Edmeades, 1999). Drought in agriculture is defined as a decline in soil moisture availability to plants that has a negative impact on crop productivity and, as a result, on agricultural profitability. It primarily focuses on rainfall deficiencies, evapotranspiration discrepancies between actual and potential, and soil water deficits (Holman et al., 2021). Drought, as a result of water stress, influences the morpho-physiological characteristics of sweet potatoes while also restricting their photosynthetic rate through diffusive stomatal conductance (Ashraf and Harris, 2013; Kapoor et al., 2020). Water stress, according to Blum (2009), has the potential to limit crop growth by inhibiting the production of lateral buds and restricting the expansion of other plant components. Water deficit impacts sweet potato yields and physiological development, according to Belehu (2005). Laurie and Magoro (2008) reported sweet potato yield of approximately 3.9-9.5 t $ha^{-1}$ on communal drought-prone gardens versus 25.2 t $ha^{-1}$ at experimental humid stations in South Africa, confirming the existence of a yield gap between low and well-endowed habitats. Nugroho and Widaryanto (2017) investigated sweet potato development during the rainy season in India and yielded roughly 44.76 t $ha^{-1}$, while Mwololo et al. (2012) reported sweet potato yield varying from 8.9-32 t $ha^{-1}$ in the semi-arid areas of eastern and coastal Kenya, owing to the low amount of rainfall obtained in the two regions. This shows that shortage of rainfall is a major constraint in crop production, challenging the abolition of food security in developing countries.

### 2.1.1 Water stress

Water shortage, among other things, is a challenge to combating global food insecurity, especially in African (Farooq et al., 2009). Discrepancies in crop productivity and attainable yields arise as a result of variations in water accessibility and crop water consumption. The presence of soil water is vital to sweet potato production, since it is susceptible to water disparity, specially at establishment; which includes vine growth, and at the reproductive stage, that includes tuber initiation and bulking (Gajanayake et al., 2013). Agro-climatic and soil water levels influence root growth and yield. Stomatal closure is the main tool for water management when the vines are experiencing water deficits, thus reducing the crops photosynthetic and vine growth rate (Smart and Coombe, 1983). Sweet potato roots, unlike cereals, can survive dormancy during dry periods or in unfavourable climatic environments and then resume growth when the conditions improve (Ravi et al., 2009). Water stress during the early stages of development is harmful to sweet potatoes, affecting their growth, development, and final tuber yield (Gajanayake et al, 2013). Low volumetric soil water content and drought conditions or lack of precipitation events retard storage root development, especially at the tuber bulking level, and therefore final tuber yield can decrease significantly as the crop grows (Thompson et al., 1992).

Gomes and Carr (2003) investigated the impact of water accessibility and vine harvesting frequency on sweet potato productive output in Mozambique and found that water consumption ranged from 360 to 800 mm during the growing season. According to the researchers, even mild pressures diminish the intensity of leaf expansion during the vegetative growth stage of most crops, reducing the leaf area and index. According to other researches, sweet potato consumes approximately 500 mm (Norman et al., 1984); 300 mm in Cuba (Castellanos,1984) and 450 mm in Nigeria (Onyekwere and Okafor, 1992). Sweet potato water needs vary with the amount of rainfall received as Gomes and Carr (2003) in Mozambique reported that during the rainy season was 800 mm, whereas it was limited to only 550 mm under drought conditions. Prolonged water stress tends to inhibit root development thus leading to shorter or misshapen roots. Nonetheless, crop performance is when the soil is kept moist at all times: below field capacity (wet but completely drained) and above wilting point (Mintz and Walker, 1993).

### 2.1.2 Physiological response of sweet potato to drought and water stress

Sweet potato is a drought-tolerant crop that responds differently to drought stress, accounting for only 25% of yearly overall production losses, compared to 50% yield loss or complete failure in staple crops such as maize (Kivuva, 2013; Oerke and Dehne, 2004). As a C3 plant, sweet potato colonises easily drought-prone environment since they pose high phenotypic plasticity, indicating its ability to alter its characteristics to acclimatize to such conditions. In most C3 plants, all photosynthetic cells are functionally equivalent, thus allowing each cell to acclimatize to new environments more autonomously than C4 plants. Because of this, photosynthetic plasticity can occur in the cell rather than the tissue, resulting in increased acclimation capacity in C3 plants. C3 metabolism necessitates its classification as a drought-tolerant crop (Xoconostle-Cazares et al., 2010). This implies that photosynthetic plasticity and assimilation result in better yields, which may also explain why sweet potato is more adaptable than conventional C4 plants.

## 2.2 Water use, efficiency and productivity

Water use (WU), productivity (WP), and efficiency (WUE) are distinct terms with considerable overlap, but they are occasionally used simultaneously. WUE is the amount of water used in a crop production system, as measured by crop growth indices. Crop water productivity (CWP) is an important concept in agronomy since it seeks to increase achievable yields per unit of water used in both rain-fed and irrigated agricultural production. WP can be accomplished through; a) crop marketable yields per unit of transpired water, b) reducing the amount of water lost from the soil water balance, and c) maximizing the utilization of rain water in the soil. WU and WUE all refer to CWP and are frequently used synonymously. WP is similar to WUE and can be found interchangeably, according to literature going back to the 1960s. Furthermore, Passioura (2006) stated that WUE was dependent on: i) the capability of the soil to capture and store water; ii) the crop's ability to take water from the soil during its growth phase; and iii) the efficiency with which water is converted to plant biomass.

### 2.2.1 Crop water use

Crop water use (CWU) is another term for evapotranspiration (ETc), which is the amount of water loss by evaporation from the soil surface and transpiration from plant leaves. The amount of water loss by the plant to the atmosphere by the stomata is referred to as evapotranspiration. Water is used in the growth process as well as a coolant during the transpiration (Molden, 1997). CWU is linked to the relations of plant roots, their ability to sift water from the surface, and the canopy's ability to effectively transpire the extracted water to the atmosphere (Morris and Garrity, 1993).

Having a sufficient level of water in the soil during the crop's growing time is critical to achieving optimal production; this refers to the amount of yield that comes from the amount of water present in the soil (Al-Kaisi and Broner, 2009). Since the soil has less matric capacity after drying, the plants use a lot of energy removing water from the soil, energy that could otherwise be used for other biochemical processes (Karuku et al., 2014). Furthermore, as soil water levels fall below field capacity, crops utilize less water, resulting in a water-stressed situation wherein the leaves and stems development decreases. Similarly, where there is insufficient water supply, expansion and division cells is slowed, thus affecting enzymes and protein development, both of which are required for development (Fahad et al., 2017).

### 2.2.2 Water use efficiency (WUE)

WUE, which indicates the amount of dry matter generated per unit of water used up in evapotranspiration, is used to quantify agricultural productivity in water-stressed areas (Molden, 1997). WUE is a useful metabolic mechanism that allows plants to resist low soil moisture content and perform well under water stress. It is characterized as total biomass generated per unit area to evapotranspiration (Shao et al., 2008). Evaporation of water from interstitial tissues of leaves happens in crops cultivated in ASALs owing to water evaporation from interstitial tissues of leaves anytime stomata open for $CO_2$ absorption, resulting in an intrinsic trade-off between carbon fixation and water depletion (Bramley et al., 2013).

Simulations on WUE have been performed all over the world, particularly on cereals and legumes, concerning monocrop and intercrop, providing substantial data on the crops' WUE and aiding in the identification of drought tolerance traits (Juma, 2012). Under severe drought, certain characteristics are important such as breeding improved WUE crops.

Physiological features that lead to higher production under mild-moderate drought might be the focus of such operations. Improvements in water consumption, water-use efficiency, and harvest index can all help crops perform better (Araus et al., 2002). Similarly, the first factor is important when soil water is available until crop maturity or when deep-rooted genotypes have access to water within the soil profile that is not normally available; the latter two conditions become even more important when all available water is depleted by the end of the crop cycle. WUE is increased by agronomic approaches aimed at limiting water losses and successfully transferring water towards the roots. Furthermore, growing WUE requires regulating physiological processes that disrupt seed transpiration and yields (Hsiao and Bradford, 1983).

Masango (2014) researching in drought prone regions of South African showed that WUE improved by reducing the volume of water used up by sweet potato. WUE values ranged between 64.8 - 97.5 kg ha$^{-1}$ mm$^{-1}$ under irrigation, whereas Onder et al. (2005) had values ranging from 33.2 -75.9 kg ha$^{-1}$ mm-$^{1}$. This symbolises that crops parade higher WUE values under low or limited water supply. Gomes and Carr (2003) on the other hand in Mozambique deduced that under irrigated conditions, sweet potato had WUE of 85 kg ha$^{-1}$ mm$^{-1}$. Supplemental irrigation practices are beneficial in such cases for optimizing WUE, especially during the most susceptible phenological stages of sweet potato development, such as tuber bulking (Dalla Costa and Giovanardi, 2000). Water supply is a prerequisite to meeting the ETcr demand and a major tool for increasing WUE. According to Li et al. (2010) substitute fractional root irrigation improved WUE and leaf relative water quality in maize plants. Increasing WUE, in particular, demands optimal irrigation and application time based on crop water requirements, which may be done by measuring soil moisture or detecting fluctuations in soil water conservation. (De Pascale et al., 2001).

### 2.2.3 Crop Water Productivity (CWP)

The several areas of production that use water may portray water productivity in diverse ways (e.g., crop production, fishery, forestry, domestic and industrial water use). WP is referred to as CWP in crop production, which is a mathematical term that denotes the link between crop productivity and the volume of water utilized during production. The CWP unit is kg m$^{-3}$. CWP can also be interpreted monetarily in terms of economic return from crop generated per volume of water, with the unit interpreted for any currency, such as USD m$^{-3}$ (SWMRG, 2003; Kadigi et al., 2004). CWP is valuable for considering a possible rise in crop yield due to improved water supply (Burke et al., 1999). It enables a quick assessment of whether yield is constrained by water availability or other factors (Augus and van Herwaarden, 2001). CWP is a good indicator for measuring the effect of an irrigation scheduling procedure. The CWP shows the percentage increment of yield per unit of water consumption, which can be used to determine the effect and value of increased water supply. Quantitative data on CWP are thus needed for successful implementation of agricultural irrigation systems in a given region.

### 2.3 Modelling for sweet potato water needs using FAO-CROPWAT MODEL 8.0

Crop models are essential tools for analyzing the impact of root and tuber production as well as potential adaptation options (Haverkort and Top, 2011). A crop model is a set of mathematical equations that explain the growth and development of a crop through time as a function of environmental variables. Models simulate crop responses under different managerial approaches and environmental variables utilizing meteorological data, soil conditions, and crop attributes. However, sweet potato crop models have not experienced the same degree of model testing and refinement as grain crop models (White et al., 2014). These crops, particularly sweet potato, have little crop physiological information, thorough field experimental data, or agronomic research. As a result, large-scale field experiments for modelling improvements are required for the sweet potato crop.

Models become a crucial tool for identifying agroecological zones and properly managing available water resources. Using meteorological, soil, and crop data, the FAO-CROPWAT 8.0 model was used to predict reference evapotranspiration (ETo) and net irrigation water needs (NIR) for most cultivated crops throughout the world (Surendran et al., 2015; Johnson et al., 2019; Apsara et al., 2021). CROPWAT for Windows version 8.0 is an application that calculates reference crop evapotranspiration using the FAO Penman-Monteith technique. These figures are used to determine crop water needs and developing indicative irrigation schedules. The irrigation water need is the difference between the crop water requirement and the amount of effective rainfall. Supplemental water is included in the irrigation to help with salt leaching and to compensate for water application inconsistency. Crop water shortage influences growth, development, and production in different ways depending on the crop, crop type, and crop growth stage (Kassam and Smith, 2001). Ky is a factor that describes the decline in relative yield produced by a decrease in ETc due to a lack of soil water.

Ky values are crop-specific and fluctuate by development stage during the growing season. As a result, understanding the length of the growth cycle and the leaf area index at maximum cover is necessary'(Kassam and Smith, 2001).

The application employs the same Penman-Monteith approach as CROPWAT versions 5.7, 7.0, and 8.0, and it makes use of the same data, such as CLIMWAT. Furthermore, the application is primarily intended to serve as a practical tool for doing standard calculations for irrigation scheme design and administration, as well as for enhancing irrigation practices and scheduling irrigation schedules under different water supply conditions. More pertinently, the model has the potential to estimate the irrigation schedule for each crop utilizing five different options: (1) irrigation as defined by the irrigation manager, (2) irrigation much below critical soil depletion, (3) irrigation at fixed intervals per stage, (4) deficit irrigation, and (5) no irrigation.

The CROPWAT Conceptual Model (Figure 1) describes the many parameters that must be calibrated before the model can be used effectively.

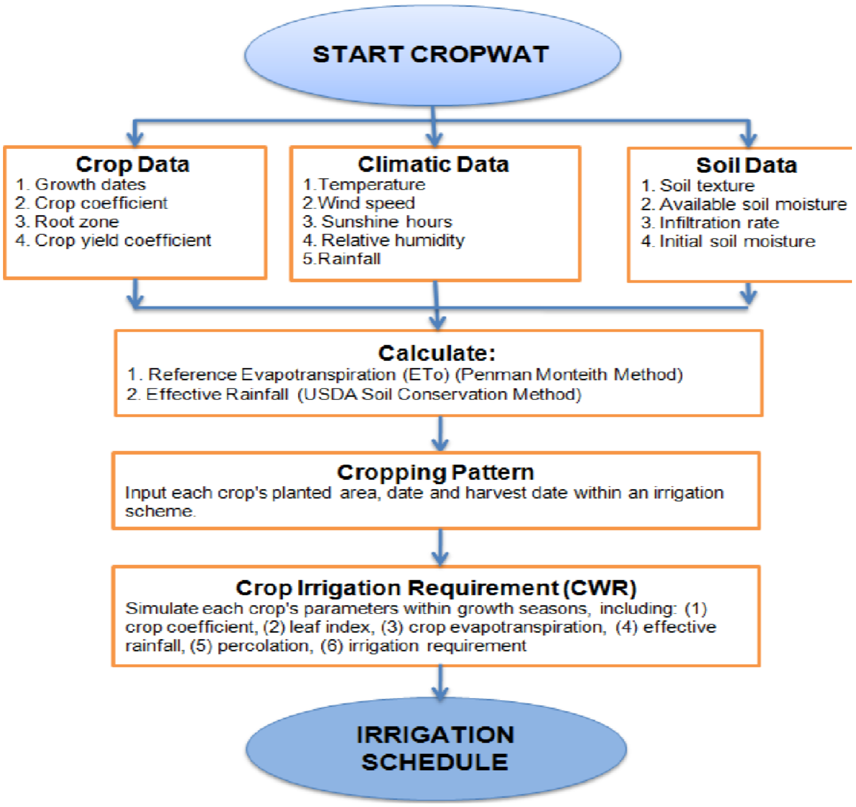


Figure 1. CROPWAT 8.0 Data framework. Source: FAO 1998

# CHAPTER THREE

# GROWTH AND YIELD OF SWEET POTATO (*Ipomoea batatas L*) MONOCROPS VERSUS INTERCROPS IN THE SEMI-ARID KATUMANI, KENYA

## 3.1 Abstract

Sweet potato growers in Kenya practice either sole cropping or relay cropping and rarely do intercropping which aims to maximize time and space, is rarely practiced. The study assessed the relative performance of sweet potato under simultaneous intercropping with common beans. This study was conducted in Katumani, Kenya over two seasons; 2018/2019 and 2019/2020. Treatments were two sweet potato varieties (Bungoma and Kabode) and cropping system, either sole crop or intercrop with common beans (*Miezi miwili*). Factorial combinations of the treatments were laid out in a randomized complete block design and replicated three times. Monocropped sweet potato and beans served as the control treatment. Weather data, leaf area, leaf area index, vine length, and percent canopy cover were collected throughout the cropping period. The data were analysed by a two-way ANOVA at 0.05% significance level was used to see how treatments and seasons affected the measured response variables. Intercropping significantly ($p < 0.05$) reduced sweet potato yields of Kabode and Bungoma varieties by 19.3 and 44%, respectively. Monocropped Kabode yielded 31.4 t $ha^{-1}$, significantly ($p< 0.05$) higher than monocropped Bungoma with 23.9 t $ha^{-1}$ whereas their common bean intercrops yielded 26.2 t $ha^{-1}$ and 18.1 t $ha^{-1}$, respectively. Land equivalent ratio showed that intercropping sweet potato varieties with common beans was biologically productive and that the percentage of the land saved averagely ranging from 8% to 33%. Yield analysis showed that orange-fleshed Kabode was the most stable variety across seasons to be grown in Katumani. More studies should be conducted to determine the extent of sweet potato allelopathy on companion crops and nutrient use under intercropping systems.

Keywords: Cropping systems, Leaf area index, Vine length, Land equivalent ratio, Aridity index

## 3.2 Introduction

Sweet potato *(Ipomoea batatas L*) (Huamari, 1992); is an important root crop after Irish potato (*Solanum tuberosum)* (Salaman and Burton, 1985), in SSA as well as a vital staple crop (Janssens et al., 2014; Affognon et al., 2015; McEwan et al., 2015). It is an annual crop that morphologically comprises of vines, leaves and tubers. The crop exhibits either an erect growth habit posing approximately 1-2 m of vine length whereas creeping varieties spread on the soil to approximately 2-3m (Nugroho and Widaryanto, 2017). Intercropping sweet potato is a popular practice in Kenya's semi-arid regions (Weerarathne et al., 2017).

Integrating legumes such as beans into cropping systems is a vital component of most farming systems, providing an advantage for optimizing on limited resources and maximizing yields with minimal input over a small production area (Kwena et al., 2018). Growth resources such as water, nutrients and light are fully absorbed, hence converted to crop biomass therefore signifying resource use; a characteristic of any cropping system. That being said, differences in the ability of individual crops to compete for growth factors between intercrop components can be noticed in yield attributes (Amini et al., 2013). Legumes raise the soil's nitrogen pool through atmospheric di-nitrogen fixation in association with root rhizobia bacteria thereby availing it to use by the consecutive or slow-maturing component crop thus improving on economic yields (Ddamulira et al., 2015; De Bruijn 2015; Karuku et al., 2019). An intercropping system comprising of late and early maturing crop experiences efficient use of the available solar radiation throughout the cropping period (Fletcher et al., 2017). Kinama et al. (2011) reported a spike in photosynthetic radiation intercepted whilst intercropping maize with cowpea and Senna, with a higher light use efficiency in intercrops relative to sole cropping of maize, in conditions where crop growth was restricted only by the amount of radiation intercepted by the crop's foliage rather than by water and nutrients.

Despite intercropping being a common practice in many cropping systems around the world, very few studies have examined the impacts of intercropping sweet potato from any perspective (Asiimwe et al., 2016; Idoko et al., 2018). Several studies have focused on yield potential under sweet potato maize relay cropping systems (Ewell and Mutuura,1991; Fischler and Wortmann, 1999; Mohammed, 2019), whereases others indicate that sweet potato can also be alley cropped between lines of agroforestry trees or shrubs, preferably fast-growing leguminous species with open crowns that allow the sunshine through (Rusoke et al., 2000; Schonbeck and Tillage, 2011). Despite this, intercropping sweet potato with grain legumes is not widely practiced in Kenya. The study aimed at contributing towards the sustainable production of sweet potato and the general food insecurity situation in Kenya by analysing the performance of sweet potato intercrops in Katumani Research Station but also to other environments with similar soil and climatic conditions in semi-arid areas. The objective was: to determine the growth, performance and yields of sweet potato intercrops versus monocrops in the ASALs of Eastern Kenya.

## 3.3 Materials and Methods

### 3.3.1 Study site

Field trials were conducted in KALRO–Katumani experimental station, Kalama ward in Machakos Town, coordinates 1°35’ 07’’ S and 37° 13’ 23’’ E at 1597m asl (Figure 2) (Jaetzold et al., 2006). Kalama ward falls under agro-ecological zone IV, categorized as a semi-arid land (Karuku et al., 2019). Ferralo-Chromic Luvisols of Makueni quartz-zitic rock is the predominant soil types found in this site, exhibiting a sandy clay loam texture with a saturated hydraulic conductivity ranging from 0.91- 1.98 $mhr^{-1}$ (Gicheru and Ita, 1987; Mwendia et al., 2017). Total available water (TAW) ranges between 10-50 mm per meter of soil depth.

Kalama experiences a bimodal rainfall distribution, such that the long rains start in late March and end in May whereas the short rains commence in late October and taper off in mid-December with a mean annual rainfall of approximately 711 mm (Jaetzold et al., 2006). The mean annual temperature ranges from 13.7 °C to 24.7 °C. The average wind speed ranges between 1.94 and 3.05 $ms^{-1}$, obtained 2m above the ground. The area is almost completely cultivated as arable land. Mixed cropping is practiced with sweet potatoes (*Ipomoea batatas L*) (Huamari, 1992), maize (*Zea mays*) (Chase, 1969), pigeon peas (*Cajanus cajan*) (Morton, 1976), beans (*Phaseolus vulgaris*) (Graham and Ranalli, 1997) and fruit trees being the main crops (Sombroek et al., 1982).

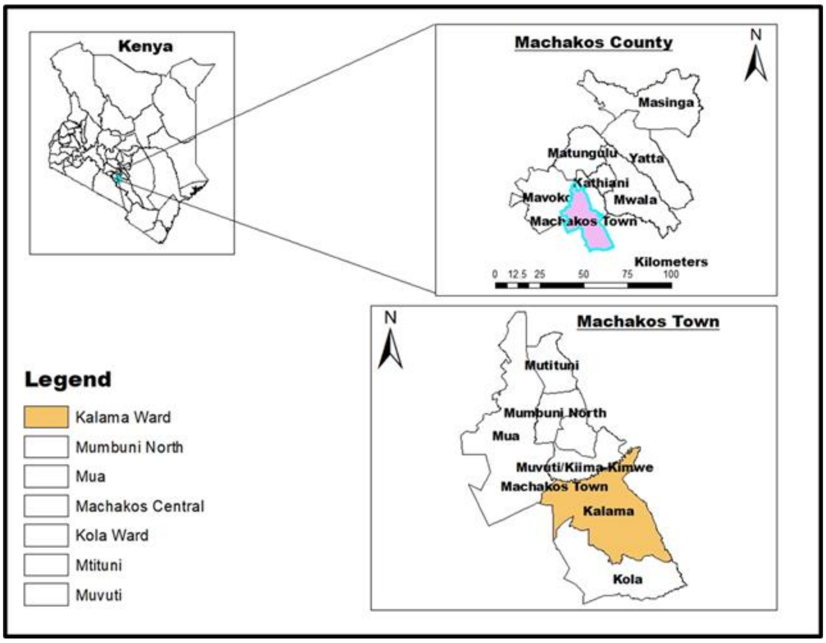


Figure 2.Study Area: Map of Kenya (top left) extract of Machakos county (top right) and Machakos town sub-county insert Kalama ward (below); Source: Generated from ARC-GIS.

### 3.3.2 Treatments

Treatment combinations comprised of;

- **(i)** **V1:** Monocropped Kabode (orange-fleshed)
- **(ii)** **V2:** Monocropped Bungoma (white-fleshed)
- **(iii)** **B:** Monocropped common beans *(mwiezi miwili)*
- **(iv)** **V1M**: Kabode + common beans intercrop
- **(v)** **V2M:** Bungoma + common beans intercrop

Sweet potato was the main crop of interest as the controls were the sole cropping of sweet potato varieties.

### 3.3.3 Experimental design and layout

A total of 15 pots were laid out in a Randomised Complete Block Design, with each block having 5 treatments replicated 3 times. The experimental plots were 4m wide and 5m long. Spaces separating the plots and the blocks were 0.5 m and 1m, respectively. The plots were laid out on a 5% natural slope between two *Fanya-chini* terraces. *Fanya-chini* terraces are created by digging and heaping the soil upwards, creating bunds at the upper sides of the ditches. A narrow ledge between the ditch and the bund prevents the soil from fading away (Tenge and Okoba, 2011).

### 3.4 Agronomic practices on the experimental plots

The land was manually cleared using a hand hoe and ridges constructed 1m apart. Sowing was done at the onset of the rains on 20th November 2018 and on 17th October 2019 for season (I) and (II), respectively. Season (I) commenced in November 2018-April 2019, whereas Season (II) from October 2019- March 2020. Sweet potato vines were planted at a spacing of 25cm×60 cm in each plot whereas common beans *(miezi miwili*) were planted on top of the ridges at 5 cm depth and 25cm spacing within the row. Hand weeding was done with the aid of a hoe soon as weeds emerged throughout the cropping period.  Plants were randomly tagged for accuracy and ease of monitoring growth and data collection. Pests and diseases were controlled upon incidence. To manage bean fly, Lambda Cyhalothrin 50g/L/Ha was sprayed on beans, and Emamectine Benzoate 19g/L/Ha was sprayed to control caterpillars. Earthing up sweet potato ridges with soil was done as the need arose. Beans were harvested upon attaining physiological maturity which was dictated by the browning of leaves and yellowing of pods (Duke, 2012; Mulube, 2017). Harvesting of sweet potato was done 160 days after sowing at the point when the end of the vines had started yellowing. This was accomplished by hand digging with a hoe up the ridges and uprooting the vine and collecting the tubers.

### 3.5 Data collection

#### 3.5.1 Climate data

Daily weather data on temperature (°C), relative humidity, and rainfall (mm) were obtained from the site meteorological weather station.

**Aridity index (AI)** was computed as a ratio of Rainfall: ETo such that: $AI \leq 0.05$ suggests a hyper-arid climate with poor rainfall levels that scarcely reach 100 mm. $AI \leq 0.2$ indicates an arid region with a high rainfall variability varying from 100 mm to 300 mm. $AI \leq 0.5$ defines a semi-arid region in which summer rainfall range from 200-250 mm to 450-500 mm. Finally, the $AI \leq 0.75$ is graded as dry sub-humid.

#### 3.5.2 Plant growth and development

Morphological growth traits data collected weekly included per cent canopy cover, vine length, leaf area, and leaf area index (LAI) for all crops throughout the cropping seasons. Sweet potato was the main crop of interest. Ten tagged plants for each crop were monitored based on their phenological growth stages which were; initiation, vegetative development, tuber bulking and maturity.

*Canopy cover measurement:* The string method recommended by Khisa et al. (2002) was employed. A 15m string was mounted diagonally and horizontally inside the experimental plot, with points intersecting with plant foliage noted. The percentage of soil cover was calculated as shown in Eqn 1:

$$\%\, cover\ =\frac{total\ number\ of\ interceptions}{Total\ no\ of\ points}\times\ 100 \qquad (1)$$

*Leaf area (LA) and Leaf area index (LAI):* Leaf area was obtained by measuring the lengths and widths of the middle leaves of the ten tagged plants in a plot. Mean of the lengths and widths of the leaves was computed to estimate the leaf area (Carvalho et al., 2017) (Eqn 2)

$$A\ (Leaf\ area) =\ 0.56\ x\ K\ x\ 6.20 \qquad (2)$$

Where: K indicated the product of sweet potato leaf length and breadth whereas 0.56 and 6.20 were constants taking care of the irregularity of sweet potato leaves.

Thereafter, the leaf area index (LAI) was estimated using Eqn 3;

$$LAI\ (leaf\ area\ index) =\ \frac{LA}{A(spacing)}\ (cm2/cm2) \qquad (3)$$

Where: LAI ($cm^2\ cm^{-2}$), LA = leaf area ($cm^2$), and A = the land area ($cm^2$).

*Tuber Yield:* Sweet potato fresh tuber weight and yield were collected from every plot, measured using a portable weighing balance. Total tuber weight was summed from all the plots then total tuber yield was computed from Eqn 4 (Nugroho and Widaryanto, 2017).

$$Tuber\ yield(kg\ Ha^{-1}) = \left(\frac{10000}{sampling\ plot\ area}\right)\times Total\ \ tuber\ yield\ from\ sampling\ area\ (4)$$

*Grain Yield:* Common beans were harvested upon attaining physiological maturity when pods started drying. Biomass and pods were harvested, sun-dried for two weeks to attain a moisture content of 3.26% to increase its storage longevity as prescribed by (Rani et al., 2013). Grain yield was therefore computed based on Eqn 5;

$$Grain\ yield(kg\ Ha^{-1})\ = \frac{grain\ dry\ yield\ (kg)}{the\ total\ area\ of\ the\ plots} \times\ 10{,}000m^2 \qquad (5)$$

*Valuating sweet potato intercropping:* The productivity indices were used in to estimate intercrop benefits and the extent of competition amongst the species (Weigelt and Jollife, 2003). These competitive indices were determined in terms of land equivalent ratio (LER) and % of the land saved.

*Land Equivalent Ratio (LER)*: estimated the beneficial effects of intercropping sweet potato with the beans. It provides an estimate of a crop system's biological efficiency, as defined by Liu et al. (2018) Eqn 6;

$$LER = \left(\frac{Yspi}{Ysp}\right) + \left(\frac{Ybi}{Yb}\right) \qquad (6)$$

Where; Yspi and Ybi are the yields of sweet potato and beans intercropped whereas Ysp and Yb are yields of sole sweet potato and beans respectively.

The percentage of land saved showing the extent to which land is saved by intercropping as opposed to mono-cropping cropping. This was computed based on Willey (1985) from Eqn7:

$$\%\ Land\ saved = 100 - \left(\frac{1}{LER} \times 100\right) \quad (7)$$

### 3.5.3 Statistical analysis

This was done with the aid of GenStat 19th edition (Lane and Payne, 1997). A two-way ANOVA was used to determine effects of treatments and seasons on the measured response variables. A Bonferroni test of significance was performed ($\alpha = 0.05$) for separation of the means.

## 3.6 Results and Discussions

### 3.6.1 Weather conditions during sweet potato growth stages

Monthly climatic data during the sweet potato growth stages are shown in Table 1.

Table 1. Climatic data observed during the sweet potato growth stages

| Season | Growth stage | Growth days | ETo (mm) | ETo/2 (mm) | R (mm) | AI | T-mean °C |
|---|---|---|---|---|---|---|---|
| Season (I) | Initiation | 40 | 180.2 | 90.1 | 150 | 0.8 | 20.2 |
| | Vegetative | 42 | 167.6 | 83.8 | 115.4 | 0.7 | 19.5 |
| | Tuber bulking | 39 | 203.9 | 102 | 3.8 | 0 | 21.1 |
| | Maturity | 39 | 218.6 | 109.3 | 8.4 | 0 | 21.6 |
| Season (II) | Initiation | 40 | 122 | 61 | 219.9 | 1.8 | 19.9 |
| | Vegetative | 42 | 136.8 | 68.4 | 211.9 | 1.5 | 19.8 |
| | Tuber bulking | 39 | 159.2 | 79.6 | 57.9 | 0.4 | 20.3 |
| | Maturity | 39 | 158.3 | 79.2 | 179 | 1.1 | 21 |

*R; rainfall, T-mean; temperature, ETo; reference evapotranspiration, AI; aridity index; derived as R/ETo*

The Aridity Index (AI) indicates the relative dryness of the locality (Bannayan et al., 2010). Aridity indices reported in season (I) especially during the critical growth stage of the crop; tuber bulking and harvesting were zero, indicating the degree of aridity severity and possible impact on economic yield. On the other hand, AI registered at initiation and vegetative was 0.8 and 0.7, respectively, indicating a dry sub-humid period in these growth stages. Low AI indices AI ≤ 0.0 during the tuber bulking and maturation processes revealed a lack of humidity as a result of a lack of moisture recharge, suggesting that the crop water requirements were not significantly fulfilled during its growing period. In season (II), lower 0.4 AI values were recorded at the tuber bulking stage, a characteristic of the semi-arid zoning. On the other hand, higher AI values observed were 1.8, 1.5 and 1.1 at initiation, development and harvesting, respectively. This indicated a certain degree of wetness due to soil water recharge from the rainfall received. This study found that an increase in the aridity index in crop production contributed to lengthening of the humid periods through prolonged wetness scenarios (Hufkens et al., 2016).

Rainfall plays a vital role facilitating soil water recharge thereby impacting positively on the soil water balance, (SWB. From observation in season (I), the minimal amount rainfall was recorded at tuber bulking stage and at final crop maturity; 3.8 and 8.4mm, respectively. On the other hand, most rainfall was recorded at planting and vegetative development stage (150 and 115.4 mm, respectively). The low rainfall recorded during tuber bulking and at harvest may have led to an overall yield reduction factor (Ky) of sweet potato as a result of water stress. In tuber production, water stress at the bulking stage may lead to malformation and reduction in tuber sizes (Motsa et al., 2015). Season (II) had a significantly higher rainfall compared to season (I) giving rise to a humid regime and a high AI value. The highest rainfall experienced was at initiation 219.9 mm, followed by the development and harvest stages at; 211.9 and 179.0 mm, respectively. The lowest amount of rainfall recorded at 57.9 mm was at tuber bulking. Sweet potato requires moist conditions from planting to a point when roots have has fully developed since it can be able to tolerate water stress and recover easily when soil water is recharged with no decline in yields (El-Sharkawy, 2006).

The observed temperatures range of 14–29 °C for season (I) and were considered high for sweet potato production. Sweet potato normally thrives well between 15 and 25 °C (Negeve et al.,1992), where temperatures below 15°C deter root formation, whereas those above 25°C affect photosynthesis (Eguchi et al., 2003). The average temperatures recorded at the bulking and harvesting stages were 21.1 and 21.6 °C, respectively and considered optimal for sweet potato development. As such, they favored the portioning of photosynthates to the storage roots (Eguchi et al., 2004). Gajanayake et al. (2015) indicated that high temperatures tend to affect the partitioning of biomass in sweet potato, thereby affecting the final yield. For season (II), the diurnal temperatures ranged between 14.2 and 26.2 °C and the highest mean temperatures recorded during the tuber bulking and at harvest were 20.3 and 21.0 °C, respectively. Ravi and Indira (1999) reported that for sweet potato production, tubers formation, enlargement, and synthesis of starch are mainly catalyzed by air temperature ranging between 14 and 22°C, concurring with those observed in the study. Furthermore, Ravi et al. (2014) discovered that the competitiveness between shoot and storage root growth in sweet potatoes is controlled by air and soil temperatures.

Figure 3 illustrates the humid periods experienced throughout the two experimental seasons. The data indicates a short humid period was experienced in season (I) with declining humidity observed in the final crop developmental stages. Accordingly, under such conditions, the season was considered to be short; since the supply of water, temperature and AI indices was met by major climatic constraints. Such water supply deficits have been caused by an erratic distribution of rainfall, which may have created a significant imbalance in the soil water budget. Increased temperatures have an impact on climate efficiency in rainfed agriculture, creating a faster rate of aging in crops and thus a shorter life span

(Thorne-Miller et al., 1983). The findings of this study are correlated with (Kang et al., 2009), who argued that climate change could negatively impact the soil water balance, thus paving the way for minimal crop coverage, thus instigating soil evaporation and, consequently, shortening the crop growth period. On the other hand, season (II) experienced a long period of humidity, which decreased on the 83rd day after planting and was therefore considered sufficient. The length of the wet seasons may be the result of a balance between rainfall and evaporation; root supply and leaf demand (Zelitch, 1975; Monteith, 1977). Throughout the production of sweet potatoes, the water deficit at the tuber bulking stage may have led to a decrease in the leaf area index (LAI), vine length and an increase in the concentration of abscisic acid (ABA) in roots and shoots (Daryanto et al., 2017). ABA causes the abscission of lateral bud development in crops (Fichtner and Lunn, 2021). Physiologically, the crop can undergo an increase in its solute osmotic pressure leading to overproduction of growth inhibitors, thereby enhancing its metabolic toxicity and subsequent yield (Obidiegwu et al., 2015). Recovering under such circumstances, the principle of drought tolerance and avoidance sets in sweet potato (Okogbenin et al., 2013). This could be accomplished through increasing crop water use efficiency, changes in xylem hydraulics, and inhibiting leaf growth (Skirycz et al., 2010; Verelst et al., 2010).

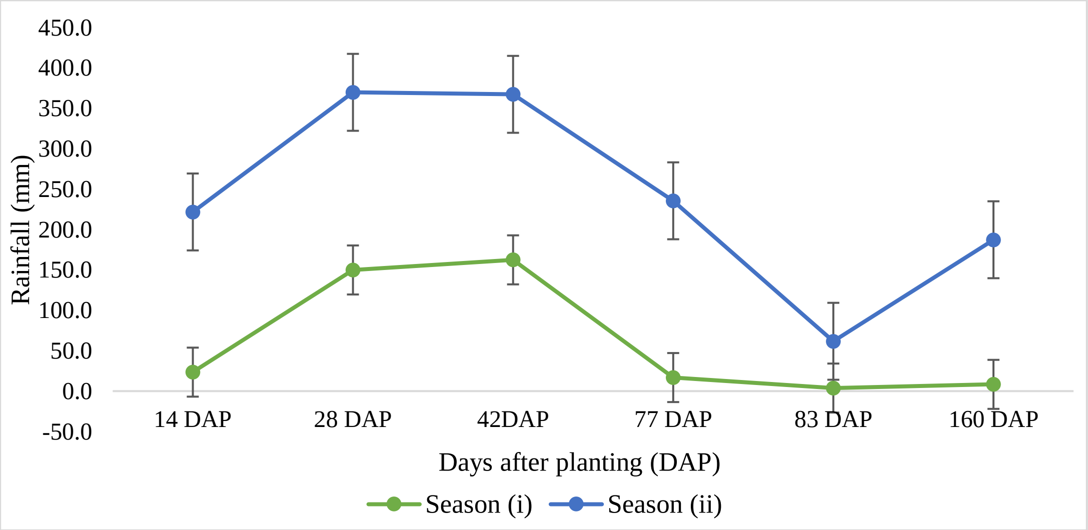


Figure 3. Beginning and ending of the humid period

*Key: error bars represent the standard error of mean rainfall.*

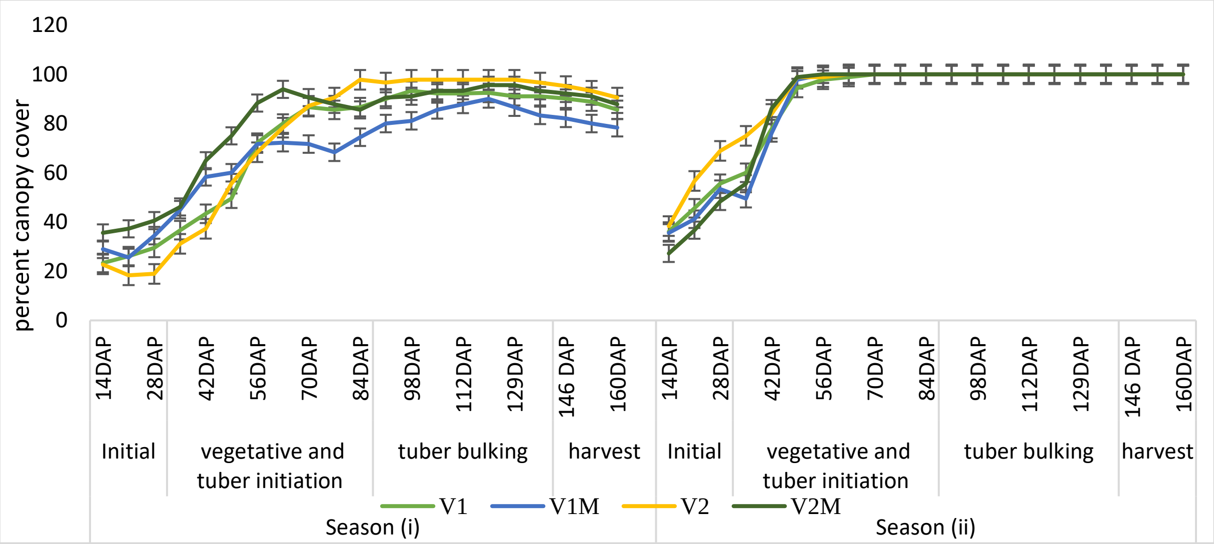
### 3.6.2 The sweet potato growth component

#### 3.6.2.1 Canopy cover

#### 3.6.2.2 Effect of intercropping systems on per cent canopy cover

Trends in per cent ground cover during the sweet potato growth stages are shown in Figure 4.

Percent canopy cover rose steadily from planting in both seasons, peaking at the vegetative and tuber stages, declining at harvest time. The duration of the growth cycle was 160 days, the initiation period was 40 days, its vegetative growth was 42 days, the tuber was 39 days and the final stage was 39 days (Wohleb et al., 2014). Similarly, Kc values for season (I) were: initiation 0.4, development 0.7, tuber bulking 1.2 and at maturity 0.8 whereas for Season (II) were: 0.4, 0.5, 0.9 and 1.2 in all phenological growth stages, respectively and depended on local conditions (Mulovhedzi et al., 2020). At establishment, the sweet potato crop had a low per cent canopy cover which may have resulted in the minimum water needed to compensate for atmospheric demand (Karuku et al., 2014).



*Key: V1 Sole Kabode (orange-fleshed), V1M Kabode+beans, V2 Bungoma variety (white-fleshed) and V2M Bungoma+beans.*

*Error bars represent standard error of mean canopy cover*

Figure 4. Trends in per cent cover of orange (V1) and white-fleshed (V2) sweet potato and their intercrops

The high percent cover recorded by Bungoma- bean (V2M) intercrop, may have created a microclimate by sheltering moist air near the soil surface, thereby reducing soil evaporation and thus retaining soil moisture (Gitari, 2018). A decrease in the percentage of the canopy cover at full crop maturity meant the emergence of leaf senescence at these stages, marked by the yellowing of the older leaves at the base of the plant that followed the fall of the leaf and eventually the death, which presumably decreased the area covered by canopy and leaf.

Season (II) experienced a steady rise in canopy characteristics. Maximum cover across all treatments was experienced from the tuber initiation to harvest. This meant that the foliage features of sweet potato experienced indeterminate growth. Contrary to season (I), the high ground in season (II) cover could be alluded to the humid period experienced, marked by soil water recharge that necessitude vine elongation, extending its life span (Chhabra et al., 2006). In intercropping, canopy structure plays a pivotal role in the absorption of photosynthetic active radiation (PAR) neighbouring leaves affect one another in the system (Liu et al., 2017). The high ground cover could be a premonition of the amount of photosynthetic radiation being intercepted (Maddonni et al., 2001). As such intra-canopy light propagation between companion crops creates a lot more PAR interception. If indeed the light penetrates the canopy, its interception increases with the LAI (Leuning et al., 1991). As vegetative growth progresses, most crops assimilate a lot of biomasses, which appears to be directly proportional to intercepted radiation, thus much yield (Monteith, 1977). Similar studies conducted by Nyawade (2015) have shown that canopy cover is a crucial determinant of the amount of PAR intercepted, which influences the photosynthetic capacity of crops and is expressed in the amount of dry matter produced. The reduction of PAR intercepted under water deficit conditions depends also on the degree of stress due to decreased leaf expansion and the number of leaves.

Table 2. Mean per cent canopy cover for the two cropping seasons

| Cropping systems | Season (I) | Season (II) |
|---|---|---|
| Kabode | 70.40$^{a}$ | 88.67$^{a}$ |
| Kabode+beans | 67.07$^{a}$ | 88.55$^{a}$ |
| Bungoma | 77.08$^{a}$ | 90.31$^{a}$ |
| Bungoma +beans | 71.69$^{b}$ | 89.29$^{a}$ |
| LSD 5% | 5.16 | 6.31 |
| SED | 2.617 | 3.2 |
| F pr. | <.001 | < .001 |

*Key: The different letters within the same column show significant differences within the comparing variables at p < 0.05*

The main effects of intercropping on per cent canopy over all phenological growth phases in season (I) differed significantly ($p < 0.05$) as sole cropping of Kabode had 70.4%, whilst its intercrop 67.1%. On the other hand, there were major variations between the sole cropping and intercropped Bungoma varieties. Sole cropping of Bungoma had 77.1 and 71.7% ($p < 0.05$) upon intercropping. Data in the study showed that all the intercropped treatments had a lower canopy cover compared to monocropped ones. These observations dispute the findings of Gitari et al. (2019) that indicate so whenever legumes are used as companion crops, have the potential of promoting the water conservation in central Kenya's wetlands. Similarly, Nyawade et al. (2019) and Lozano-Parra et al. (2018) argued that higher canopy cover goes hand in hand with a rise in soil moisture and a decrease in soil temperature which has a positive effect on the soil microclimate and hence on the overall productivity of crops.

In season (II), the sole cropping of Bungoma variety recorded the highest canopy cover of 90.3 and 89.3% on intercropping with common beans. Similarly, the sole cropping of Kabode variety had 88.7 and 88.6% when intercropped with common beans *(Miezi miwili*). Generally, Bungoma variety had the highest groundcover and morphologically, the variety (Bungoma) has broad leaves that spread on the ground. Whereas the lower ground cover from the Kabode variety may be attributed to the narrow leaves forming a small canopy architecture as it depicts an erect growth pattern.

Ground cover varied significantly ($P < 0.05$) between the two seasons, as it was highest in season (II) and lowest in season (I). These differences may be attributed to the favorable climate conditions such as high rainfall and AI values observed in season (II), which may have necessitude soil water recharge. Such that $ETa = ETm$, thus the more available soil water content may have favoured the optimal multiplication of vegetative parts leading to a high canopy cover (Wiryawan and Hairiah,1983). Intercropping yielded lower ground cover possibly due to competition between species on nutrients, area, and time (Fukai and Trenbath,1993). Competing for growth resources among crop components in the intercrop system tends to reduce crop growth and biomass accumulation relative to monocropping (Dasbak and Asiegbu, 2009). Across the experimental periods, Bungoma variety posed the highest percent canopy cover. It's likely that the crop might have used the available soil water more effectively, resulting in a higher canopy cover and, ultimately, more biomass generated (Karuma et al., 2011; Nyawade, 2015). In this regard, varieties with high per cent canopy cover may serve dual purposes (Mwololo et al., 2012).

### 3.6.3 Effect of intercropping on vine length, leaf area index and yield attributes of sweet potato

#### 3.6.3.1 Vine length

Table 3 presents the interactive cropping effects on the length of sweet potato vines during their phenological growth stages in both seasons.

Table 3. The length of sweet potato vines across the two production seasons

| VINE LENGTH (cm) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Season (I) | | | | Season (II) | | | |
| Growth stage | V1 | V1M | V2 | V2M | V1 | V1M | V2 | V2M |
| Initial | 21.46$^{a}$ | 22.79$^{a}$ | 25.19$^{a}$ | 21.40$^{a}$ | 23.9$^{a}$ | 25.1$^{a}$ | 35.3$^{a}$ | 30.4$^{a}$ |
| Vegetative | 30.32$^{ab}$ | 31.63$^{ab}$ | 49.94$^{ab}$ | 43.20$^{b}$ | 91.4$^{b}$ | 88.1$^{b}$ | 124.7$^{ab}$ | 117.6$^{b}$ |
| Tuber initiation | 43.78$^{bc}$ | 42.82$^{bc}$ | 78.62$^{bc}$ | 65.91$^{c}$ | 161.6$^{c}$ | 150.4$^{b}$ | 212.9$^{bc}$ | 192.9$^{bc}$ |
| Tuber bulking | 52.62$^{c}$ | 52.30$^{c}$ | 96.44$^{c}$ | 78.54$^{c}$ | 237.0$^{d}$ | 215.7$^{c}$ | 288.2$^{c}$ | 260.7$^{c}$ |
| Harvest | 50.31$^{c}$ | 52.07$^{c}$ | 95.19$^{c}$ | 77.92$^{c}$ | 225.2$^{cd}$ | 214.0$^{c}$ | 288.2$^{c}$ | 246.4$^{c}$ |
| F pr. | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 |
| s.e.d | 3.82 | 3.51 | 8.79 | 5.47 | 18.78 | 17.56 | 25.76 | 21.15 |
| l.s.d (5%) | 8.52 | 7.82 | 19.58 | 12.18 | 41.84 | 39.12 | 57.4 | 47.13 |
| CV % | 11.8 | 10.7 | 15.6 | 11.7 | 15.6 | 15.5 | 16.6 | 15.3 |

*Key: V1 Sole Kabode (orange-fleshed), V1M Kabode+beans, V2 Bungoma variety (white-fleshed), and V2M Bungoma+beans;*

*The different letters across the rows show significant differences among the treatments at p < 0.05.*

The highest mean vine length in season (I) was recorded in monocrops relative to intercrops. On average, the sole cropping of Kabode variety had a mean vine length of 40.4 cm, its intercrop with common beans (*Miezi mbili* variety); was 40.8 cm while the monocropped Bungoma variety had a value of 70.7 cm significantly higher than its corresponding intercrop (57.8cm) (P<0.05). These were lower than those observed by Nugroho and Widaryanto (2017) during the long rain season in India and may be due to interspecies competition for water and nutrients. On the other hand, the longest mean length of vines was recorded in season (II) from the Bungoma variety (both sole cropping of 181.4 cm and intercropped 167.6 cm), while the sole cropping of and intercropped Kabode variety were 147.3 and 137.5 cm, respectively. The length of the vines in all the growing systems increased continuously as the test crops approached the tuber bulking and harvesting phases. This has shown that; apart from tubers, the two varieties could also be a good source of vines, especially in circumstances aimed at the multiplication of the vines.

From observation, Kabode variety had shorter vines compared to Bungoma variety. Coincidentally, Kabode variety produced the highest tuber yields across the two seasons. These results depict Kabodes’ efficiency in converting its photosynthetic products to the storage roots. Most of the organophosphates were translocated to the roots instead of vines. Similar results were reported by Parwada et al. (2011) who observed high tuber yield in cultivars that had a low vine length. Significant differences ($P < 0.05$) in the length of vines between season (I) and (II) could be attributed to the presence and lack of humid periods observed during the growth of sweet potato. Water stress continued to impede cell enlargement as opposed to their division, thereby reducing the stem or vine expansion and internode diameter of many sweet potato cultivars which can be due to the discrepancies in the length of vines thus percent canopy cover (Pramuk and Runkle, 2005; Lebot, 2019). Under these conditions, the crop was alive and was able to regenerate quickly during the rainy days, presumably as a result of the reverse translocation of assimilates from the roots to the canopy, lowering yield. The pruning of sweet potato vines helped to improve the efficiency of translocating organo-phosphates to storage roots (Nugroho and Widaryanto, 2017). If the vegetative growth is high, they'd restrict tuber formation, such that the little organophosphates will be left for root formation and thereby creating an imbalance in its accumulation and hence fewer and smaller tubers formed (Dubois et al., 2013; Isa et al., 2015).

#### 3.6.3.2 Leaf Area Index (LAI)

Table 4 indicates the variations in the Leaf area indices of the treatments throughout the experimental seasons.

The leaf area indices had substantial variations ($P < 0.05$) between the treatments and within their phenological growth stages throughout the experimental seasons. Averagely season (I) had a lower LAI ranging from 0.5-0.7, whereas season (II) ranged between 1.1 to 2.2. During the vegetative growth phases, the maximum LAI presented for season (I) was (0.8- 1.2) and (1.6-2.2) for season (II).

Table 4. Trends in leaf area indices for the two cropping seasons

| LEAF AREA INDEX | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Season (I) | | | | Season (II) | | | |
| Growth stage | V1 | V1M | V2 | V2M | V1 | V1M | V2 | V2M |
| Initial | $0.4780^{a}$ | $0.5195^{a}$ | $0.7008^{a}$ | $0.7610^{a}$ | $1.117^{a}$ | $1.010^{a}$ | $1.435^{ab}$ | $1.521^{a}$ |
| Vegetative | $0.7662^{d}$ | $0.7733^{b}$ | $1.0538^{c}$ | $1.2037^{b}$ | $1.662^{b}$ | $1.689^{b}$ | $2.084^{b}$ | $2.155^{b}$ |
| Tuber initiation | $0.6717^{cd}$ | $0.6594^{ab}$ | $1.0100^{bc}$ | $1.1203^{ab}$ | $1.609^{b}$ | $1.539^{ab}$ | $1.884^{ab}$ | $1.673^{a}$ |
| Tuber bulking | $0.6228^{bc}$ | $0.5526^{a}$ | $0.9290^{bc}$ | $0.9916^{ab}$ | $1.532^{ab}$ | $1.467^{ab}$ | $1.575^{ab}$ | $1.421^{a}$ |
| Harvest | $0.7662^{d}$ | $0.5064^{a}$ | $0.7008^{a}$ | $0.8814^{ab}$ | $1.117^{a}$ | $1.175^{ab}$ | $1.067^{a}$ | $1.204^{a}$ |
| F pr. | <.001 | <.001 | 0 | 0.01 | 0 | 0.01 | 0.01 | <.001 |
| s.e.d | 0.04 | 0.05 | 0.06 | 0.1 | 0.12 | 0.17 | 0.24 | 0.13 |
| l.s.d (5%) | 0.09 | 0.1 | 0.14 | 0.23 | 0.26 | 0.37 | 0.53 | 0.29 |
| cv % | 7.9 | 9.4 | 8.6 | 12.5 | 10 | 14.7 | 18.1 | 10.2 |

*Key: V1 Sole Kabode (orange-fleshed), V1M Kabode+beans, V2 Bungoma variety (white-fleshed), and V2M Bungoma+beans*

*The numbers within the same column followed by the same letters are not significantly different.*

Regardless of the seasons, LAI values were lower than those reported by Nugroho and Widaryanto (2017) and Nedunchezhiyan et al. (2012) who found indices ranging from 3.1 to 4.7 and 2.3 to 2.9 respectively, ascribing to the variations in genetic composition of varieties.

Plant leaves poise as the largest percentage of canopy and plays a crucial role in all crop physiological processes, such as PAR absorption, transpiration and photosynthetic potential of the crop, are wholly reliant on LAI (Xu et al., 2008). Similar to the length of vines, a higher LAI to a greater extent may pose difficulty the formation of generative organs such as roots (Nugroho and Widaryanto, 2017). Thus, the translocation organic phosphate is more he focused to the vegetative organs rather than the roots. Conversely, Dukuh (2011) reported that higher LAI in sweet potatoes did not have a positive effect on tuber development as the continuous growth of leaves restricted tuber formation. This study is consistent with the findings of Mithra and Somasundaram (2008) which showed that higher LAI in sweet potatoes did not confer any advantage in the final root yield. As a result, it is strongly recommended to prune the vegetative parts at the initiation and bulking stage as it reduces the obstruction of tuber growth.

### 3.6.4 Tuber yield

The interactive effect of intercropping on sweet potato tuber yield is shown in Table 5. Tuber production in season (I) was not significant across treatments ($p \geq 0.05$), such that the sole cropping of Bungoma and Kabode varieties yielded 5.6 and 5.2 tha$^{-1}$, respectively. On the other hand, intercropped Bungoma and Kabode variety yielded 3.8 tha$^{-1}$ and 4.2 tha$^{-1}$, respectively. The low tuber yield reported from both varieties can be due to the humid conditions encountered during the critical growth phase of the crop.

Table 5. Effect of intercropping on sweet potato yield in semi-arid areas

| | Tuber yield (t ha$^{-1}$) | |
|---|---|---|
| Cropping system | Season I | Season II |
| Kabode | 5.167$^{a}$ | 57.62$^{c}$ |
| Kabode+beans | 4.217$^{a}$ | 48.17$^{bc}$ |
| Bungoma | 5.633$^{a}$ | 42.17$^{ab}$ |
| Bungoma+beans | 3.833$^{a}$ | 32.42$^{a}$ |
| F pr. | 0.603$^{ns}$ | 0.001$^{s}$ |
| S.E.D. | 1.441 | 3.16 |
| L.S.D. (5%) | 3.527 | 7.73 |
| CV% | 37.5 | 8.6 |
| F pr. | 0.603 | 0.001 |

*Key:(s) significant, (ns) Not significant. The numbers within the same column followed by the same letter (s) are not significantly different at 0.05.*

Similarly, in South Africa, Laurie and Magoro (2008) obtained approximately 3.9-9.5 t ha$^{-1}$ for communal drought-prone gardens compared to 25.2 t ha$^{-1}$ at experimental humid stations, supporting the yield gap between poor and well-endowed rainfall environments. The low tuber yield may result from drought-like conditions that may have caused lignification of roots and thus hindering their growth (Ravi and Indira, 1999). Additionally, the high temperatures observed may have aided in redirecting photosynthates towards forming fibrous roots relative to storage roots (Eguchi et al., 2003).

Tuber yield in Season (II) was significantly different among the varieties as they presented higher yields under sole cropping of cropping than when intercropped. The sole cropping of Bungoma and Kabode variety yielded 42.2 and 57.6 t ha$^{-1}$, respectively. Over the same season, their intercrops had 32.4 and 48.2 t ha$^{-1}$ for Bungoma and Kabode varieties, respectively. Tuber yields were significantly ($p < 0.05$) higher in season (II) compared to season (I). This may be attributable to the prevailing weather conditions such as the higher amount of rainfall received necessitating soil water recharge, raising the amount of photo transpirable soil water and thus favouring photosynthesis and yields formation (Wakrim et al., 2005). Differences in the attained tuber yields among the two varieties may can also be attributed to variations in their genetic composition, championing for their adaptability in such a peculiar environment. Intercrop experiments by Belehu (2003) involving sweet potato and taller legumes showed yield reduction. This may have been evidenced by a decrease in photosynthetic activity that can be exacerbated by taller beans due to shading and thus a reduction in insolation. From the current results, the study recommends a shift in the spatial arrangement of sweet potato cropping systems.

### 3.6.5 Bean yield

The interactive effect of intercropping on common bean grain yields are shown in Table 6. There were no significant differences ($p \leq 0.05$) in grain yields from the treatments as the sole cropping of crop yielded 0.7 t ha$^{-1}$, *Miezi miwili* +Kabode and *Miezi miwili* +Bungoma intercrop yielded 0.5 t ha$^{-1}$ and 0.4 t ha$^{-1}$, respectively. It was also notice that intercropping common beans with sweet potato similarly decreased the grain yield by 31.4 and 50.9 % with both Kabode and Bungoma varieties, respectively. This showed that Kabode was the better fit companion crop with beans in such setting. It was also noticed that sole cropping of treatments yielded more than intercropped ones. This may be due to the inter-specific competition among the crops on growth resources such as water resulting from experienced in season (I).

Table 6. Effect of intercropping sweet potato on grain yield of common beans

| | Bean yield (t ha$^{-1}$) | |
|---|---|---|
| Cropping system | Season I | Season II |
| Sole cropping of *Miezi mbili* beans | 0.736$^{a}$ | 1.674$^{b}$ |
| *Miezi mbili* +Kabode | 0.505$^{a}$ | 0.517$^{a}$ |
| *Miezi mbili* +Bungoma | 0.362$^{a}$ | 0.393$^{a}$ |
| S.E.D | 0.111 | 0.139 |
| L.S.D (5%) | 0.3074 | 0.388 |
| CV% | 25.4 | 19.9 |
| F pr. | 0.065$^{ns}$ | 0.001$^{s}$ |
| Key | s | significant |
| | ns | not significant |

*Note: Numbers within the same column followed by the same letter (s) are not significantly different at 0.05.*

The sole *Miezi miwili* variety, on the other hand, yielded more in season (II) than the intercropped ones. Sole cropping had 1.7 tha$^{-1}$ while the intercropped ones had 0.5 and 0.4 tha$^{-1}$ for Kabode and Bungoma varieties, respectively. Bean and Bungoma sweet potato intercrop had the highest yield reduction of 76.6 %, while Kabode was 69.1%, in line with (Egbe and Isang, 2015), which observed a decrease in grain yield under the sweet potato soybeans intercrop system linking it to the smothering and allelopathic effect caused by sweet potatoes. Studies by Xuan et al. (2012) on sweet potato allelopathy also revealed a decreased in cogon grass growth by 50 per cent. This meant that sweet potatoes could act as a smoother against invasive species or companion crops.

### 3.6.7 Intercrop economics:

Table 7. Land equivalent ratio and percentage of the land saved in sweet potato/bean intercropping system

| Season | Cropping system | LER (land equivalent ratio) | % of the land saved |
|---|---|---|---|
| Season (I) | Kabode+beans | 1.5 | 33.3% |
| | Bungoma+beans | 1.2 | 16.7% |
| Season (II) | Kabode+beans | 1.1 | 9.1% |
| | Bungoma+beans | 1 | 0.0% |

In season (I) the mixed crop LER was; Kabode+ beans (1.5) and Bungoma+beans (1.2), while in season (II) the LER registered in Kabode was 1.1 and 1.0, respectively. LER's highest value was registered as opposed to season (II) in season (I). Sweet potato and common bean mixtures with LER=1.0 suggested that there was no advantage over sole cropping of cultivation, while those mixtures with LER > 1 showed a multiple cropping advantage over monoculture biological output and also an indication of genotypic compatibility between the two crops. These findings are consistent with (Njoku et al., 2011), reporting similar results in the Okra sweet potato cropping system in Nigeria. The highest percentage of the land saved during the two growing seasons was obtained by intercropping Kabode with common beans season (I) (33.33%) and season (II) (9.10%), while in intercropping Bungoma variety with beans in Season (II), 16.67% of the land was saved whereas in season (I) land was saved implying resource utilization in intercropping.

### 3.6.8 Conclusions and Recommendations

Orange and white sweet potato varieties showed a relatively high growth response to the semi-arid climate. Intercropping provided a higher ground cover recommended for most conservation farming practices. The land was efficiently used in intercropping (LER > 1.0). Sweet potato yields were significantly ($p<0.05$) lower in intercrops than sole treatments. The Kabode variety (orange-fleshed) was suggested as a super variety which should be grown in these regions due to its high yield potential. It is evident from our study that sweet potato-bean intercrops, despite decreasing sweet potato tuber yields were more productive as sole cropping of crops. Further research should be carried out to determine the degree of sweet potato allelopathy to companion crops and nutrient use under intercropping.

# CHAPTER FOUR

## WATER PRODUCTIVITY OF SWEET POTATO (*Ipomoea batatas L.*) GROWN ON FERRALO-CHROMIC LUVISOLS OF SEMI-ARID KATUMANI, KENYA

### 4.1 Abstract

Water is the most valuable agricultural resource. Agricultural growth in semi-arid eastern Kenya is essentially dependent on sporadic rainfall. An accurate estimate of sweet potato water usage is considered a significant feature of conservation agriculture under such climatic conditions. The research was conducted for two seasons, from December 2018 to April 2019 and October 2019 to March 2020, with the aim of quantifying the water use efficiencies of two sweet potato varieties, Kabode and Bungoma. Assuming that there were no variations in water-use efficiency between the two varieties. experiment was established as RCBD for the two seasons. Treatments comprised of sole sweet potato varieties of Kabode and Bungoma, together with their intercrops with common beans. Correlation analyses were carried out to determine the correlates of the climatic and soil environments on the water use efficiencies of the two test crops. Saturated hydraulic conductivity of Ferralo chromic Luvisols ranged from 28.8-35.6 cm day$^{-1}$, whereas, the total (TAW) and readily available water (RAW) within the profile were 330.4 and 214.7 mm, respectively. Water use efficiencies for Kabode and Bungoma varieties were; 39.8 and 30.0 kg ha$^{-1}$ mm$^{-1}$, whereas their Harvest Indices were 47.5 and 41.1%, respectively. CWP in terms of rain water use was 1.11 and 0.95 kgm$^{-3}$ for Kabode and Bungoma varieties, respectively. Correlation analysis revealed that WUE was significantly ($p>0.05$) influenced by ΘFC, ΘPWP and TAW and negatively by the soil bulk density. WUE of the sweet potato crop increased from warm-dry to warm-wet climate, as Kabode portrayed higher adaptability. Results provide pertinent information to policymakers on crop variety development with enhanced WUE. More research to be done to enhance an understanding of the mechanisms involved in the unexplained variability in WUE among sweet potato cultivars.

Keywords; Water use efficiency, soil physical and hydraulic properties, harvest index, chromic luvisols

## 4.2 Introduction

The soil is a non-renewable natural resource which supports activities such as soil-plant-water movements and other land use productivities (Giddens, 2009; Schoonover and Crim, 2015). Ferralo-chromic luvisols are the most prevalent soil types in eastern Kenya, characterized by a base saturation determined by $NH_4OAc$ at pH 7.0 $\geq$ 50 per cent, posing a low to moderate fertility. Most luvisols in the Kenyan dry areas form a strong surface sealing that causes a low rate of infiltration paving way for a high runoff, hence eroding the topsoil (Muchena and Gachene, 1988). Studies by Karuku and Machoge (2016) on various forms of nitrogen in Katumani luvisols indicated the existence of a low amino acid-N (23.1-30.8%) of total N and low organic matter content.

Luvisols are typically acceptable for crop production; nevertheless, continuous cultivation alters aspects of their physical and hydraulic characteristics, resulting in compaction, decreased permeability, and interference with the soil-plant water continuum (Kahlon and Khurana, 2017). In agricultural production, compaction of the soil is a major challenge hindering crop production since it negatively impacts on the available soil water, air permeability (pore size), bulk density, porosity and inhibits root penetration (Hakl et al., 2007; Nawaz et al., 2013). Water retention characteristics are fundamental aspects of solving problems related to crop water needs and soil water motions. The transport of soil water is primarily determined by pedo-transfer functions of texture, organic matter content and bulk density (Hillel, 1998; Karuku, 2011; Karuku et al., 2012). Most water and irrigation management challenges require knowledge of soil hydraulic properties (Shwetha and Varija, 2015). Henceforth, insights into the mechanisms involved in soil water flows is now a key component of reviving sustainable food production.

A clearer picture of a crop's water use is an important decision-making tool, particularly in water-stressed areas (Debaeke and Aboudrare, 2004). Agricultural water use, productivity, efficiency, and yield are important indicators to consider when evaluating how climate change affects crop production. As the climate is changing, precipitation is projected to decrease, while evaporation and evapotranspiration are expected to rise (Kamruzzaman, 2020). This means that the supply of soil water required for plant development would diminish, necessitating the adoption of drought-tolerant crops like sweet potato. There is little data in Kenya on the extent to which soil hydraulic characteristics influence sweet potato water consumption efficiency. The objectives of this research were to (i) determine how water retention of Ferralo-chromic Luvisols of Katumani effects sweet potato WUE based on the RETC code, and (ii) determine the extent to which different climatic indicators affect crop water use efficiency in rain-fed agriculture.

## 4.3 Materials and methods

The study site, treatments, experimental design and layout and the key agronomic practices are outlined in chapter 3; section 3.3.1, 3.3.2, 3.3.3 and 3.4, respectively.

## 4.4 Data collection

### 4.4.1 Weather data

Rainfall (mm), relative humidity, saturation pressure deficit (Kpa), and dew point temperatures (°C) were collected daily from the site meteorological weather station.

Based on the relative humidity measurements at the location**, dewpoint temperatures and saturation water vapour pressure** were calculated using the dew point calculator**.** (https://www.calculator.net/dew-point-calculator.html) (Logan and Nordstrom, 1985).

**Effective rainfall** was computed based on the United States Department of Agriculture, Soil Conservation Service (USDA-SCS) method as described in FAO publication by Dastane (1978) Eqn 8.

$$eff = \frac{tot \times 125 - 0.2tot}{125} \qquad (8)$$

*Where,* $_{eff}$ *= effective rainfall (mm) and* $_{tot}$ *= total rainfall (mm).*

### 4.4.2 Site characterization

A profile pit (Figure 5) was dug out in the field and undisturbed soil samples obtained from different horizon depth using a core ring. The samples were used to determine the soil water content (SWC), dry bulk density (pb), total porosity, and total soil water potential. Saturated hydraulic conductivity, Reynolds and Elrick's (2002) constant head approach was used to calculate Ksat. Soil water retention was measured using ceramic plates pressure plates with pF values of 0.0, 2, 2.5, 3.7, and 4.2, as reported by Schofield (1935).

Figure 5. Profile pit with core rings collecting undisturbed soil samples in Katumani

### 4.4.3 Soil water computations

After oven-drying at 105 °C for 24 hours and then utilizing Eqn 9, 10, and 11, the gravimetric technique was used to estimate soil moisture using the core rings as the ratio of the volume of water in the soil sample to the dry weight of the soil.

$$\%\, GSMC = \frac{Mw - Md}{Md} x\ 100 \qquad (9)$$

*where: Mw = Weight of fresh wet soil Md= weight of oven-dry soil*

$$Volumetric\ soil\ water = Gravimetric\ soil\ moisture \times bulk\ density \qquad (10)$$

$$Water\ storage\ in\ a\ horizon\ (mm) = \frac{volumetric \times soil\ depth}{10} \qquad (11)$$

Total available water (TAW) was calculated as the soil's ability to hold water and make it available to crops following rainfall It's a measure for how much water a plant obtains from its roots zone. Equation 12;

$$TAW = 1000(\theta FC - 0.5\theta PWP)Zr(mm) \qquad (12)$$

*Where; TAW as the quantity of water in the root zone;* ***Zr*** *representing the rooting depth; θ FC; field capacity; θ PWP permanent wilting point* ($m^3m^3$).

Readily available water (RAW) indicates the fraction of readily available water in which a crop can extract devoid of stress (Karuku et al., 2011; Karuku et al., 2012). RAW was computed using Eqn 13.

$$RAW = pTAW(mm) \qquad (13)$$

Where p factor is the average available water index (TAW) that can be exhausted from the before the reduction in ET occurs and optimal yield cannot be realized. Most crops $\boldsymbol{p}$ ranges between 0-1. For the sweet potato, the p-factor was 0.65. However, $\boldsymbol{p}$ is only applicable when ETc = 5mm/day. Therefore, in situations where ETc > 5mm/day, $\boldsymbol{p}$ is given by Eqn 14;

$$p = p(0.65) + 0.04\,(5 - ETc) \qquad (14)$$

### 4.4.4 Modelling for soil water retention using the RETC Model

The retention curve model (RETC) is a computer software that is used to calculate the hydraulic conductivities and water retention functions of unsaturated soils in field circumstances (Huang et al., 2021). Given the pedo-transfer functions (PTFs), the model may be used to estimate the soil moisture characteristic curve of any given soil. This model incorporates three predictors PTFs: i) soil textural classes, ii) sand, silt, and clay percentages (SSC) and iii) % Sand, silt, clay and soil bulk density. The unknown model parameters are estimated using non-linear least square calculations based on observed retention and diffusion data, in cooperating a van Genuchten model (Schaap and Leij, 2000). Using undisturbed soil samples, the soil moisture characteristic curve (SMCC) was fitted by measuring soil water content at six matric potentials. Pressure chambers were employed for pressure potentials of 0.1, 1 kPa, 20 kPa, 32 kPa, 100 kPa, 500 kPa, and 1500 kPa. Cornelis et al. (2005) and Karuku et al. (2012) explained the process. For fitting the SWRC, the Van Genuchten (1980) equation (Eqn.15) was fitted on a set of discrete points obtained in the laboratory using the Leven Marquardt approach (Marquardt, 1963).

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{(1+)(\alpha|\varphi|)^n)^{1-1/n}} \qquad (15)$$

*where; $\theta(\psi)$ volumetric soil water content $cm^{-3}cm^{-3}$; $|\varphi|$ suction pressure; $\theta_s$ saturated soil water content $m^{-3}m^{-3}$; $\theta_r$ residual soil water content $cm^{-3}cm^{-3}$; n is the measure of pore size distribution and α indicating the inverse of the air entry suction.*

### 4.4.5 Water use efficiency

Because it was impractical to calculate WUE for each component crop in the intercrop system, WUE was only calculated for the single sweet potato crop based on fresh tuber production and cumulative evapotranspiration (Koech et al., 2016; Djaman et al., 2018) Eqn 16;

$$WUE\ (kg\ /ha/mm)\ =\ \frac{Economic\ Yields}{Evapotranspiration\ (mm)} \qquad (16)$$

The water productivity of rain-fed sweet potatoes were calculated in terms of seasonal crop consumption (Igbadun et al., 2006) Eqn 17;

$$CWP\ = \frac{price \times crop\ yield}{(seasonal\ evapotranspiration)} \qquad (17)$$

The harvest index was also determined using Eqn 18:

$$HI = \frac{tuber\ weight(kg)}{weight\ of\ total\ biomass(kg)} \times 100\% \qquad (18)$$

## 4.5 Statistical data analysis

Data on all collected parameters were tabulated in an excel spreadsheet. A Pearson's correlation analysis performed using IBM-SPSS software as described by Green and Salkind (2016) to estimate the associations between climatic conditions; (effective rainfall, saturated vapour pressure deficit, ETc), soil physico-hydraulic properties, harvest indices, water use efficiencies of the test crops.

## 4.6 Results and discussions

### 4.6.1 Climate environment as a factor of crop water use and efficiency

Table 8 indicates the effective rainfall, dew point temperatures and saturation pressure deficit during the growth stages.

Table 8. Climate data collected during the phenological phases of sweet potato growth

| Season | Growth stage | Growth days | ER (mm/dec) | Dew point (°C) | SVP (Kpa) |
|---|---|---|---|---|---|
| Season (I) | Initial | 40 | 91.6 | 14.11 | 2.4 |
| | Vegetative and tuber initiation | 42 | 183.7 | 14.54 | 2.3 |
| | Tuber bulking | 39 | 18.5 | 12.78 | 2.5 |
| | Harvest | 39 | 8.4 | 10.44 | 2.6 |
| Season (II) | Initial | 40 | 159.2 | 14.92 | 2.3 |
| | Vegetative and tuber initiation | 42 | 185.1 | 15.86 | 2.3 |
| | Tuber bulking | 39 | 164.5 | 15.09 | 2.4 |
| | Harvest | 39 | 130.4 | 15.55 | 2.5 |

*Key: ER; effective rainfall, SVP; saturated water vapour pressure*

#### 4.5.1.1 Effective rainfall

In semi-arid regions effective rainfall illustrates in totality of rain water available in the crop root zone. It necessitates soil water recharge and enables a crop to meet its evapotranspiration demand (Karuku et al., 2014). Effective rainfall is mainly influenced by the land, soil, groundwater, rainfall and crop characteristics (Athar, 2020). In this regard, un-even distribution of rainfall decreases the ER, whereas a higher ET in crops creates a larger moisture depletion, hence the ER becomes indirectly proportional to the rate of water uptake by crops (Dastane, 1974; Croke and Jakeman, 2004). Lower effective rainfall values were recorded in season (I) throughout the tuber bulking and harvesting stages; 18.5 and 8.4 mmdec$^{-1}$, respectively. Similarly, higher ER were observed at initiation and vegetative development stage yielding 91.6 and 183.7 mmdec$^{-1}$, respectively. Low rainfall meant little recharge of the soil, decreasing the available water and increasing the soil matric potential, thus, decreasing plant water uptake and productivity (Kendy et al., 2003). Low ER observed in the tuber bulking stage of sweet potatoes may result in a decrease in leaf area index (LAI), vine length, and a rise in the concentration of Abscisic acid (ABA) in roots and shoots, raising metabolic toxicity and affecting production (Obidiegwu et al., 2015). These conditions are consistent with the results of (Picotte et al., 2007), which suggest that most crops have higher water use under drought conditions, thus prompting them to strengthen their competitiveness due to low available moisture. On the contrary, season (II) at the tuber bulking stage, sweet potato encountered a significantly ($p <0.05$) higher ER such that; tuber bulking, vegetative, initiation and harvesting were reported at 164.5, 185.1, 159 and 130.4 $mmdec^{-1}$, respectively, yielding a higher amount of soil water recharge relative to the atmospheric demand. Related to findings of (Karuku et al., 2014), demonstrating the effects of low rainfall on soil water as a precursor to low crop yields. These differences in ER between the two seasons (I) and (II) may be referred to as a warm-dry season with maximum water use (ETc) and a minimal water use warm-wet season.

#### 5.5.1.2 Dew point temperatures

Given constant air pressure, the dew point temperature is the temperature at which water vapour in the air condenses into dew or water droplets. It may also be described as the temperature at which both the saturation and actual vapour pressures are identical (Merva, 1975). The quantity of moisture in the air may be calculated using the dew point temperature and relative humidity. It also gives a decent indication of near-surface humidity; therefore the dew point temperature can influence stomatal closure in plants, and low humidity can impair plant production. (Kimball et al. 1997). Among other agro-climatic factors, agricultural production of sweet potatoes is also influenced by frost or dew point temperatures (Raymundo et al., 2014). Dew point temperature below 0°C are referred to as the frost point (Shank et al., 2008). Dew point temperatures recorded in season (I) ranged from 10-15 °C with lower values recorded at harvesting and tuber bulking as 10.4 and 12.8 °C, respectively. Higher dew temperatures were recorded at planting and during the vegetative growth recording 14.1 and 14.5 °C, respectively. The low dew point temperatures recorded in the critical crop’s growth stage (tuber bulking) may have impacted negatively on sweet potato survival since it experienced a low vapour condensation, hence a low soil moisture recharge thus raising crop water use in such a stage. Presence of dew creates temporary humid conditions, replenishing soil moisture and thus reducing soil water loss in ASALs (Mott and Parkhurst, 1991). On the other hand, season (II) had significantly ($p < 0.05$) higher dew point temperatures across all the growth stages. These were: 14.9, 15.9, 15.1 and 15.6 °C at planting, development, tuber bulking and upon full crop maturity, respectively. Such dew point temperatures are consistent with the findings of (Spence and Humphries, 1971), who stated that sweet potato growth is mainly affected by dew temperatures ranging from below 10 °C and damaged at 1 °C. Thus, dew point temperature together with wet-bulb temperature can be vital in determining a crops critical-damage air hence, helpful in predicting impacts of climate variation in crop production especially in semi-arid areas (Snyder and de Melo-Abreu, 2005).

#### 5.5.1.3 Saturated vapour pressure

In the changing climate regimes, saturated vapour pressure plays a hidden role especially in producing drought-resistant crops (Hsiao et al., 2019). From the study, the observed saturated water vapour pressure deficit in season (I) was; 2.4, 2.3, 2.5 and 2.6 Kpa at initiation, vegetative development, tuber bulking and harvesting stages, respectively. The lowest deficit in vapour pressure experienced was during the stage of vegetative growth and higher at tuber bulking and harvesting stages. Under high SVP conditions, transpiration increases in most terrestrial crops, hence reducing photosynthesis and carbon uptake, crop growth and thus a low water use efficiency (McDowell et al., 2008). At a higher SVP, most plants close their stomata thus decreasing $CO_2$ hence a reduction in photosynthesis, biomass production and the resultant yield. Similarly, Howell and Dusek (1995) reported a vapour pressure deficit of approximately 1.8 Kpa which resulted in a higher WUE in most crops. Similarly, these results are in collaboration with the optimum range of SVP (0.5 to 2.5 Kpa) described by Wang et al. (2004). Therefore, higher SVP at harvesting (2.6 Kpa) had no significant effect on water use since the vegetative parts had withered thus posing a unique transpiration pattern (Tambussi et al., 2007). In season (II), the observed SVP increased as the crop approached harvesting. SVP recorded were; 2.3, 2.3, 2.4 and 2.5 Kpa at planting, vegetative development, tuber bulking and upon the crop’s maturity, respectively. In general, season (II) was a warm-wet season marked by a lower SVP relative to the season (I). In conditions with a lower SVP, crops undergo a reduced transpiration rate that does not reflect water-saving capacity (Fletcher et al., 2017). Saturation vapor pressure deficits govern air dryness, and thus an increase in saturation vapor pressure may lead to a subsequent decrease in dewpoint temperature, especially in semi-arid areas, which explains the differences between season (I) and (II). Therefore, considering the effects of vapour pressure deficits on crop water use and yields is a vital aspect for future projections under rainfed agriculture with the rising levels of $CO_2$.

### 4.6.2 Soil physical characteristics: Bulk density and texture concerning crop water use efficiency

Table 9 shows the sites soil physical characteristics observed throughout the soil profile

Table 9. Soil physical characteristics

| Depth(cm) | *Pb*(g/cm$^3$) | Porosity % | Sand % | Silt % | Clay % | Textural class |
|---|---|---|---|---|---|---|
| 0-15 | 1.5301 | 42.26 | 68 | 15 | 17 | Sandy loam |
| 15-30 | 1.4689 | 44.57 | 64 | 13 | 23 | Sandy clay loam |
| 30-45 | 1.3831 | 47.81 | 60 | 15 | 25 | Sandy clay loam |
| 45-60 | 1.3025 | 50.85 | 60 | 11 | 29 | Sandy clay loam |
| Average | 1.4211 | 46.37 | 63 | 14 | 24 | Sandy clay loam |

*Key: Pb;Bulk density*

The soils in the top strata (0-15 cm) were heavily compacted due to a high bulk density that decreased down the profile. The high bulk density may have formed due to previous shallow ploughing which created an impervious layer. In such conditions, soil pores are reduced from large to intermediate, thereby impeding root penetration, water infiltration, drainage and air circulation, ensuing less plant growth thus lower yields, especially during drought (Karuku et al., 2012; Karuku and Machoge, 2016). The percentage sand decreased as clay increased down the profile, though classified as sandy clay loam textural in compliance with the USDA soil texture classification. These textural classifications correspond to those found by (Kwena et al., 2018), who found sandy clay loam texture at a depth of 0–20 cm and increasing clay content at a lower depth at the same location. Soil texture influences other soil physical properties such as soil structure, moisture availability, soil erodibility, root penetration, and fertility, as well as the physio-chemical components of the soil (Karuma et al., 2014). Producing crops under sandy soil is a promising solution to address hunger especially in developing countries (Ismail and Ozawa, 2007). However, the major issue associated with such a textural class is water deficiency and repellence (DeBano, 1981). Water repellence could be solved by the addition of a small clay content thus improving on its water retention ability (Castellini et al., 2015). In the same way, the upper horizon (0-15cm) of the soil has large interconnected pores and propensity to adjust to the degree of saturation at a rapid rate as values of suction increase, thus having a low available water capacity which affects both soils hydro limits as well as crop production.

### 4.6.3 Soil moisture retention concerning crop water use efficiencies and yields

#### 4.6.3.1 Soil moisture characteristic curve (SMCC)

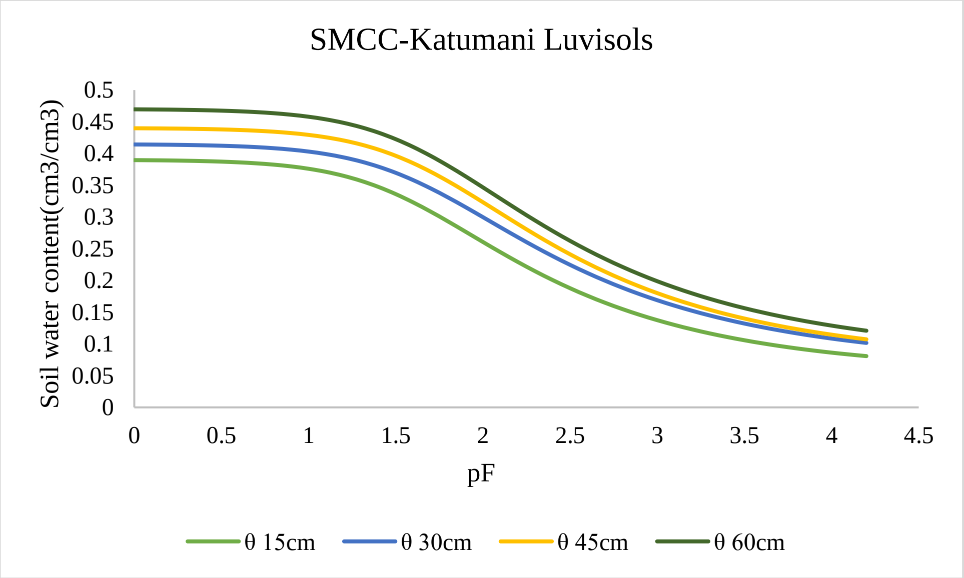


Figure 6. Soil moisture characteristic curve for Katumani Luvisols

Figure 6 presents the soil moisture characteristic curve (SMCC) for Katumani Chromic Luvisols.

The SMCC is critical in current agricultural, ecological, and environmental soil research because it emphasizes the hydro-physical link between soil water content and energy state (Cornelis et al., 2001). It provides the maximum amount of moisture that can be retained in soil and the degree of dryness to which plants can reduce the moisture content of the soil to avail moisture to plants under a particular matric (Richards and Weaver, 1944). Its slope represents the amount of moisture stored in unsaturated soils, which can be represented as gravimetric water content, volumetric water content, or saturation degree (Tian, 2014). The soils in the study area read attained field capacity at pF 2.0 and PWP at 4.2. Readily available water (RAW) ranged from between pF 3.0 to and 4.0. The soil had a greater portion of water release at pF 1.5 (water content near saturation), and decreasing as it approaches pF 3.0, though some reasonable amount of moisture was still retained in the soil pores signifying the dry and wet range of moisture in the soil. In such clay textured soils, the gradual reduction in soil water content with increased matric suction may be attributable to the pore size distribution and adsorptive forces retaining the water (Barbour, 1998; Or et al., 2002). As the soil dries, it becomes more difficult for the plant to extract water from the soil. At field capacity (maximum water content), plants use draw water at the maximum rate in this regard, when and as water content drops below field capacity, plants use draw less of its water, thus acting as an early warning system, thus facilitating agricultural production. The soil is moist and contains all the water it can keep against gravity at "Field Capacity" (FC). When soil is dry and the plant can no longer draw any more water at the "Permanent Wilting Point" (PWP). The quantity of soil water accessible for absorption by plants is determined by the difference in soil water content between field capacity and the permanent wilting point. Researchers can calculate the necessary irrigation frequency based on the plant's accessible water and the pace at which this water is drained by crops. Besides irrigation scheduling, this information can be valuable in crop growth modelling and yield prediction.

#### 5.5.3.2 Soil hydraulic functions

Table 10 show the van Genuchten parameters obtained from the RETC water equation model. The air entry suction (α) and pore size distribution (n) (van Genuchten soil parameters) for the horizons ranged from 0.0272 to 0.0218 and 1.3896 to 1.4247 $m^{-3}m^{-3}$, respectively, and higher in the top 0-15cm.

Table 10. saturated soil water content (θs,) residual soil water content (θr) and inverse of the air entry suction (α) of the study area.

| Depth (cm) | θr ($m^{-3}$ $m^{-3}$) | θs ($m^{-3}$ $m^{-3}$) | α ($cm^{-1}$) | n (-) |
|---|---|---|---|---|
| 0-15 | 0.0553 | 0.3902 | 0.0272 | 1.4247 |
| 15-30 | 0.0662 | 0.4148 | 0.023 | 1.3896 |
| 30-45 | 0.0711 | 0.4403 | 0.0208 | 1.4008 |
| 45-60 | 0.0791 | 0.4702 | 0.0218 | 1.3826 |

*Key: θs saturated soil water content* $m^{-3}m^{-3}$*; θr residual soil water content* $m^{-3}m^{-3}$ *and α indicating the inverse of the air entry suction*

Air entry value indicates the matric suction from which air starts to penetrate into the soil (Corey, 1977) voids as water empties. In unsaturated soils, the air entry suction mainly influences the seepage and the soil shear strength (Lin et al.,2021). The observed values were higher than those found by Karuku et al. (2012) in Kabete Nitisols; 0.019 and 1.922, α and n, respectively. An increase in clayey texture influenced the soil water holding capacity and consequently soil plant water relations, resulting in an increase in pore size distribution below the profile. However, the n and α in this case was relatively uniform, indicating more uniformity and distribution of pores unlike those of Karuku et al. (2012) in Kabete nitisol which has a higher clay percentage than the case of luvisols. Conversely, these parameters are dependent on the type of soil, size of voids and the depth of ground water table which determines the matric suction governing the difference between nitisols and luvisols. In chemically active soils like clay, pore fluid (water) chemistry and mineral composition are influencing parameters as well.

Table 11. Soil water content at saturation (θs), field capacity (Θfc), permanent wilting point (θpwp), total available water and the readily available water (RAW)

| Depth | θs ($m^3/m^3$) | Θfc ($m^3/m^3$) | θpwp ($m^3/m^3$) | S (mm) | FC (mm) | PWP (mm) | TAW (mm) | RAW (mm)p |
|---|---|---|---|---|---|---|---|---|
| 15cm | 0.390 | 0.188 | 0.081 | 58.44 | 28.16 | 12.12 | 16.05 | 10.43 |
| 30cm | 0.414 | 0.225 | 0.102 | 124.29 | 67.38 | 30.48 | 36.90 | 23.99 |
| 45cm | 0.440 | 0.241 | 0.107 | 197.93 | 108.56 | 48.26 | 60.30 | 39.19 |
| 60cm | 0.470 | 0.262 | 0.121 | 281.79 | 157.45 | 72.49 | 84.96 | 55.22 |

*Θs; saturated soil water content, Θfc; field capacity; θ PWP permanent wilting point; SFC cumulative water storage at field capacity; SPWP cumulative storage of water at wilting point; TAW, total available water; RAW (p) readily available water for sweet potato*

The total (TAW) and readily available water (RAW) increased down profile reflecting a change in soil texture and structure. The upper 0-15cm had low TAW which may be ascribed to the high bulk density which resulted from compaction, reducing the large soil pores to intermediate thus lowering the available water content. The observed RAW increased down the profile. This may be attributed to the differences in the textural class; from sandy loam to sandy clay loam (Table 10). On the other hand, both total (TAW) and readily available water (RAW) within the 0.6m profile depth was 49.55 and 32.21 mm, respectively. Muya et al. (2011) had similar findings with approximately 20-35 mm of the TAW in the 20 – 30cm depth on Salic luvisols coupled with a low hydraulic conductivity citing compaction as the major limiting factor in soils of the ASALs in Northern Kenya, similar to this study. The readily available water required at the critical growth stage for sweet potato was 233.0 mm, thus creating an opportunity towards adopting appropriate irrigation schedules for sustainable production of sweet potato, improving crop water uptake hence an improved economic use (WUE).

### 4.6.4 Water use efficiency, productivity and Harvest index

Table 12 presents the WUE and Harvest Index (HI) of sweet potato throughout the experimental period.

Table 12.Water Use Efficiency (WUE) and productivity

| | Season (I) | | | Season (II) | | |
|---|---|---|---|---|---|---|
| Variety | WUE ($Kg\ ha^{-1}mm^{-1}$) | HI % | CWP ($Kgm^{-3}$) | WUE ($Kg\ ha^{-1}mm^{-1}$) | HI % | CWP ($Kgm^{-3}$) |
| Kabode | 6.56 | 40.8 | 0.22 | 73.08 | 54.2 | 2 |
| Bungoma | 6.44 | 35.4 | 0.21 | 53.48 | 46.8 | 1.7 |
| LSD (5%) | 4.268 | 18.8 | 0.1408 | 9.81 | 8.1 | 0.3237 |
| SED | 1.744 | 7.71 | 0.0576 | 2.83 | 3.31 | 0.1323 |
| F pr. | 0.603 | 0.237 | 0.603 | 0.001 | 0.036 | 0.001 |
| CV % | 37.5 | 28.5 | 37.5 | 8.6 | 7.8 | 8.6 |

*Key: WUE (tuber); water use efficiency (kg $ha^{-1}mm^{-1}$), HI: harvest index, CWP: crop water productivity ($Kgm^{-3}$)*

Water use efficiency was expressed on a fresh tuber mass basis in both experimental seasons. In season (I), WUE values for Kabode and Bungoma varieties were 6.56 and 6.44 kg $ha^{-1}mm^{-1}$, respectively. On the contrary, season (II) recorded the highest WUE as Kabode and Bungoma variety yielded 73.08 and 53.48 kg $ha^{-1}mm^{-1}$, respectively. In this case, WUE depicts the economic yield produced per the unit amount of water consumed by a crop. In this regard, most crops parade lower WUE values under low or limited water supply scenarios (Jones, 2004). Lower WUE values in season (I) could have alluded to the high amount of water use (ETc) influenced by high SVP and low dew point temperatures compared to season (II) (Zhang et al., 2015). Furthermore, low WUE might occur since most crop growth phases are very long due to low-slung metabolic rates. Higher WUE values recorded in season (II) resulted from a decrease in the amount of water used up by sweet potato. This shows that in the production of sweet potato, a continuous supply of water throughout the season is needed and more interested should be taken at the tuber bulking stage (Mbayaki and Karuku 2021b). Similarly, the study observed that; an increase in water use efficiency corresponded with a decrease in sweet potato water use (ETc). This is in contrast with the findings of Jones (2004) who observed that plants tend to experience a higher water use efficiency with a low supply of water based on environmental conditions. Thus, most crops within the semi-arid experience a short humid period (warm-dry season) within their production phased and thus much water is lost to the atmosphere via transpiration and very little is actually utilized for construction of carbohydrates and composition of plant tissues (Karuku et al., 2014; Mbayaki and Karuku, 2021).

In season (I) the HI of the two varieties was 40.8 and 35.4% for Kabode and Bungoma, respectively. Whereas in season (II) an increase in the HI was observed. A such, Kabode variety had 54.2 % whereas the Bungoma variety recorded a 46.8 % harvest index. The harvest index (HI) points to the efficiency in converting of photosynthates into an economic yield (Masango, 2015). The differences in HI values between the two seasons may have resulted from the difference in watering during the growing period (ER). Similarly, Rodiyati et al. (2005) showed that prolonged water stress reduced the rate of producing biomass and may end up changing its partitioning to the storage parts thereby impacting the economic yield.

Crop water productivity (CWP) is a measure of how much crop is produced per volume of water used (Kang et al.,2017). The CWP indices in season (I) were 0.22 and 0.21 $kgm^{-3}$ for Kabode and Bungoma varieties, respectively. Whereas in season (II) higher CWP values were recorded compared to season (I) as Kabode had CWP indices of 2.0 $kgm^{-3}$ while Bungoma variety had 1.7 $kgm^{-3}$. Climate, irrigation water management, and soil nutrient status can all be accounted for differences in CWP indices (Zwart and Bastiaanssen, 2004). Studies by Dong et al. (2001) in China found that the maximum CWP may go up to 2.20 $kgm^{-3}$ upon application of manure and mulch improved soil water and temperature. Similarly, Karuku et al. (2014) indicated that incorporating residue in a cropping system may optimize on increasing soil water storage and thereby increasing crop economic yields as well as crop water productivity.

### 4.6.5 Correlation matrix on the influence of climatic and soil environment on sweet potato water use efficiency

The relationship between climatic, soil environment and water use and productivity are shown in Table 13.

Table 13. Pearson's correlation with sweet potato water use, to climatic and soil parameters

| | Pb | DEW | SVP | ΘFC | ΘPWP | TAW | WUE |
|---|---|---|---|---|---|---|---|
| DEW | -0.858 | | | | | | |
| SVP | -0.284 | -0.154 | | | | | |
| ΘFC | -.964* | 0.842 | 0.101 | | | | |
| ΘPWP | -.994** | 0.812 | 0.384 | 0.938 | | | |
| TAW | -.983* | 0.816 | 0.420 | 0.900 | .994** | | |
| WUE | -.991** | 0.791 | 0.331 | .970* | .990* | .968* | |
| CWP | -0.805 | .994** | -0.197 | 0.778 | 0.756 | 0.769 | 0.725 |

***. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).*

Correlation analysis revealed significant positive and negative associations among the parameters. Strong positive significant correlations ($P < 0.05$) were found between WUE and ΘFC, ΘPWP and TAW were; R= 0.970*, 0.990* and 0.968*, respectively. Whilst negatively correlated with bulk density (R= - 0.991*). Likewise, sweet potato water productivity also had a positive significant correlation with ($P < 0.05$) dew point temperatures (R=0.994**). The soil bulk density on the other hand yielded a significant negative correlation with all the soil water parameters such as ΘFC, ΘPWP and TAW yielding -0.964* -0.994** and -0.983*, respectively. A positive correlation mainly depicts a situation whereby both variable increases with the same magnitude whereas in a negative correlation, one increases whereas the other decreases (and vice versa). It can be observed that most soil water parameter, positively correlated with WUE and CWP. This implied that water availability in the soil-plant water relation plays a key role in photosynthesis as well as dry matter production in most crops (Muller et al., 2011). A decrease in TAW creates water deficit conditions hence have a resultant decrease in photosynthesis and WUE. Under such conditions, stomatal closure lessens $CO_2$ uptake hence reduction in biomass production as well as WUE and productivity. This, therefore, calls for developing appropriate irrigation schedules to substantiate the water needed for producing crops in such an environment. Significant ($P< 0.05$) negative correlation between pedo-transfer functions of bulk density with WUE, CWP and TAW were observed. As such, TAW decreased with increasing soil bulk density, similar to the findings of Zhou et al. (2010). This could be linked to compaction which reduced the air capacity and soil available water capacity. Changes in soil bulk density may strongly influence the permeability, drainage of the soil not limited to root penetration (Archer and Smith, 1972).

### 4.6.6 Conclusion and Recommendation

The current research looked at the effect of soil and environmental conditions on sweet potato water productivity. Kabode and Bungoma varieties varied greatly in their ability to effectively use water, demonstrating their adaptability in such a peculiar climate. The dew point temperatures and saturation pressure deficit had no significant impact on sweet potato WUE. The soil bulk density negatively impacted on TAW and RAW thus, sweet potato water productivity. There is also an unknown source of heterogeneity in sweet potato WUE that may be due to other variables not included in this analysis. These results can be useful in making decisions in the context of climate change. The findings call for further research into the relationships between crop water productivity in relation to nutrient and Photosynthetic Active Radiation (PAR) intercepted by the crop.

# CHAPTER FIVE

# PREDICTING THE IMPACT OF CLIMATE CHANGE ON WATER REQUIREMENTS FOR DIRECTLY SOWN RAIN-FED SWEET POTATO IN THE SEMI -ARID KATUMANI REGION, KENYA

## 5.1 Abstract

In the wake of the changing climate, the current water crisis seems to be tightening its hold on the human race, hence estimation is an integral part of planning, development and management of water resources of the country based on several meteorological parameters. The study hypothesized no significant changes in water requirements sweet potato crop for the next 20 years in Katumani, Kenya. The study predicted the implications of climate change on crop water requirements for the short rain seasons between 1991-2016 (baseline) and future from 2020-2039 in Katumani with the aid of the CROPWAT 8.0 model. Crop Water Requirements (CWR) were projected in two scenarios: i) Average rainfall and temperature of baseline period (1991-2016), ii) rainfall and temperature predicted in 2039 based on Relative Concentration Pathways (RCP); 8.5 and 2.6 scenarios, adopting the global circulation models (GCM) of IPSL-CM5A-MR and GFDL-CM3 for predicting monthly rainfall and temperature, respectively. To achieve effective water allocation and planning, data on sweet potato water requirements, irrigation withdrawals, soil types and climate conditions were gathered from the study area. Assumptions: The study assumed no change in the conditions relating to irrigation and crop production in the future. Sweet potato water requirement in the baseline period were modelled at 579.9 mm whereas predicted under RCP 2.6 and 8.5 to be 634.1 and 639.3mm, respectively. However, during the actual production period, the sweet potato had WR of 622.1 and 448.1mm and thus demanding 339.5 and 89.7mm of irrigation water for S(I) and S(II), respectively. Averagely, a 16.7% decrease in effective rainfall may increase the overall sweet potato WR by 10.2%. This may be due to increased temperature and reduced rainfall. Short rain season is the most appropriate for production of rain fed crops in Katumani. This study is useful in explaining the adverse impacts of climate change mostly on sweet potato water needs in Katumani and in helping to plan and manage water resources for many other crops in arid regions.

Key words; Water conservation, sweet potato production, irrigation scheduling, temperature and rainfall

## 5.2 Introduction

The advancement in agricultural modelling has smoothed precision farming and subsequently improved on producing crops (Muli et al., 2015). To adjust varying weather patterns, especially rainfall events, crop simulation models have compelled early warnings, thus aided in agricultural insurance (Johnson et al., 2018). Because of this, climate change has threatened food security, which has adversely affected smallholder farmers. (Niles and Salerno, 2018).

Globally, food security in the 21st century is threatened by climate change and projected to pose more significant impacts pertaining rain-fed agriculture (Mimi and Jamous, 2010). In most perspectives a shift in climate tends to lengthen growing seasons and rise in temperatures which may bring along negative implications such as reduced precipitation thus affecting availability of water and in turn crop water needs (Molua and Lambi, 2006; Eitzinger and Kubu, 2009).

The presence of crop water productivity models has paved way for the conjunctive assessment of environment and management factors that affect the attainment of optimal yields (Geerts et al., 2010). Combining crop water simulation models with a regular analysis of observed series of climate change scenarios, crop growth and measured soil water tension, could be optimized to resolve the varying weather conditions (Geerts et al., 2010). Crop simulation models mainly in-cooperate crop development, soil and meteorological data for the determination of crop water needs (Karuku et al., 2014).

Crop water requirements (CWR) have been predicted by various methods, however CROPWAT and AQUACROP models have been recommended by FAO since they are best suited at estimating CWR under various climate change scenarios (Raes et al., 2009). CROPWAT and AQUACROP are user-friendly models that have been widely used for computing crop water requirements and scheduling for supplemental irrigation of major rainfed crops (Oiganji et al.,2017). These computerized programs are convenient due to their simplistic to use and their input variables are much less strenuous compared to other models like DSSAT, ISAREG and APSIM (Karuku and Mbindah, 2020). CROPWAT is indeed a practical tool that allows scientists visualize results, make more informed decisions and achieve meaningful comparative output, and as such is suitable in the perspective of this study (Chowdhury et al., 2016). This model shows the percent reduction in yield resulting from water stress, and is therefore capable of calculating the requisite irrigation water needs to for optimal crop yields. (Muigai et al., 2019). A further exceptional feature of this model is that it is capable of extending deductions from studies to real scenarios that are yet to be tested in the field. (Allen et al., 1998). It also gives practical advice to farmers and extension agents on planning for additional irrigation and scheduling under varying water supply scenarios, for sustainable agriculture as well as crop growth conditions (Taylor and Bhasme, 2018).

In Kenya, several studies have predicted water consumption rates for various field crops in different regions. However, studies trying to focus on the potential impacts of climate change on CWR of sweet potato is lacking. In Katumani, sweet potato is mainly grown for food and its adoption has not been widely exploited probably due to variation in rainfall events that bring about problems in timing of planting dates (Mwololo et al., 2012). Farmers and agronomists strive to achieve sustainability in producing crops (Medrano et al., 2015). For a better managerial aspect of available scarce resources in crop production, it is more critical to understand CWR, the current level of water supplies and the possible implications of climate change in the future. The study aimed at understanding the implications of climate change on sweet potato water requirements in a semi-arid area and develop indicative irrigation schedules using the CROPWAT model as an early warning system to possible impacts of climate change and variation. Information obtained will be used in guiding farmers and agronomists on using available rainwater effectively as well as timing their crops' growth stages with rains and water requirements. These will promote the efficient effective use of such a limited resource and focus on improving realizable yields by farmers at local, county, national government and at global tiers.

## 5.3 Materials and methods

The study site, treatments, experimental design and layout and the key agronomic practices are outlined in chapter 3; section 3.3.1, 3.3.2, 3.3.3 and 3.4, respectively.

## 5.4 Data collection

### 5.4.1 Climate model

The baseline and predicted weather elements Katumani were obtained from the Climate Change Knowledge Portal of the world bank (https://climateknowledgeportal.worldbank.org-2020). This was based on the Global

Circulation Models (GCMs) adopting the IPSL-CM5A-MR and GFDL-CM3 since they provided a high correlation with the baseline average monthly precipitation and temperature, respectively (Scher, 2018; Nashwan and Shahid, 2020). This was achieved by keying in the study site's geographical coordinates. The GCM models projected; rainfall, maximum and minimum temperature based on four Representative Concentration Pathways (RCPs) representing the concentration of carbon delivering global warming per square meter across the earth. Such that; RCP 8.5 (High emission), a global warming of approximately 8.5 Wm-2, with a decreasing magnitude to RCP 6.0, 4.5 and 2.6 Wm-2 (Wayne, 2014). Such magnitudes are projected to deliver a radiation temperature rise by 2100, relative to pre-industrial temperature (Masui et al., 2011). Higher RCP numbers describe a scarier fate: which implies that more carbon dioxide has been emitted to the atmosphere, hence warming the earth and acidifying the ocean. This implies RCP 2.6 and 8.5 as the best and worst-case scenarios, respectively. This study assumed that there was no change in the conditions relating to crop production in future as each year had one cropping season which was assumed to commence in October and tapper off in March.

### 5.4.2 CROPWAT Model

This is a computer-aided application for the calculation of crop water and irrigation needs based on; soil, climate and crop. (Smith, 1992). It is an irrigation problem corresponding software which helps to determine the amount of water and timing of irrigation schedules under rain water supply based on monthly meteorological data obtained. Crop growth and soil data were collected directly from the field (Karuku et al., 2014; Ikudayisi and Adeyemo, 2017).

#### 5.4.2.1 Crop water requirements (CWR)

In order to estimate water needs of sweet potato, the model required the following datasets from the site: (a) Monthly rainfall data (b) Sweet potato data included cropping pattern, dates of planting and harvesting, data on crop coefficients ($K_c$ values), rooting depth and days at each growth stage, moisture depletion fraction (c) Total area planted (ha) (d) $ET_o$ values based on daily/decade/monthly climatic data on relative humidity, sunshine hours, maximum and minimum temperature and the speed of wind, utilizing the Penman-Monteith (1948) equation as described by Beven (1979) and updated by Allen et al. (2006) in calculating crop evapotranspiration, Eqn 19.

$$\gamma ETo = \frac{\Delta(Rn - G) + \rho a\, Cp \frac{es - ea}{ra}}{\Delta + \gamma(1 + \frac{rs}{ra})} \qquad (19)$$

Where Rn - net radiation, G- soil heat flux, (es - ea) - air vapour pressure deficit, ρa- mean air density under constant pressure, Cp- specific heat capacity of the air, Δ- slope of the relationship between saturation vapour pressure and temperature, γ is the psychometric constant, and rs and ra are the (bulk) surface and aerodynamic resistances

Sweet potato water requirement was calculated using equation 20; (Gomes and Carr, 2003), based on the growth stage, crop coefficient values and the sites reference evapotranspiration.

$$ET\ sweet\ potato = ETo \times Kc \qquad (20)$$

### 5.4.2.2 Scheduling for irrigation

An irrigation schedule specifies the time and quantity of water to be supplied to the crop under soil moisture deficit conditions. It is primarily intended to supply water in the precise amounts and time. In order to accomplish these, the CROPWAT model required in-situ data on; (a) Type of soil, initial soil moisture depletion, maximum sweet potato rooting depth, total available water in soil (TAW) reflects the difference in moisture levels between field capacity and wilting point (b) Scheduling category had several computations relating to the timing as well as the depth of water application which should be irrigated in order to restore the soils water status to field capacity once the available soil moisture has been exhausted.

Effective rainfall was computed based on the United States Department of Agriculture in the model, Soil Conservation Service (USDA-SCS) method as described by Dastane (1978) using Eqn 21.

$$eff = \frac{tot \times 125 - 0.2tot}{125} \qquad (21)$$

where, $_{\text{eff}}$ = effective rainfall (mm) and $_{\text{tot}}$ = total rainfall (mm) was used since $_{\text{tot}} \leq 250$ mm.

TAW was calculated according to FAO irrigation and drainage paper 56 Eqn 22.

$$TAW = 1000(\Theta fc - \Theta wp)Zr \quad (22)$$

Where TAW-total available water in the root zone, FC-field capacity, WP-wilting point and Zr rooting depth of the crop in question.

## 5.5 Statistical analysis

This was done with the aid of GenStat 19th edition (Lane and Payne, 1997). A two-way ANOVA was used to determine means significant differences in the current and projected sweet potato water needs. A Bonferroni test of significance was performed at $P \leq 0.05$ on climate change scenarios effect on sweet potato irrigation water needs.

## 5.6 Results and discussion

### 5.6.1 Weather data

The modelled baseline and predicted monthly climatic data are shown in Table 14 and 15, respectively.

Table 14.Monthly climatic data experienced during the baseline period 1991-2016

| Month | T-Max°C | T-Max°C | RH % | Wind (km/day) | SH | Rad (MJ/m²/day | ETo (mm/day) | Rain (mm) | Eff rain (mm) |
|---|---|---|---|---|---|---|---|---|---|
| January | 12.3 | 25.5 | 69 | 95 | 10.5 | 25.2 | 4.53 | 32.9 | 31.2 |
| February | 13.2 | 26.4 | 59 | 112 | 10.4 | 25.7 | 4.93 | 23.6 | 22.7 |
| March | 12.4 | 26.7 | 49 | 120 | 9.3 | 24.1 | 4.94 | 58.9 | 53.3 |
| April | 11.7 | 26.1 | 60 | 112 | 7.9 | 21.1 | 4.25 | 113 | 92.6 |
| May | 11.4 | 25.2 | 68 | 95 | 7.7 | 19.6 | 3.72 | 82.3 | 71.5 |
| June | 10.7 | 24.1 | 70 | 95 | 7.7 | 18.8 | 3.45 | 35.9 | 33.8 |
| July | 10.2 | 23.5 | 61 | 112 | 6 | 16.7 | 3.36 | 26.6 | 25.5 |
| August | 10.4 | 23.8 | 52 | 130 | 4.9 | 16.1 | 3.62 | 30.8 | 29.3 |
| September | 11.2 | 24.6 | 61 | 166 | 7.5 | 20.9 | 4.31 | 28.8 | 27.5 |
| October | 11.8 | 25.3 | 69 | 164 | 8.6 | 22.8 | 4.46 | 66.6 | 59.5 |
| November | 11.6 | 25.1 | 73 | 120 | 8.1 | 21.6 | 4.07 | 102.4 | 85.6 |
| December | 11.2 | 25.1 | 79 | 112 | 8.6 | 22 | 3.97 | 55.9 | 50.9 |
| Average | 11.5 | 25.1 | 64 | 119 | 8.1 | 21.2 | 4.14 | 657.7 | 583.3 |

*Key: RH; relative humidity, T-max; maximum temperature, T-min; minimum temperature, SH; sun hours per day, Rad; radiation; ETo; evapotranspiration*

*Source: https://climateknowledgeportal.worldbank.org*

Table 15.Predicted monthly climate for the year 2039.

| | RCP 2.6 (2039) | | | | | RCP 8.5 (2039) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Month | T-Max°C | T-Max°C | Rain (mm) | ER (mm) | ETo (mm/day) | T-Max°C | T-Max°C | Rain (mm) | ETo (mm/day) | ER (mm) |
| Jan | 18.8 | 29.3 | 21 | 20.3 | 5.01 | 18.6 | 29.6 | 23.9 | 4.99 | 23 |
| Feb | 19.6 | 32.1 | 22.3 | 21.5 | 5.58 | 20 | 32.3 | 18.8 | 5.61 | 18.2 |
| Mar | 21 | 33.2 | 49.6 | 45.7 | 5.68 | 21 | 33.3 | 49.4 | 5.69 | 45.5 |
| Apr | 22.1 | 32.6 | 110.3 | 33.2 | 5 | 22.1 | 32.9 | 41.9 | 5.03 | 88.2 |
| May | 21.8 | 30.5 | 87.9 | 43.2 | 4.36 | 21.8 | 30.7 | 43.6 | 4.38 | 71.6 |
| Jun | 20.3 | 28.8 | 28.1 | 26.8 | 4 | 20.3 | 29.1 | 31.6 | 4.01 | 30 |
| Jul | 19.6 | 28.7 | 25.8 | 24.7 | 3.87 | 19.9 | 28.9 | 25.5 | 3.89 | 24.5 |
| Aug | 20 | 28.9 | 29.9 | 28.5 | 4.16 | 20.1 | 29.3 | 27.8 | 4.19 | 26.6 |
| Sep | 20.6 | 29.6 | 27.5 | 26.3 | 4.99 | 20.7 | 29.7 | 24.1 | 5.01 | 23.2 |
| Oct | 20.8 | 28.6 | 35.2 | 90.8 | 5.05 | 20.9 | 28.4 | 106.2 | 5.03 | 39.1 |
| Nov | 20.1 | 26.1 | 55.4 | 50.5 | 4.42 | 20.2 | 26.3 | 56.3 | 4.46 | 51.2 |
| Dec | 18.9 | 26.2 | 45.5 | 75.5 | 4.26 | 18.8 | 23.6 | 82.5 | 4.08 | 40.6 |
| Average | 20.3 | 29.6 | 538.5 | 486.1 | 4.7 | 20.4 | 29.5 | 531.6 | 4.7 | 481.6 |

*Key: T-max; maximum temperature, T-min; minimum temperature, ETo; evapotranspiration, ER; Effective rainfall Source: https://climateknowledgeportal.worldbank.org*

### 6.5.1.1 Reference evapotranspiration

Reference evapotranspiration (ETo) values in the baseline period (1991-2016) and predicted scenarios are presented in Table 14 and 15, respectively. In the baseline period, ETo values ranged from 33–49 $m^{-3}ha^{-1}day^{-1}$. The highest ETo values observed in march and February were 49.3 and 49.4$m^{-3}ha^{-1}day^{-1}$, respectively. On the other hand, the lowest ETo recorded in June and July were 34.5 and 33.6 $m^{-3}ha^{-1}day^{-1}$, respectively. ETo reflects the capacity of atmospheric evaporation on the crop water needs relative to the prevailing weather conditions (Croitoru et al., 2013). The higher ETo could be due to the low amount of rainfall received in February and march as well as high temperatures experienced which depicted dry summer conditions. Such variations in ETo may be an indicator of how the time of planting tends to affect the crop water needs and the resultant economic yield. Essentially, CWR are mainly pegged on the balance between rainfall and evapotranspiration (root and leaf demand), thus influencing soil moisture status which may call for supplemental irrigation (Doria, 2011). In 2020-2039, the projected ETo ranged between 39 to 57 $m^{-3}ha^{-1}day^{-1}$ for both RCP 2.6 and 8.5. Similar to the baseline period, highest projected ETo were 56.8 and 5.69 $m^{-3}ha^{-1}day^{-1}$ for RCP 2.6 and 8.5, in February and march, respectively. On the other hand, the lowest projected ETo in RCP 2.6 and 8.5 was and 38.7 and 38.9 $m^{-3}ha^{-1}day^{-1}$, respectively. 2020-2039 was projected to experience 13.5 % rise in mean annual ETo. Additionally, a rise in the projected ETo may generate stress to sweet potato as a result of intense evapotranspiration experienced thus, affecting its water requirements as well as modifying its growth cycle

(Motsa et al., 2015. Such may be due to the decreasing humid conditions predicted thus, a premonition that the highest sweet CWU may be experienced in 2039, especially in February and March whereas lowest in June and July. Therefore, most crops under rainfed should be grown between October and March in Katumani since projections indicate that most crop will have a low water consumptive rate.

#### 6.5.1.2 Effective rainfall

Rainfall is pivotal when it comes to rainfed agriculture like Katumani. Its distribution and intensity effects the production of crops, since agricultural drought turns out to be the major uncertainty in attaining food security. Effective rainfall of Katumani was computed based on the (USDA Soil Conservation Service) from rainfall received during the baseline period and that projected to occur between 2020-2039. The total effective rainfall received in in the baseline period was 583.3mm, with lowest recorded in February, July and September being 22.7mm, 25.5mm and 27.5mm, respectively. This preceded the start of the second short rain season. This short rain season recorded a higher effective rainfall in October, November and December having 66.6mm, 102.4mm and 55.9 mm, respectively. However, this was not the same case in January and February which recorded a low amount of rainfall; 32.9mm and 23.6mm, respectively. On the other hand, the predicted annual effective rainfall from 2020-2039 was 486.1 and 481.6mm from RCP 2.6 and 8.5, respectively; recorded a 16.7% decline. Discrepancies in the proportion of effective rainfall received during the baseline and projected period may be due to climate change and variation and showed that the effect of rainfall variations may lead to an increase in irrigation water needs. In this regard, planting sweet potato between low rainfall months from April to September under rainfed conditions may not be practical as the crop may demand a higher amount of irrigation water to argument for its transpiration needs to satisfy the atmospheric evaporative demand (Karuku et al., 2014).

#### 6.5.1.3 Temperature

Temperatures observed during the baseline cropping season ranged from 10°C to 26°C with the highest recorded in March and lowest in July as 26.7 and 10.2 °C, respectively. However, this temperature range has been considered high for sweet potato production by Negeve et al. (1992), which thrives well at 15-25 °C. On the other hand, the projected mean annual temperature from 2020-2039 will be 6.7°C higher than one experience during the baseline period (1991-2016). As such, average maximum and minimum temperature were 29.6 and 20.3°C, and 29.5 and 20.4°C for RCP 2.6 and 8.5, respectively. This was a 36.3% increase in mean annual temperatures, thereby suggesting a significant warming trend in the study area. Chowdhury et al. (2013) had similar findings and stated that a 1% increase in temperature may increase the overall CWR by 2.9% and concurs with our study. For sweet potato production, temperatures < 15°C deter root formation, whereas those >25°C affect photosynthesis as well as partitioning of biomass since the plants to use more energy for respiration for their maintenance and with less to support their growth (Eguchi et al., 2003). Additionally, higher temperatures cause plants to complete their growth cycle more rapidly with less time to reproduce and more likely, lower sweet potato yields (Craufurd and Wheeler, 2009; Hatfield et al., 2011). The shorter life span in sweet potato may be probably due to variances in partitioning dry mater to fibrous roots rather than the storage roots thus reding the sink strength of the test crop (Thorne et al., 1983).

### 5.6.2 Crop and irrigation water requirement (CWR)

#### 5.6.2.1 Effects of climate change on sweet potato water needs

Tables 16,17 and 18 indicates the baseline and predicted modelled WR for sweet potato

Table 16.Sweet potato water requirement for under rain fed agriculture in Katumani Research station for the baseline period (1991-2016).

| Month | Decade | Stage | Kc coeff | ETc (mm/day) | ETc (mm/dec) | Eff rain (mm/dec) | CIR (mm) |
|---|---|---|---|---|---|---|---|
| Oct | 2 | Init | 0.4 | 1.78 | 7.1 | 8 | 0 |
| Oct | 3 | Init | 0.4 | 1.73 | 19 | 22.9 | 0 |
| Nov | 1 | Init | 0.4 | 1.68 | 16.8 | 27.5 | 0 |
| Nov | 2 | Init | 0.4 | 1.63 | 16.3 | 31.4 | 0 |
| Nov | 3 | Deve | 0.43 | 1.73 | 17.3 | 26.6 | 0 |
| Dec | 1 | Deve | 0.6 | 2.41 | 24.1 | 20.4 | 3.7 |
| Dec | 2 | Deve | 0.79 | 3.16 | 31.6 | 16.3 | 15.3 |
| Dec | 3 | Deve | 1 | 4.14 | 45.6 | 14.3 | 31.2 |
| Jan | 1 | Mid | 1.18 | 5.12 | 51.2 | 12.2 | 39 |
| Jan | 2 | Mid | 1.21 | 5.47 | 54.7 | 9.9 | 44.8 |
| Jan | 3 | Mid | 1.21 | 5.63 | 62 | 9.1 | 52.8 |
| Feb | 1 | Mid | 1.21 | 5.8 | 58 | 7.3 | 50.7 |
| Feb | 2 | Late | 1.16 | 5.75 | 57.5 | 5.8 | 51.7 |
| Feb | 3 | Late | 0.99 | 4.89 | 39.1 | 9.8 | 29.3 |
| Mar | 1 | Late | 0.8 | 3.97 | 39.7 | 14.1 | 25.6 |
| Mar | 2 | Late | 0.6 | 2.95 | 29.5 | 17.4 | 12.1 |
| Mar | 3 | Late | 0.44 | 2.08 | 10.4 | 10 | 0 |
| Cumulative | | | | | 579.9 | 263.1 | 356.1 |

Table 17. Predicted water requirement for sweet potato under rain fed agriculture in Katumani Research station in 2039 based on RCP 2.6

| Month | Decade | Stage | Kc Coeff | ETc (mm/day) | ETc (mm/dec) | Eff rain (mm/dec) | CIR (mm) |
|---|---|---|---|---|---|---|---|
| Oct | 2 | Init | 0.4 | 0.81 | 8.1 | 4.2 | 2.8 |
| Oct | 3 | Init | 0.4 | 2.13 | 21.3 | 12.7 | 8.6 |
| Nov | 1 | Init | 0.4 | 1.85 | 18.5 | 15.7 | 2.8 |
| Nov | 2 | Init | 0.4 | 1.77 | 17.7 | 18 | 0 |
| Nov | 3 | Deve | 0.43 | 1.87 | 18.7 | 16.7 | 2 |
| Dec | 1 | Deve | 0.6 | 2.53 | 25.3 | 15.4 | 9.9 |
| Dec | 2 | Deve | 0.78 | 3.26 | 32.6 | 14.7 | 17.9 |
| Dec | 3 | Deve | 0.98 | 4.35 | 47.9 | 12 | 35.8 |
| Jan | 1 | Mid | 1.16 | 5.51 | 55.1 | 8.5 | 46.6 |
| Jan | 2 | Mid | 1.19 | 5.94 | 59.4 | 5.7 | 53.7 |
| Jan | 3 | Mid | 1.19 | 6.17 | 67.8 | 6.2 | 61.6 |
| Feb | 1 | Mid | 1.19 | 6.39 | 63.9 | 6.3 | 57.6 |
| Feb | 2 | Late | 1.14 | 6.38 | 63.8 | 6.1 | 57.6 |
| Feb | 3 | Late | 0.97 | 5.47 | 43.7 | 9.2 | 34.6 |
| Mar | 1 | Late | 0.79 | 4.47 | 44.7 | 11.9 | 32.8 |
| Mar | 2 | Late | 0.59 | 3.36 | 33.6 | 14.3 | 19.3 |
| Mar | 3 | Late | 0.44 | 2.4 | 12 | 8.9 | 2.2 |
| Cumulative | | | | | 634.1 | 186.6 | 445.9 |

*Key: Init; initiation; Dev = development, Mid; reproductive, late; maturity, Eff; effective rain, CIR; Crop irrigation requirements, Kc; crop coefficient, ETc; sweet potato crop evapotranspiration*

Table 18. Predicted crop water requirement for sweet potato under rain fed agriculture in Katumani Research station in 2039 based on RCP 8.5

| Month | Decade | Stage | Kc coeff | ETc (mm/day) | ETc (mm/dec) | Eff rain (mm/dec) | CIR (mm). |
|---|---|---|---|---|---|---|---|
| Oct | 2 | Init | 0.4 | 0.81 | 8.1 | 5.3 | 1.5 |
| Oct | 3 | Init | 0.4 | 1.93 | 21.3 | 14.5 | 6.8 |
| Nov | 1 | Init | 0.4 | 1.85 | 18.5 | 16.4 | 2.1 |
| Nov | 2 | Init | 0.4 | 1.77 | 17.7 | 18.1 | 0 |
| Nov | 3 | Deve | 0.43 | 1.88 | 18.8 | 16.6 | 2.2 |
| Dec | 1 | Deve | 0.6 | 2.59 | 25.9 | 14.9 | 11 |
| Dec | 2 | Deve | 0.78 | 3.36 | 33.6 | 13.8 | 19.8 |
| Dec | 3 | Deve | 0.98 | 4.45 | 48.9 | 11.8 | 37.2 |
| Jan | 1 | Mid | 1.16 | 5.54 | 55.4 | 9.2 | 46.2 |
| Jan | 2 | Mid | 1.19 | 5.97 | 59.7 | 7.1 | 52.6 |
| Jan | 3 | Mid | 1.19 | 6.2 | 68.2 | 6.8 | 61.4 |
| Feb | 1 | Mid | 1.19 | 6.43 | 64.3 | 5.6 | 58.7 |
| Feb | 2 | Late | 1.15 | 6.42 | 64.2 | 4.6 | 59.7 |
| Feb | 3 | Late | 0.98 | 5.5 | 44 | 8.1 | 35.9 |
| Mar | 1 | Late | 0.79 | 4.5 | 45 | 11.7 | 33.3 |
| Mar | 2 | Late | 0.59 | 3.37 | 33.7 | 14.5 | 19.2 |
| Mar | 3 | Late | 0.44 | 2.41 | 24.1 | 8.8 | 2.3 |
| Cumulative | | | | | 639.3 | 187.8 | 449.7 |

*Key: Init; initiation; Dev = development, Mid; reproductive, late; maturity, Eff; effective rain, CIR; Crop irrigation requirements, Kc; crop coefficient, ETc; sweet potato crop evapotranspiration*

The modelled baseline period sweet potato water requirements for the short rain season were 579.9mm, whereas the predicted were 631.4 and 639.3mm, based on RCP 2.6 and 8.5 scenarios, respectively. From the observed baseline period, the highest ET sweet potato was at the tuber bulking stage (mid-season) amounting to 56.5mmdec$^{-1}$, with lowest recorded during initiation 14.8 mmdec$^{-1}$. During the sweet potato tuber bulking stage, the ET increased from 5.12, 5.47, 6.63 and 5.8 mmday$^{-1}$ for decade 1, 2 3 and 1, respectively (Table 16). Similarly, the total effective rainfall in these stages was 38.5 and 89.5 mmdec$^{-1}$ at the sweet potato tuber bulking and initiation stages, respectively.

The low kc value recorded at sweet potato initiation stage (0.4) signified that the crop had not been fully developed and hence water losses were mainly through evaporation from the soil hence low water needs. Similarly, the high kc value at tuber bulking stage (1.19) showed a fully developed sweet potato crop, with a larger leaf area and canopy cover and thereby having a high-water use and hence it needed much water for to argument for the one transpires (Karuku et al., 2014). This is because the sweet potato had increased its proportion of transpiration relative to the amount of soil evaporation. Sweet potato sensitivity to water shortages sets in at the tuber bulking stage and therefore effective rainfall recorded at the bulking stage was not sufficient for the production of biomass which probably may have led to the entire sweet potato yield reduction (Ky) (Gajanayake et al., 2013).

The projected modeled sweet potato water requirements between 2020-2039 were significantly ($p < 0.05$) higher than the baseline period, demonstrating implication of climate change on the soil water balance, resulting to changes of soil evaporation and plant transpiration and thus impacting on water productivity. Increasing CWR may pose a major challenge to the non-renewable ground water resources in Katumani region. Such observations concur with the highest amount of predicted sweet potato irrigation water needs in Table 17 and 18. Similarly, Onyancha et al. (2017) within the same county in Mwala, recorded 674.9 mm water needs for maize during the dry season, stating that most crops parade a higher water use during dry season compared to the wet ones.

In regions characterized with warm-dry seasons have a maximum water use (ETc), then the warm-wet season have a low water use, similar to our case. The modeled projected ET sweet potato at RCP 2.6 during; initiation, vegetative, tuber bulking and at harvest were 65.6, 124.2, 246.2 and 197.8 mm, respectively. This calls for a higher irrigation water demand to meet sweet potato evapotranspiration demand in Table 17 and 18. At the tuber bulking stage, the actual evapotranspiration is projected to be less than the maximum crop evapotranspiration (ETa < ETm) and therefore the crop is expected to experience water deficits and the model suggested an irrigation requirement of 219.5 mm in order to realize optimal yields. This clearly shows that future predictions of climate change especially in areas with high rainfall will receive more while the dry areas will become drier and thus have a higher demand for water (Liu and Allan, 2013). This reduction in rainfall will have a greater impact in areas where soils have a low level of organic carbon and therefore retain less water at low moisture potential, thus calling for appropriate soil and water management strategies (Clair and Lynch, 2010).

#### 5.6.2.1.1 Actual sweet potato water requirements for SI and SII during the study

Table 19 presents the water needs for sweet potato on real-time basis for the two production seasons (SI and SII)

Table 19.Sweet potato water requirements

| | | **S (I)** | | **S (II)** | |
|---|---|---|---|---|---|
| Stage | Kc | ETc (mm/dec) | CIR (mm/dec) | ETc (mm/dec | CIR (mm/dec) |
| Init | 0.4 | 0 | 0 | 0 | 0 |
| Init | 0.4 | 0 | 0 | 0 | 0 |
| Init | 0.4 | 0 | 0 | 0 | 0 |
| Init | 0.4 | 35.3 | 25.9 | 35.6 | 17.6 |
| Deve | 0.41 | 14 | 22 | 66.5 | 9.2 |
| Deve | 0.54 | 0 | 0 | 31.7 | 0 |
| Deve | 0.74 | 0 | 0 | 28.9 | 0 |
| Deve | 0.94 | 5.5 | 27.2 | 32 | 0 |
| Mid | 1.14 | 34 | 74 | 68.2 | 0 |
| Mid | 1.21 | 54.7 | 37.9 | 53.1 | 1.2 |
| Mid | 1.21 | 62.1 | 47.4 | 79.5 | 19.1 |
| Mid | 1.21 | 177.5 | 93.6 | 62.6 | 20.3 |
| Late | 1.19 | 239 | 11.5 | 30 | 22.3 |
| Late | 1.05 | 0 | 0 | 0 | 0 |
| Late | 0.87 | 0 | 0 | 0 | 0 |
| Late | 0.66 | 0 | 0 | 0 | 0 |
| Late | | 0 | 0 | 0 | 0 |
| Cumulative | | 622.1 | 339.5 | 488.1 | 89.7 |

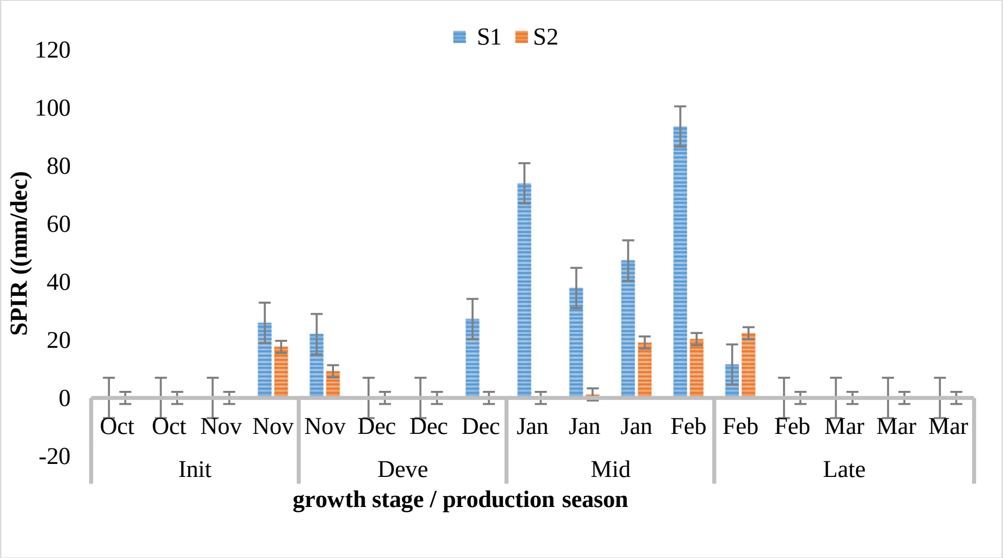
*Key: Init; initiation; Dev = development, Mid; reproductive, late; maturity, Eff; effective rain, CIR; Crop irrigation requirements, Kc; crop coefficient, ETc; sweet potato crop evapotranspiration Source: CROPWAT 8.0 output.*

During the study period, the cumulative seasonal actual ET for sweet potato in S (I) was 622.1mm, whereas in S (II), it was 488.1 mm. This accounted for a 2.2% decrease in ETa, necessitating 339.5 and 89.7mm of irrigation water, respectively. Similarly, across both seasons, the highest water use was recorded during the tuber development stage in S(I) and S(II) were 262.9 and 40.6 mm, respectively, depicting 85% decrease in ET sweet potato.

Most regions in the ASALs are characterised by warm-dry climatic scenarios, and crops exhibit a maximum water use (ETcrop) whereas in the warm-wet ones there is low water use. Such scenarios could have been aggravated by the low amount rainfall received in S(I), creating minimal soil water recharges, low aridity indices and eventually shortening the humid period (Karuku et al., 2014). Such water supply deficits are caused by an erratic distribution of rainfall, creating a significant imbalance in the soil water budget, hence senescence of crops at a faster rate and thus a shorter life span to escape water stress. This therefore explains the discrepancies in the rates of water use in the two seasons (Thorne-Miller et al., 1983). The low (ETcrop) observed in S (II) may have been created by a longer wet seasons which may have created a balance between rainfall and evaporation (ETa=ETm); root supply and leaf demand thus minimal ETsweet potato and this probably could lead to a high-water use efficiency (Zelitch, 1975; Monteith, 1977; Mbayaki and Karuku, 2021).

### 5.6.2.1.2 Sweet potato irrigation water requirements

Figure 7 presents the trends in sweet potato irrigation water requirements during the production period on real time basis



*Error bars presents standard errors of mean irrigation water needs*

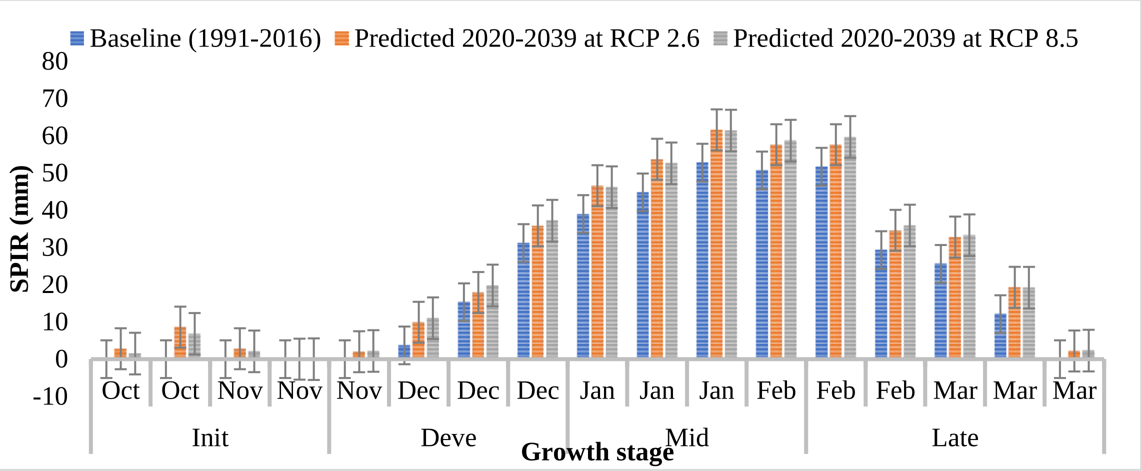
Figure 7 .Trends in sweet potato irrigation requirements the two cropping short rain seasons.

The data indicate, S(I) experienced highest irrigation water demand with tuber bulking stage of 2529 $m^{-3}ha^{-1}day^{-1}$, whereas the lowest at crop maturity stage of 115 $m^{-3}ha^{-1}day^{-1}$. The high amount of water required at tuber bulking stage could have resulted from discrepancies in the amount of water received and the resultant soil wetting condition. This implied that there was little or no water recharge in soils at this stage to argument for one lost, hence $ETa \leq ETm$. Conversely, effective rainfall (ER) was lower than the crop water need (ETc) throughout the growth period. Henceforth, maintaining soil moisture content at field-capacity in the root zone tends to maximize crop yield (Karuku et al., 2014). However, this is challenging in sandy soils with a shallow water table and low water holding capacity. Hence during such stages supplemental water plays pivotal in yield and biomass formation. Additionally, in order to achieve optimum crop performance and production of quality yield sweet potato (Opafola et al., 2018).

S(II) had significantly lower ($p \leq 0.05$) irrigation water needs ranging between 90 - 410 $m^{-3}ha^{-1}day^{-1}$, with the highest experienced at tuber bulking and lowest at the vegetative stage at 406 and 92 $m^{-3}ha^{-1}day^{-1}$, respectively. Season (II) recorded a 77.9% decrease of the total irrigation water needs for sweet potato from S(I) which cumulatively had 3395 $m^{-3}ha^{-1}day^{-1}$. The decrease could be alluded to the length of the humid period experience, characterised by frequent soil wetting and thus ETa=ETm. Sweet potato tuber formation thrives well in well-watered environments as it experiences lesser strife in obtaining eater hence more biomass is partitioned to the storage roots and thus yield and therefore supplementary irrigation is necessary during the early and late growing seasons of the crop.

### 5.6.2.2 Climate change effects on sweet potato irrigation requirements (SPIR)

Trends in sweet potato irrigation water needs at all stages of growth are shown in Figure 8.



*Error bars presents standard errors of mean irrigation demands*

Figure 8.Trends in sweet potato irrigation requirements for the short rain season of baseline period (1991-2016) and predicted from 2020-2039.

Table 20.Effects of climate change on predicted mean sweet potato irrigation needs

| | 1991-2016 | 2020-2039 | |
|---|---|---|---|
| Growth stage | Baseline | RCP 2.6 | RCP 8.5 |
| Initiation | 0.00$^{a}$ | 3.55$^{a}$ | 2.6$^{a}$ |
| Development | 12.55$^{ab}$ | 16.40$^{a}$ | 17.55$^{a}$ |
| Tuber bulking | 29.68$^{bc}$ | 54.88$^{b}$ | 54.73$^{b}$ |
| Harvest | 46.83$^{c}$ | 29.30$^{ab}$ | 30.08$^{ab}$ |
| F pr. | <.001 | 0.001 | 0.001 |

*The different letters within the same column show significant differences within the comparing variables at $p < 0.05$.*

SPIR is the amount of additional water needed for irrigation beyond precipitation in order to meet the growing season requirements for water to ensure optimum yield (Keller et al., 2008). Depicts differences between ETm and Effective Rainfall (ER) (Eteng and Nwagbara, 2014). SPIR for the baseline scenario were modeled at 356.1 mm, significantly lower than (P<0.05) the predicted were at 445.8 and 449.9 mm at RCP 2.6 and 8.5, respectively; recording a 26.3% increase. In C3 plants like sweet potato, photosynthesis relies mainly on $CO_2$ concentration (Flexas and Medrano, 2002). When crop water needs are not met, water deficit may lead to stomatal closure thus reducing the amount of water lost through evapotranspiration (Blum, 2009). Though, when the soil and plant water status are not replenished, stomatal closure lessens $CO_2$ uptake hence reduction in biomass production. In the presence of global warming, an increase in ET and $CO_2$ will lead to decrease in soil moisture deterring the soil- plant water relations (Kimball and Bernacchi, 2006). Similarly, the proportion of water transpired per unit $CO_2$ fixed brings about a crops transpiration efficiency (TE) (Blum, 2011). Under drought like conditions, TE plays a vital role in maximizing the production of biomass and the crops' primary productivity through increased $CO_2$ fixation (Gherardi and Sala, 2020). This accounts for the high irrigation requirements at the tuber bulking stage (mid) in all modeled scenarios. Such that; deficits in sweet potato water needs may lead to reduced growth and development hence yields may be affected (Kassam and Smith, 2001). Different ASALs poise varied behavior with response to the variation of rainfall and temperatures thus, farmers and agronomist should embrace irrigation schedules. Proper scheduling of irrigation will increase sweet potato yield, thus conserving water and energy, thereby reducing environmental impacts.

## 5.7 Developing indicative irrigation schedules for rain-fed sweet potato

Modeled baseline and projected irrigation schedules for sweet potato are present in Table 20

Table 21. Actual irrigation requirement, deficiency irrigation and moisture deficit at harvest of rain-fed sweet potato

| Parameter | Sweet potato | | |
|---|---|---|---|
| | (1991-2016) | Predicted (2020-2039) | |
| | Baseline | RCP 2.8 | RCP 8.5 |
| Total rainfall loss (mm) | 134.7 | 47.7 | 67.3 |
| Total irrigation losses (mm) | nil | nil | nil |
| ETa (mm) | 577.8 | 631.3 | 636.7 |
| ETm (mm) | 577.8 | 631.7 | 636.9 |
| Yield response Ky | 0.9 | 0.9 | 0.9 |
| Deficiency irrigation schedule (%) | nil | 0.1 | 0.0 |
| Efficiency irrigation schedule (%) | 100% | 100 | 100 |
| Moisture deficit at harvest (mm) | 7.6 | 26.0 | 4.8 |
| Actual irrigation requirement(mm) | 452.3 | 477.4 | 500.4 |
| Efficiency in rainfall (%) | 54.9 | 76.4 | 67.0 |

The crop evapotranspiration (ETa) required in attaining optimal sweet potato yields in Katumani during the baseline period with the aid of CROPWAT model was 579.9 mm (Table 16). Additionally, actual evapotranspiration (ETa) was equal to maximum evapotranspiration (ETm) at 577.8 mm for baseline. As such, maximum evapotranspiration (ETm) depicts growth conditions when soil water supply is not limited (Allen et al., 1998). Therefore, the modelled baseline available soil water was adequate to the crop for 160 days as the soil supplies water adequate hence the crops evapotranspiration demand and water uptake were equal, hence nil deficiency irrigation schedule recorded. However, upon maturity sweet potato encountered a 7.6 mm moisture deficit at harvest, water lost to runoff may increase deficits during rainy seasons and thereby requiring 452.3 mm irrigation water.

The predicted CWR from 2020-2039 based on GCM at RCP 2.6 and 8.5 were 634.1 and 639.3mm, respectively. Similarly, ETa and ETm using the RCP 2.6 scenario were 631.3 and 631.7mm, respectively whereas at RCP 8.5 were 636.7 and 636.9 mm, respectively. Under the modeled scenarios, ETa ≤ ETm, which implied that water supply was limited, hence sweet potato water requirements were not fully met, resulting to 0.1% yield reduction, that is reflected in the overall economic yield, hence a 477.4 and 500.4mm supplemental irrigation is required for optimal yields under RCP 2.6 and 8.5, respectively. A 0.9 Yield response (Ky) was also predicted to occur under both GCMs. Ky showed the relationship between production and water use sweet potato crop. The modelled Ky <1, showed that sweet potato was tolerant to water deficits and hence experienced a lesser reduction in yield with low water use. Sweet potato Ky <1 acted as a synthesis parameter in measuring its tolerance to water stress and an indicator to promoting successful irrigation schedules (Doorenbos and Kassam, 1979).

Table 22. Crop yield and evapotranspiration reductions at each phenological development stage

| Time | Scenarios | Growth stage | Ini | Dev | Rep | Mt | Season |
|---|---|---|---|---|---|---|---|
| 1991-2016 | baseline | Reduction in ETc | 0 | 0 | 0 | 0 | 0% |
| | | Yield response factor Ky | 0.2 | 0.4 | 0.55 | 0.2 | 0.9 |
| | | Yield Reduction | 0 | 0 | 0 | 0 | |
| | | Cumulative yield reduction | 0 | 0 | 0 | 0 | 0% |
| Predicted 2020-2039 | RCP 2.6 | Reduction in ETc | 0.6 | 0 | 0 | 0 | 0.1% |
| | | Yield response factor Ky | 0.2 | 0.4 | 0.55 | 0.2 | 0.9 |
| | | Yield Reduction | 0.1 | 0 | 0 | 0 | |
| | | Cumulative yield reduction | 0.1 | 0.1 | 0.1 | 0.1 | 0.1% |
| | RCP 8.5 | Reduction in ETc | 0.3 | 0 | 0 | 0 | 0% |
| | | Yield response factor Ky | 0.2 | 0.4 | 0.55 | 0.2 | 0.9 |
| | | Yield Reduction | 0.1 | 0 | 0 | 0 | |
| | | Cumulative yield reduction | 0.1 | 0.1 | 0.1 | 0.1 | 0% |

*Key: ETc; crop evapotranspiration and Ky; yield reduction factor, Ini; initiation (40days), Dev: development (42 days), Rep; reproductive (39 days), Mat: maturity (39 days).*

The baseline scenario experience nil reduction in ETc upon sweet potato maturity and in all other growth stages. This probably happened because Eta was equal to ETm implying that sweet potato fully transpired and hence met its atmospheric evaporative demand since there was sufficient moisture supply in the growth stages. Similarly, the predicted reduction in ETc in 2039 based in RCP 2.6 and 8.5 were 0.1 and nil at maturity and were considered negligible. However, at initiation, a 0.6 and 0.3% reduction in ETc was also projected to occur by RCP 2.6 and 8.5, respectively. This could be due to the rising atmospheric $CO_2$, increased saturation vapor pressure deficit and low soil moisture content caused by changes in precipitation thus affecting the soil water balance, resulting to ETa ≤ ETm (Kruijt et al., 2008). This shows that in the phase of climate change the crop was resilient and hence minimal loss of yield is expected.

### 5.8 Conclusions

Climate change in 2039 based on GCM on RCP 2.6 and 8.5 will affect the production of sweet potatoes in the study area as follows;

- Annual effective rainfall will be reduced by 16.7% thus modifying evaporation, runoff and soil moisture storage leading to an increased demand for irrigation water.
- Sweet potato water requirements will increase by 10.2% hence a decline in yields is expected.
- Supplemental irrigation will increase by 26.3% as an impact of climate change.
- Farmers are required to brace themselves with appropriate water conservation practices to increase their resilience in future when climate change impact is felt particularly in the ASALs of Kenya

# CHAPTER SIX

## GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATION

## 6.1 Discussion

### 6.1.1 Percent canopy cover, leaf area index, vine length, tuber yields and intercrop economics as influenced by a sweet potato-bean intercropping system

Legumes are important in intercropping systems because they are thought to increase the intercrop system's production. However, there is little evidence on the extent to which legume companion crops influence sweet potato productivity in terms of growth and performance, particularly in dry and semiarid areas of Kenya and Sub-Saharan Africa. In Chapter 4, the feasibility of intercropping sweet potatoes and common beans was established. In the context of this study, intercropping sweet potato varieties with common beans saved approximately 8 to 33% of land and thus considered biologically efficient. On the other hand, tuber yields in season (I) were significantly ($p<0.05$) lower than season (II) and this was probably because of the low amount of rainfall and aridity index values during the tuber bulking stage thus limiting biomass production. Similar to the yield obtained under intercropping systems demonstrating that sweet potato wasn't a better companion crop.

### 6.1.2 Sweet potato water use efficiency and productivity under chromic Luvisols

Producing crops under a water-limited environment is a challenging aspect. Chapter 5 demonstrates how soil physico- hydraulic properties and water retention properties of Ferralo chromic Luvisols influenced sweet potato water use efficiency and productivity. Results indicated that soil compaction negatively affected the TAW and RAW and thus the sweet potato water use efficiency and productivity. This indicated that soil bulk density played a bigger effect in plant water interactions than previously thought.

### 6.1.3 Implications of climate change on sweet potato productivity in a semiarid area

This study established that; anthropogenic climate change does not only affect weather patterns but also crop water needs. Future water needs will solely rely on the effect of the changing climate on the demand for irrigation water as illustrated in chapter 6. Based on the Relative Concentration Pathways, the study presents an in-depth analysis of the consequences of climate change; rainfall, temperature and evapotranspiration on sweet potato irrigation water needs and yield response to water stress. It's clear that, as climatic conditions change between the 2020s and 2030s, Katumani will likely face greater water demands as a result of rising temperatures and low effective rainfall, making climate change's negative impact more significant than its unpredictability.

## 6.2 Conclusions

- The study has established that incorporation of common beans in sweet potato-based cropping systems biologically efficient.
- The physico-hydraulic state of the soil influences soil-plant water relations, altering crop root penetration, water flow, and crop water productivity and efficiency.
- Under rain-fed agricultural production, water deficits are mainly encountered during most reproductive stages of growth, reducing their harvest indices (HI) and yield. The study showed that HI plays a generative success under drought stress and hence. A major avenue for yield improvement is to avoid lack of soil moisture in such stage.
- Because arid and semi-arid regions receive little annual rainfall, it is crucial to use available water resources for agricultural purposes via irrigation in order to ensure food security.
- With the changing climate, breeding should be geared towards producing crops adapted to climate change impacts especially in the arid and semi-arid areas of Kenya (ASALs).

## 6.3 Recommendations

- More research is needed to establish the impact of sweet potato allelopathy on companion crops now that intercropping is a viable practice in sweet potato cropping systems.
- The study suggests that further research be conducted on the same site to determine interactive differences between crop water use efficiency and the effective use of water with respect to nutrients and PAR availability
- Further studies be done to examine the influence of dew point temperatures and saturated pressure deficits on crop water productivity indices in the study area.
- Developing appropriate crop and site-specific irrigation schedules will aid in increasing crop yields, thus to improve on the principle of “more crop per drop”.

# 7.0 REFERENCES

Adubasim, C. V., Law-Ogbomo, K. E., and Obalum, S. E. (2017). Sweet potato (Ipomoea batatas) growth and tuber yield as influenced by plant spacing on sandy loam in a humid tropical environment. Agro-Science, 16(3), 46-50.

Affognon, H., Mutungi, C., Sanginga, P., and Borgemeister, C. (2015). Unpacking postharvest losses in sub-Saharan Africa: a meta-analysis. World Development, 66, 49-68.

Agata, W. and Takeda, T. 1982, Studies on matter production in sweet potato plants 1. The characteristics of dry matter and yield production under field conditions. Journal Faculty Kyushu University 21: 65-73.

Al-Kaisi, M. M., Broner, I., and Andales, A. A. (2009). Crop water use and growth stages. Fact sheet (Colorado State University. Extension). Crop series; no. 4.715.

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. (1998). Crop Evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. FAO, Rome, 300(9), D05109.

Amedie, F. A. (2013). Impacts of climate change on plant growth, ecosystem services, biodiversity, and potential adaptation measures. Master’s Thesis. Program Study of Biological and Environmental Science, University of Gothenberg, Sweden.

Amini, R., Shamayeli, M., and Dabbagh Mohammadi Nasab, A. (2013). Assessment of yield and yield components of corn (*Zea mays* L.) under two and three-strip intercropping systems. International Journal of Biosciences, 3(3), 65-69.

Anders, M. M., Potdar, M. V., and Francis, C. S. (1995). Significance of intercropping in cropping systems. Series on International Agricultural Research, 3, 1-18.

Apsara, J. A., Najim, M. M. M., and Begum, S. L. R. (2021). Optimization of irrigation scheduling under Kapuwaththa irrigation tank in Hambantota district, Sri Lanka.

Araus, J. L., Slafer, G. A., Reynolds, M. P., & Royo, C. (2002). Plant breeding and drought in C3 cereals: what should we breed for. Annals of botany, 89(7), 925-940.

Archer, J. R., and Smith, P. D. (1972). The relation between bulk density, available water capacity, and air capacity of soils. Journal of Soil Science, 23(4), 475-480.

Ashraf, M. H. P. J. C., and Harris, P. J. (2013). Photosynthesis under stressful environments: an overview. Photosynthetica, 51(2), 163-190.

Asiimwe, A., Tabu, I. M., Lemaga, B., and Tumwegamire, S. (2016). Effect of maize intercrop plant densities on yield and β-carotene contents of orange-fleshed sweet potatoes. African Crop Science Journal, 24(1), 75-87.

Athar, H. (2020). Water supply and effective rainfall impacts on major crops across irrigated areas of Punjab, Pakistan. Theoretical and Applied Climatology, 142(3), 1097-1116.

Augus, J.F., van Herwaarden, A.F., (2001). Increasing water use and water use efficiency in dryland wheat. Agron. J. 93, 290–298

Bacastow, R. B. (1976). Modulation of atmospheric carbon dioxide by the Southern Oscillation. Nature, 261(5556), 116-118.

Bannayan, M., Sanjani, S., Alizadeh, A., Lotfabadi, S. S., and Mohamadian, A. (2010). Association between climate indices, aridity index, and rainfed crop yield in the northeast of Iran. Field crops research, 118(2), 105-114.

Belehu, T. (2003). Agronomical and physiological factors affecting growth, development, and yield of sweet potato in Ethiopia (Doctoral dissertation). Retrieved from an Electronic Thesis and Dissertations–UPeTD (University of Pretoria).

Ben-Asher, J., Alpert, P., and Ben-Zvi, A. (2010). Dew is a major factor affecting vegetation water use efficiency rather than a source of water in the eastern Mediterranean area. Water Resources Research, 46(10).

Biamah, E. K. (2005). Coping with drought: options for soil and water management in semi-arid Kenya. Wageningen University and Research Centre.

Blum, A. (2009). Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. Field crops research, 112(2-3), 119-123.

Blum, A. (2011). Drought resistance and its improvement. In Plant breeding for water-limited environments (pp. 53-152). Springer, New York, NY.

Bramley, H., Turner, N. C., and Siddique, K. H. (2013). Water use efficiency. In Genomics and breeding for climate-resilient crops (pp. 225-268). Springer, Berlin, Heidelberg.

Brown, L. R. (2012). Outgrowing the Earth: the food security challenge in an age of falling water tables and rising temperatures. Taylor and Francis.

Burke, S., Mulligan, M., Thornes, J.B., (1999). Optimal irrigation efficiency for maximum plant productivity and minimum water loss. Agric. Water Manage. 40 (2/3), 377–391

Carvalho, J. L., Hudiburg, T. W., Franco, H. C., and DeLucia, E. H. (2017). Contribution of above-and belowground bioenergy crop residues to soil carbon. Gcb Bioenergy, 9(8), 1333-1343.

Castelhanos, A., Martinez, R. and Roque, R. (1984). Ciencia y tecnica en la agricultura. [Actual evapotranspiration in sweet potato clones.] Riego y drenage 7:55–68.

Castellini, M., Giglio, L., Niedda, M., Palumbo, A. D., and Ventrella, D. (2015). Impact of biochar addition on the physical and hydraulic properties of a clay soil. Soil and Tillage Research, 154, 1-13.

Chhabra, A., Geist, H., Houghton, R. A., Haberl, H., Braimoh, A. K., Vlek, P. L., ... and Lambin, E. F. (2006). Multiple impacts of land-use/cover change. In Land-use and land-cover change (pp. 71-116). Springer, Berlin, Heidelberg.

Chukaliev, O. (2017). Review of the research in crop water requirement and its use in the Republic of Macedonia. Contributions, Section of Natural, Mathematical and Biotechnical Sciences, 37(1).

Clair, S. B. S., and Lynch, J. P. (2010). The opening of Pandora's Box: climate change impacts on soil fertility and crop nutrition in developing countries. Plant and Soil, 335(1), 101-115.

Collins, J. O. (2013). Breeding maize for early maturity and drought tolerance in Kenya using anthesis to silking interval (MSc Thesis, University of Nairobi).

Cornelis, W. M., Ronsyn, J., Van Meirvenne, M., and Hartmann, R. (2001). Evaluation of pedotransfer functions for predicting the soil moisture retention curve. Soil Science Society of America Journal, 65(3), 638-648.

Cosgrove, W. J., and Loucks, D. P. (2015). Water management: Current and future challenges and research directions. Water Resources Research, 51(6), 4823-4839.

Craufurd, P. Q., and Wheeler, T. R. (2009). Climate change and the flowering time of annual crops. Journal of Experimental botany, 60(9), 2529-2539.

Croitoru, A. E., Piticar, A., Dragotă, C. S., and Burada, D. C. (2013). Recent changes in reference evapotranspiration in Romania. Global and Planetary Change, 111, 127-136.

Croke, B. F., and Jakeman, A. J. (2004). A catchment moisture deficit module for the IHACRES rainfall-runoff model. Environmental Modelling and Software, 19(1), 1-5.

Dalla Costa, L., and Giovanardi, R. (2000, May). Nitrogen use efficiency in tomato and potato as affected by water regime and N fertilisation. In Proc. COST 814 Final Conf (pp. 10-13).

Dasbak, M. A. D., and Asiegbu, J. E. (2009). Performance of pigeon pea genotypes intercropped with maize under humid tropical ultisol conditions. J. Anim. Plant Sci, 4(2), 329-340.

Dastane, N. G. (1978). Effective rainfall in irrigated agriculture, vol. 4, no. 1. Food and Agriculture Organization of the United Nations.

Ddamulira, G., Santos, C. A. F., Obuo, P., Alanyo, M., and Lwanga, C. K. (2015). Grain yield and protein content of Brazilian cowpea genotypes under diverse Ugandan environments. American Journal of Plant Sciences, 6(13), 2074.

De Bruijn, F. J. (2015). Biological nitrogen fixation. In Principles of Plant-Microbe Interactions (pp. 215-224). Springer, Cham.

De Pascale, S., Dalla Costa, L., Vallone, S., Barbieri, G., and Maggio, A. (2011). Increasing water use efficiency in vegetable crop production: from plant to irrigation systems efficiency. HortTechnology, 21(3), 301-308.

Debaeke, P., and Aboudrare, A. (2004). Adaptation of crop management to water-limited environments. European Journal of Agronomy, 21(4), 433-446.

DeBano, L. F. (1981). Water repellent soils: a state-of-the-art (Vol. 46). US Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station.

Deckers, J., Nachtergaele, F., and Spaargaren, O. (2010). Tropical soils in the classification systems of USDA, FAO and WRB. Evolution of Tropical Soil Science, 79.

Djaman, K., O'Neill, M., Owen, C. K., Smeal, D., Koudahe, K., West, M., ... and Irmak, S. (2018). Crop evapotranspiration, irrigation water requirement and water productivity of maize from meteorological data under semiarid climate. Water, 10(4), 405.

Doorenbos, J., and Kassam, A. H. (1979). Yield response to water. Irrigation and drainage paper, (33), 257.

Doria, R. O. (2011). Impact of climate change on crop water requirements in eastern Canada. McGill University (Canada).

Duke, J. (2012). Handbook of legumes of world economic importance. Springer Science and Business Media.

Dukuh, I.G. (2011). The effect of defoliation on the quality of sweet potato tubers. Asian Journal of Agricultural Research 5 (6): 300-305.

Egbe, O.M., and J.A. Idoko, (2009). Agronomic assessment of some sweet potato varieties for intercropping with pigeon pea in Southern Guinea Savanna of Nigeria. ARPN J. Agric. Biol. Sci., 4: 22-32

Eguch, T., Kitano, M., Yoshida, S., and Chikushi, J. (2003). Root temperature effects on tuberous root growth of sweet potato (Ipomoea batatas Lam.). Environment Control in Biology, 41(1), 43-49.

EguciI, T., and Yoshida, S. (2004). A cultivation method to ensure tuberous root formation in sweet potatoes (Ipomoea batatas (L.) Lam.). Environment Control in Biology, 42(4), 259-266.

Eitzinger, J. and Kubu, G., (2009). Impact of climate change and adaptation in agriculture: extended abstracts [of the] International symposium, Vienna, 22-23 June 2009 (Doctoral dissertation, Univerza v Ljubljani, Biotehniška fakulteta).

El-Sharkawy, M. A. (2006). International research on cassava photosynthesis, productivity, eco-physiology, and responses to environmental stresses in the tropics. Photosynthetica, 44(4), 481-512.

Eteng, E. U., and Nwagbara, M. O. (2014). Estimating Water Needs of Soybean (Glycine Max) Using the Penman Model Method in Umudike Southeastern, Nigeria. International Journal of Agricultural Science and Research (IJASR), 4(4), 49-58.

Fahad, S., Bajwa, A. A., Nazir, U., Anjum, S. A., Farooq, A., Zohaib, A., ... and Huang, J. (2017). Crop production under drought and heat stress: plant responses and management options. Frontiers in plant science, 8, 1147.

Fan, M., Shen, J., Yuan, L., Jiang, R., Chen, X., Davies, W. J., and Zhang, F. (2012). Improving crop productivity and resource use efficiency to ensure food security and environmental quality in China. Journal of experimental botany, 63(1), 13-24.

FAO/WHO Joint Expert Committee on Food Additives. Meeting, and World Health Organization. (2006). Safety evaluation of certain contaminants in food (Vol. 82). Food and Agriculture Org.

Farooq, M., Wahid, A., Kobayashi, N., Fujita, D. B. S. M. A., and Basra, S. M. A. (2009). Plant drought stress: effects, mechanisms and management. In Sustainable agriculture (pp. 153-188). Springer, Dordrecht.

Fichtner, F., and Lunn, J. E. (2021). The role of trehalose 6-phosphate (Tre6P) in plant metabolism and development. Annual Review of Plant Biology, 72.

Fischer, B. M., Manzoni, S., Morillas, L., Garcia, M., Johnson, M. S., and Lyon, S. W. (2019). Improving agricultural water use efficiency with biochar–A synthesis of biochar effects on water storage and fluxes across scales. Science of the Total Environment, 657, 853-862.

Fletcher, A. L., Moot, D. J., and Stone, P. J. (2008). Solar radiation interception and canopy expansion of sweet corn in response to phosphorus. European Journal of Agronomy, 29(2-3), 80-87.

Fletcher, A., Lawes, R., and Weeks, C. (2017). Crop area increases drive earlier and dry sowing in Western Australia: implications for farming systems. Crop and Pasture Science, 67(12), 1268-1280.

Flexas, J., and Medrano, H. (2002). Energy dissipation in C3 plants under drought. Functional Plant Biology, 29(10), 1209-1215.

Furat, S., and Uzun, B. (2010). The use of agro-morphological characters for the assessment of genetic diversity in sesame (Sesamum indicum L.). Plant Omics, 3(3), 85-91.

Gajanayake, B., Reddy, K. R., Shankle, M. W., and Arancibia, R. A. (2013). Early-season soil moisture deficit reduces sweetpotato storage root initiation and development. HortScience, 48(12), 1457-1462.

Geerts, S., Raes, D., and Garcia, M. (2010). Using Aqua-Crop to derive deficit irrigation schedules. Agricultural water management, 98(1), 213-216.

Gherardi, L. A., and Sala, O. E. (2020). Global patterns and climatic controls of belowground net carbon fixation. Proceedings of the National Academy of Sciences, 117(33), 20038-20043.

Gicheru, P. T., and Ita, B. N. (1987). Detailed soil survey of the Katumani National Dryland Farming Research Station Farms (Machakos District). The Republic of Kenya, Ministry of Agriculture, National Agricultural Laboratories, Kenya Soil Survey

Giddens, A. (2009). Politics of climate change. Polity.

Gitari, H. I. (2018). Potato-legume intercrop effects on water and nutrients use efficiency, crop productivity, and soil fertility in a Humic Nitisol, Kenya (Doctoral dissertation, Faculty of Agriculture, University of Nairobi).

Gitari, H. I., Gachene, C. K., Karanja, N. N., Kamau, S., Nyawade, S., Sharma, K., and Schulte-Geldermann, E. (2018). Optimizing yield and economic returns of rain-fed potato (Solanum tuberosum L.) through water conservation under potato-legume intercropping systems. Agricultural water management, 208, 59-66.

Gomes, F., and Carr, M. K. V. (2003). Effects of water availability and vine harvesting frequency on the productivity of sweet potato in southern Mozambique. II. Crop water use. Experimental Agriculture, 39(1), 39.

Green, S. B., and Salkind, N. J. (2016). Using SPSS for Windows and Macintosh, books a la carte. Pearson.

Hakl, J., Šantrùèek, J., Fuksa, P., and Krajíc, L. (2010). The use of indirect methods for the prediction of lucerne quality in the first cut under the conditions of Central Europe. Czech Journal of Animal Science, 55(6), 258-265.

Hatfield, J. L., Boote, K. J., Kimball, B. A., Ziska, L. H., Izaurralde, R. C., Ort, D., .and Wolfe, D. (2011). Climate impacts on agriculture: implications for crop production. Agronomy Journal, 103(2), 351-370.

Haverkort, A. J., and Top, J. L. (2011). The potato ontology: delimitation of the domain, modelling concepts, and prospects of performance. *Potato Research*, *54*(2), 119-136.

Heisey, P. W., and Edmeades, G. O. (1999). CIMMYT 1997/98 world maize facts and trends; maize production in drought-stressed environments: technical options and research resource allocation (No. 557-2016-38824).

Hillel, D. (1998). Environmental soil physics: Fundamentals, applications, and environmental considerations. Elsevier.

Holman, I., Knox, J., Hess, T., McEwen, L., Salmoral Portillo, G., Rey Vicario, D., ... & Quinn, N. (2021). Coping with drought and water scarcity: lessons for the agricultural sector.

Howell, T. A., and Dusek, D. A. (1995). Comparison of vapor-pressure-deficit calculation methods—southern high plains. Journal of irrigation and drainage engineering, 121(2), 191-198.

Hsiao, T. C., and Bradford, K. J. (1983). Physiological consequences of cellular water deficits. Limitations to efficient water use in crop production, 227-265.

Hsiao, T. C., Heng, L., Steduto, P., Rojas-Lara, B., Raes, D., and Fereres, E. (2009). AquaCrop—the FAO crop model to simulate yield response to water: III. Parameterization and testing for maize. Agronomy Journal, 101(3), 448-459.

Huang, X., Wang, H., Zhang, M., Horn, R., & Ren, T. (2021). Soil water retention dynamics in a Mollisol during a maize growing season under contrasting tillage systems. Soil and Tillage Research, 209, 104953.

Hufkens, K., Keenan, T. F., Flanagan, L. B., Scott, R. L., Bernacchi, C. J., Joo, E., ... and Richardson, A. D. (2016). Productivity of North American grasslands is increased under future climate scenarios despite rising aridity. Nature Climate Change, 6(7), 710-714.

Idoko, J. A., Akaazua, B. W., and Oga, J. I. (2018). Evaluation of five improved maize varieties for intercropping with sweet potato in Makurdi, southern guinea savanna ecology of Nigeria. Asian Research Journal of Agriculture, 1-11.

Igbadun, H. E., Tarimo, A. K., Salim, B. A., and Mahoo, H. F. (2007). Evaluation of selected crop water production functions for an irrigated maize crop. Agricultural Water Management, 94(1-3), 1-10.

Iizumi, T., and Ramankutty, N. (2015). How do weather and climate influence cropping area and intensity. Global Food Security, 4, 46-50.

Ikudayisi, A., and Adeyemo, J. (2016). Effects of Different Meteorological Variables on Reference Evapotranspiration Modeling: Application of Principal Component Analysis. International Journal of Geological and Environmental Engineering, 10(6), 664-668.

Ismail, S. M., and Ozawa, K. (2007). Improvement of crop yield, soil moisture distribution and water use efficiency in sandy soils by clay application. Applied Clay Science, 37(1-2), 81-89.

Jaetzold, R., Schmidt, H., Hornetz, B., and Shisanya, C. (2006). Farm Management Handbook of Kenya. Natural Conditions and Farm Information. Vol. II, Part C, East Kenya. Subpart C1, Eastern Province.

Jalilian, J., Najafabadi, A., and Zardashti, M. R. (2017). Intercropping patterns and different farming systems affect the yield and yield components of safflower and bitter vetch. Journal of Plant Interactions, 12(1), 92-99.

Janssens, M., Rutunga, V., Mukamugenga, J., Mukantagengwa, S., and Marijnissen, R. (2014). Improvement of Sweet potato (Ipomoea batatas (L.) Lam) Production with Fertilizer and Organic Inputs in Rwanda. In Challenges and Opportunities for Agricultural Intensification of the Humid Highland Systems of Sub-Saharan Africa (pp. 201-215). Springer, Cham.

Johnson, A., Ashika, N. P., Parvathy Nayana, N., and Joseph, A. (2019). Crop water requirement and irrigation scheduling of selected crops using cropwat: A case study of Pattambi region (Doctoral dissertation, Department of Irrigation and Drainage Engineering).

Johnson, Y. K., Ayuke, F. O., Kinama, J. M., and Sijali, I. V. (2018). Effects of tillage practices on water use efficiency and yield of different drought tolerant common bean varieties in Machakos county, Eastern Kenya. American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS), 40(1), 217-234.

Jones, H. (2004). What is water use efficiency? Water use efficiency in plant biology, 27-41.

Kadigi, R. M., Kashaigili, J. J., and Mdoe, N. S. (2004). The economics of irrigated paddy in Usangu Basin in Tanzania: water utilization, productivity, income and livelihood implications. Physics and Chemistry of the Earth, Parts A/B/C, 29(15-18), 1091-1100.

Kahlon, M. S., and Khurana, K. (2017). Effect of land management practices on physical properties of soil and water productivity in wheat-maize system of North West India. Applied Ecology and Environmental Research, 15(4), 1-13.

Kamruzzaman, M., Hwang, S., Choi, S. K., Cho, J., Song, I., Song, J. H., ... and Yoo, S. H. (2020). Evaluating the Impact of Climate Change on Paddy Water Balance Using APEX-Paddy Model. Water, 12(3), 852.

Kang, S., Hao, X., Du, T., Tong, L., Su, X., Lu, H., ... and Ding, R. (2017). Improving agricultural water productivity to ensure food security in China under changing environment: From research to practice. Agricultural Water Management, 179, 5-17.

Kang, Y., Khan, S., and Ma, X. (2009). Climate change impacts on crop yield, crop water productivity and food security–A review. Progress in natural Science, 19(12), 1665-1674.

Kapoor, D., Bhardwaj, S., Landi, M., Sharma, A., Ramakrishnan, M., and Sharma, A. (2020). The impact of drought in plant metabolism: how to exploit tolerance mechanisms to increase crop production. Applied Sciences, 10(16), 5692.

Karuku, G. N., and Mochoge, B. O. (2016). Nitrogen forms in three Kenyan soils nitisols, luvisols and ferralsols. Int. J. Innov. Educ. Res, 4(10), 17-30.

Karuku, G. N., Gachene, C. K. K., Karanja, N., Cornelis, W., and Verplacke, H. (2014). Effect of different cover crop residue management practices on soil moisture content under a tomato crop (Lycopersicon esculentum). Tropical and Subtropical Agroecosystems, 17(3), 509-523.

Karuku, G. N., Gachene, C. K. K., Karanja, N., Cornelis, W., and Verplancke, H. (2014). Use of CROPWAT Model to predict water use in irrigated tomato production at Kabete, Kenya. E. Afr. agric. For. J. (2014), 80(3), 175-183.

Karuku, G. N., Gachene, C. K. K., Karanja, N., Cornelis, W., Verplancke, H., and Kironchi, G. (2012). Soil hydraulic properties of a nitisol in Kabete, Kenya. Tropical and Subtropical Agroecosystems, 15, 595-609.

Karuku, G. N., Onwonga, R. N., Chepkemoi, J., and Kathumo, V. M. (2019). Effects of tillage practices, cropping systems, and organic inputs on soil nutrient content in Machakos County, Kenya. Journal of Agriculture and Sustainability.

Karuku, G., and Mbindah, B. (2020). Validation of AQUACROP model for simulation of rainfed bulb onion (Allium cepa L.) yields in west Ugenya sub-county, Kenya. Tropical and Subtropical Agroecosystems, 23(1).

Karuma, A. N., Gachene, K., Charles, K., Msanya, B. M., Mtakwa, P. W., Amuri, N., and Gicheru, P. T. (2014). Soil morphology, physico-chemical properties and classification of typical soils of Mwala District, Kenya. International Journal of Plant & Soil Science 4(2): 156-170, 2015; Article no. IJPSS.2015.017 ISSN: 2320-7035

Karuma, A., Gachene, C. K., Gicheru, P. T., Mwang'ombe, A. W., Mwangi, H. W., Clavel, D., ... and Ekaya, W. (2011). Effects of legume cover crop and sub-soiling on soil properties and maize (Zea mays L) growth in the semi-arid area of Machakos District, Kenya. Tropical and Subtropical Agroecosystems, 14(1), 237-243.

Kassam, A., and Smith, M. (2001, December). FAO methodologies on crop water use and crop water productivity. In *Expert meeting on crop water productivity, Rome* (p. 18).

Kassam, A., and Smith, M. (2001, December). FAO methodologies on crop water use and crop water productivity. In Expert meeting on crop water productivity, Rome (p. 18).

Khisa, P., Gachene, C. K. K., Karanja, N. K., and Mureithi, J. G. (2002). The effect of post-harvest crop covers on soil erosion in a maize-legume based cropping system in Gatanga, Kenya. Journal of Agriculture in the Tropics and Subtropics, 103(1), 17-28.

Kimball, B. A., and Bernacchi, C. J. (2006). Evapotranspiration, canopy temperature, and plant water relations. In Managed ecosystems and CO2 (pp. 311-324). Springer, Berlin, Heidelberg.

Kimball, J. S., Running, S. W., & Nemani, R. (1997). An improved method for estimating surface humidity from daily minimum temperature. Agricultural and forest meteorology, 85(1-2), 87-98.

Kinama, J. M., Habineza, J. P., and Jean Pierre, H. M. (2018). A review of the advantages of the cereals-legumes intercropping system: a case of promiscuous soybeans varieties and maize. Int. J. Agron. Agric. Res, 12, 155-165.

Kinama, J. M., Stigter, C. J., Ong, C. K., and Gichuki, F. N. (2005). Evaporation from soils below sparse crops in contour hedgerow agroforestry in semi-arid Kenya. Agricultural and forest meteorology, 130(3-4), 149-162.

Kinama, J., Stigter, C., Ong, C., Ng'ang'a, J., and Gichuki, F. (2007). Alley cropping (contour hedgerow intercropping) maize or cowpea/senna for increased dry matter production in the semi-arid areas of eastern Kenya. Proceedings of African Crop Science Society (ACSS) in Melkia–Egypt.

Kiseve, S. M. (2012). Evaluation of legume cover crops intercropped with coffee (MSc Thesis, University of Nairobi,).

Kivuva, B. M. (2013). Breeding sweetpotato (Ipomoea batatas [L.] Lam.) for drought tolerance in Kenya (Doctoral dissertation).

Koech, O. K., Kinuthia, R. N., Karuku, G. N., Mureithi, S. M., and Wanjogu, R. (2015). Water use efficiency of six rangeland grasses under varied soil moisture content levels in the arid Tana River County, Kenya. African Journal of Environmental Science and Technology, 9(7), 632-640.

Kruijt, B., Witte, J. P. M., Jacobs, C. M., and Kroon, T. (2008). Effects of rising atmospheric CO2 on evapotranspiration and soil moisture: A practical approach for the Netherlands. Journal of Hydrology, 349(3-4), 257-267.

Kundu, C. A., Karanja, N. K., Jefwa, J., Ndolo, P. J., and Mwangi, E. (2013, October). Response of orange fleshed sweet potato to Arbuscular Mycorrhizal fungi inoculation and fertilizer application in western Kenya. In Joint Proceedings of the 27th Soil Science Society of East Africa and the 6th African Soil Science Society Conference.

Kwena, K. M., Ayuke, F. O., Karuku, G. N., and Esilaba, A. O. (2018). No rain but bumper harvest: the magic of pigeonpea in semi-arid Kenya. International Journal of Agricultural Resources, Governance and Ecology, 14(2), 181-203.

Lane, P. W., and Payne, R. W. (1997). Genstat for a windows-an introductory course (p. 154pp). Numerical Algorithms Group, Oxford.

Laurie, S. M., and Magoro, M. D. (2008). Evaluation and release of new sweet potato varieties through farmer participatory selection. African Journal of Agricultural Research, 3(10), 672-676.

Law-Ogbomo, K. E., and Osaigbovo, A. U. (2017). The performance and profitability of sweet potato (Ipomoea batatas L.) as influenced by propagule length and application rates of cattle dung in humid Ultisols. Agro-Science, 16(1), 17-25.

Lebot, V. (2019). Tropical root and tuber crops. Cabi.

Leuning, R., Kriedemann, P. E., and McMurtrie, R. E. (1991). Simulation of evapotranspiration by trees. Agricultural water management, 19(3), 205-221.

Li, Q., Dong, B., Qiao, Y., Liu, M., and Zhang, J. (2010). Root growth, available soil water, and water-use efficiency of winter wheat under different irrigation regimes applied at different growth stages in North China. Agricultural Water Management, 97(10), 1676-1682.

Lin, P., Zhang, J., Huang, H., Huang, Y., Wang, Y., and Garg, A. (2021). Strength of Unsaturated Granite Residual Soil of Shantou Coastal Region Considering Effects of Seepage Using Modified Direct Shear Test. Indian Geotechnical Journal, 1-13.

Liu, C., and Allan, R. P. (2013). Observed and simulated precipitation responses in wet and dry regions 1850–2100. Environmental Research Letters, 8(3), 034002.

Liu, L., Guan, L., and Liu, X. (2017). Directly estimating diurnal changes in GPP for C3 and C4 crops using far-red sun-induced chlorophyll fluorescence. Agricultural and Forest Meteorology, 232, 1-9.

Logan, M. C., and Nordstrom, J. T. (1985). U.S. Patent No. 4,512,161. Washington, DC: U.S. Patent and Trademark Office.

Lozano-Parra, J., Schnabel, S., Pulido, M., Gómez-Gutiérrez, Á., and Lavado-Contador, F. (2018). Effects of soil moisture and vegetation cover on biomass growth in water-limited environments. Land degradation and development, 29(12), 4405-4414.

Lusweti, C. M. (1994). Effect of stubble height and harvesting intervals on yield and nutritive value of three sweet potato (ipomea batatas (l) lam) cultivars (Doctoral dissertation, University of Nairobi).

Maddonni, G. A., Chelle, M., Drouet, J. L., and Andrieu, B. (2001). Light interception of contrasting azimuth canopies under square and rectangular plant spatial distributions: simulations and crop measurements. Field Crops Research, 70(1), 1-13.

Mancosu, N., Snyder, R. L., Kyriakakis, G., and Spano, D. (2015). Water scarcity and future challenges for food production. Water, 7(3), 975-992.

Marquardt, D. W. (1963). An algorithm for least-squares estimation of nonlinear parameters. Journal of the society for Industrial and Applied Mathematics, 11(2), 431-441.

Masango, S. (2014). Water use efficiency of orange-fleshed sweet potato (M. Sc. Thesis University of Pretoria, South Africa).

Masui, T., Matsumoto, K., Hijioka, Y., Kinoshita, T., Nozawa, T., Ishiwatari, S., and Kainuma, M. (2011). An emission pathway for stabilization at 6 Wm− 2 radiative forcing. Climatic change, 109(1-2), 59.

Mayisela, M. D., Ossom, E. M., and Rhykerd, R. L. (2010). Influence of different groundnut (Arachis hypogaea L.) populations on physiological growth indices and yields under intercropping with a fixed sweet potato [*Ipomoea batatas (L.)* Lam.] population. Journal of Applied Sciences Research, (February), 165-176.

Mbayaki, C. W., and Karuku, G. N. (2021). Growth and yield of sweet potato (Ipomoea Batatas L.) Monocrops Versus Intercrops in the semi-arid Katumani, Kenya Tropical and Subtropical Agroecosystems, 24(3).

McDowell, N., Pockman, W. T., Allen, C. D., Breshears, D. D., Cobb, N., Kolb, T., ... and Yepez, E. A. (2008). Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought? New phytologist, 178(4), 719-739.

McEwan, M., Almekinders, C., Abidin, P. E., Andrade, M., Carey, E. E., Gibson, R. W., ... and Schulz, S. (2015). Can small still be beautiful? Moving local sweet potato seed systems to scale in sub-Saharan Africa. Potato and sweet potato in Africa: transforming the value chains for food and nutrition security, 289-310.

Medrano, H., Tomás, M., Martorell, S., Flexas, J., Hernández, E., Rosselló, J., and Bota, J. (2015). From leaf to whole-plant water use efficiency (WUE) in complex canopies: Limitations of leaf WUE as a selection target. The Crop Journal, 3(3), 220-228.

Merva, G. E. (1975). Physioengineering principles (No. 581.191 M4).

Mgcibelo, M. N. (2014). Agronomic and physiological approaches to improving productivity of selected sweet potato (Ipomoea Batatas L.) cultivars in KwaZulu-Natal: a focus on drought tolerance (Doctoral dissertation).

Miglietta, F., Bindi, M., Vaccari, F. P., Schapendonk, A. H. C. M., Wolf, J., and Butterfield, R. E. (2000). Crop ecosystem responses to climatic change: root and tuberous crops. Climate Change and Global Crop Productivity. CABI Publishing, Wallingford, UK, 189-212.

Mimi, Z. A., and Jamous, S. A. (2010). Climate change and agricultural water demand: Impacts and adaptations. African Journal of Environmental Science and Technology, 4(4).

Mintz, Y., and Walker, G. K. (1993). Global fields of soil moisture and land surface evapotranspiration derived from observed precipitation and surface air temperature. Journal of Applied Meteorology, 32(8), 1305-1334.

Mithra, V. S., and Somasundaram, K. (2008). A model to simulate sweet potato growth. World applied sciences journal, 4(4), 568-577.

Mittler, R., and Blumwald, E. (2010). Genetic engineering for modern agriculture: challenges and perspectives. Annual review of plant biology, 61, 443-462.

Mobasser, H. R., Vazirimehr, M. R., and Rigi, K. (2014). Effect of intercropping on resources use, weed management and forage quality. IJPAES, 4, 706-713.

Molden, D. (1997). Accounting for water use and productivity (No. 42). Iwmi.

Molua, E. L., and Lambi, C. M. (2006). Assessing the impact of climate on crop water use and crop water productivity: The CROPWAT analysis of three districts in Cameroon. University of Pretoria: Pretoria, South Africa, 44.

Monneveux, P., Ramírez, D. A., and Pino, M. T. (2013). Drought tolerance in potato (S. tuberosum L.): Can we learn from drought tolerance research in cereals. Plant Science, 205, 76-86.

Monteith, J. L. (1977). Climate and the efficiency of crop production in Britain. Philosophical Transactions of the Royal Society of London. B, Biological Sciences, 281(980), 277-294.

Morris, R. A., and Garrity, D. P. (1993). Resource capture and utilization in intercropping: water. Field Crops Research, 34(3-4), 303-317.

Motsa, N. M., Modi, A. T., and Mabhaudhi, T. (2015). Sweet potato (Ipomoea batatas L.) as a drought tolerant and food security crop. South African Journal of Science, 111(11-12), 1-8.

Mott, K. A., and Parkhurst, D. F. (1991). Stomatal responses to humidity in air and helox. Plant, Cell and Environment, 14(5), 509-515.

Muchena, F. N., and Gachene, C. K. K. (1988). Soils of the highland and mountainous areas of Kenya with special emphasis on agricultural soils. Mountain Research and Development, 183-191.

Muigai, D. K., Onwonga, R. N., Karuku, G. N., and Mohammed, A. Effect of irrigation schedules on maize (Zea mays l.) growth and yield in Bura irrigation scheme, Tana River County.

Muli, M. N., Onwonga, R. N., Karuku, G. N., Kathumo, V. M., and Nandukule, M. O. (2015). Simulating soil moisture under different tillage practices, cropping systems and organic fertilizers using CropSyst model, in Matuu division, Kenya. Journal of Agricultural Science; Vol. 7, No. 2; 2015. ISSN 1916-9752 E-ISSN 1916-9760.Published by Canadian Center of Science and Education.

Muller, B., Pantin, F., Génard, M., Turc, O., Freixes, S., Piques, M., and Gibon, Y. (2011). Water deficits uncouple growth from photosynthesis, increase C content, and modify the relationships between C and growth in sink organs. Journal of experimental botany, 62(6), 1715-1729.

Mulovhedzi, N. E., Araya, N. A., Mengistu, M. G., Fessehazion, M. K., Du Plooy, C. P., Araya, H. T., and Van der Laan, M. (2020). Estimating evapotranspiration and determining crop coefficients of irrigated sweet potato (Ipomoea batatas) grown in a semi-arid climate. Agricultural Water Management, 233, 106099.

Mulube, M. (2017). Pre-breeding of architectural traits related to direct harvesting in dry bean (Doctoral dissertations).

Muya, E. M., Obanyi, S., Ngutu, M., Sijali, I. V., Okoti, M., Maingi, P. M., and Bulle, H. (2011). The physical and chemical characteristics of soils of Northern Kenya Aridlands: Opportunity for sustainable agricultural production. Journal of Soil Science and Environmental Management, 2(1), 1-8.

Mwendia, S. W., Yunusa, I. A., Sindel, B. M., Whalley, R. D., and Kariuki, I. W. (2017). Assessment of Napier grass accessions in lowland and highland tropical environments of East Africa: water stress indices, water use and water use efficiency. Journal of the Science of Food and Agriculture, 97(6), 1953-1961.

Mwendwa, S. M., Mbuvi, J. P., Kironchi, G., and Gachene, C. K. (2020). A Geopedological Approach to Soil Classification to Characterize Soils of Upper Kabete Campus Field, University of Nairobi, Kenya. Tropical and Subtropical Agroecosystems, 23(2).

Mwololo, J. K., Mburu, M. W. K., and Muturi, P. W. (2012). Performance of sweet potato varieties across environments in Kenya.

Nashwan, Mohamed Salem, and Shamsuddin Shahid. "A novel framework for selecting general circulation models based on the spatial patterns of climate." International Journal of Climatology (2020).

Nawaz, M. F., Bourrie, G., and Trolard, F. (2013). Soil compaction impact and modelling. A review. Agronomy for sustainable development, 33(2), 291-309.

Neale, C. M., Jayanthi, H., and Wright, J. L. (2005). Irrigation water management using high resolution airborne remote sensing. Irrigation and Drainage Systems, 19(3-4), 321-336.

Nedunchezhiyan, M., Byju, G., and Jata, S. K. (2012). Sweet potato agronomy. Fruit, Vegetable and Cereal Science and Biotechnology, 6(1), 1-10.

Niles, M. T., and Salerno, J. D. (2018). A cross-country analysis of climate shocks and smallholder food insecurity. PLoS One, 13(2), e0192928.

Njoku, S.C., C.O. Muoneke, D.A. Okpara, and F.M.O. Agbo, 2007. Effect of intercropping varieties of sweet potato and Okra in an ultisol of southeastern Nigeria. Afr. J. Biotechnol., 6: 1650-1654.

Norman, M. J. T., Pearson, C. J. and Searle, P. G. E. (1984). Sweet potato (Ipomoea batatas). Chapter 16 in The Ecology of Tropical Food Crops, 291–304. Cambridge: Cambridge University Press.

Nugroho, A., and Widaryanto, E. (2017). Yield response of ten varieties of sweet potato (Ipomoea batatas L.) cultivated on dryland in the rainy season. Journal of Degraded and Mining Lands Management, 4(4), 919.

Nyawade, S. O. (2015). Effect of potato (Solanum tuberosum L.) cropping systems on soil and nutrient losses through runoff in a humic nitisol (MSc dissertation, University of Nairobi).

Nyawade, S. O., Karanja, N. N., Gachene, C. K., Gitari, H. I., Schulte-Geldermann, E., and Parker, M. L. (2019). Intercropping optimizes soil temperature and increases crop water productivity and radiation use efficiency of rainfed potato. American Journal of Potato Research, 96(5), 457-471.

Obidiegwu, J. E., Bryan, G. J., Jones, H. G., and Prashar, A. (2015). Coping with drought: stress and adaptive responses in potato and perspectives for improvement. Frontiers in plant science, 6, 542.

Oerke, E. C., and Dehne, H. W. (2004). Safeguarding production—losses in major crops and the role of crop protection. Crop protection, 23(4), 275-285.

Oiganji, E., Igbadun, H. E., Mudiare, O. J., and Oyebode, M. A. (2017). Development of deficit irrigation for maize crop under drip irrigation in samaru-nigeria.

Okogbenin, E., Setter, T. L., Ferguson, M., Mutegi, R., Ceballos, H., Olasanmi, B., and Fregene, M. (2013). Phenotypic approaches to drought in cassava. Frontiers in physiology, 4, 93.

Onder, S., Caliskan, M.E., Onder, D., Caliskan, S., 2005. Different irrigation methods and water stress effects on potato yield and yield components. Agric. Water Manage. 73, 73–86

Onyancha, D. M., Gachene, C. K. K., and Kironchi, G. (2017). Fao-cropwat model-based estimation of the crop water requirement of major crops in Mwala, Machakos county. Research Journal’s Journal of Ecology, 4(2).

Onyekwere. P. S. N. and Okafor, E. C. (1992). Water requirements of sweet potato. Proceedings of the 4th International Symposium for Tropical Root Crops – African Branch Kinshasa, Zaire, 335–336

Opafola, O. T., David, A. O., Lawal, N. S., and Babalola, A. A. (2018). Estimation of Water Needs of Sweet Potato (Ipomea batata) Using the Penman-Monteith Model in Abeokuta, South-western Nigeria. Arid Zone Journal of Engineering, Technology and Environment, 14(1), 143.

Oshunsanya, S. O., Nwosu, N. J., and Li, Y. (2019). Abiotic stress in agricultural crops under climatic conditions. In Sustainable agriculture, forest and environmental management (pp. 71-100). Springer, Singapore.

Ossom, E. M., and Rhykerd, R. L. (2007). Phaseolus vulgaris L. population density affects intercropped Ipomoea batatas (L.) Lam. Trans. Illinois State Acad. Science, 100(1), 13-23.

Parwada, C., Gadzirayi, C. T., and Sithole, A. B. (2011). Effect of ridge height and planting orientation on Ipomea batatas (sweet potato) production.

Passioura, J. (2006). Increasing crop productivity when water is scarce—from breeding to field management. Agricultural water management, 80(1-3), 176-196.

Picotte, J. J., Rosenthal, D. M., Rhode, J. M., and Cruzan, M. B. (2007). P lastic responses to temporal variation in moisture availability: consequences for water use efficiency and plant performance. Oecologia, 153(4), 821-832.

Prabawardani, S., and Suparno, A. (2015). Water use efficiency and yield of sweet potato as affected by nitrogen and potassium application.

Pramuk, L. A., and Runkle, E. S. (2005). Photosynthetic daily light integral during the seedling stage influences subsequent growth and flowering of Celosia, Impatiens, Salvia, Tagetes, and Viola. HortScience, 40(4), 1099C-1099.

Raes, D., Steduto, P., Hsiao, T. C., and Fereres, E. (2009). AQUACROP—the FAO crop model to simulate yield response to water: II. Main algorithms and software description. Agronomy Journal, 101(3), 438-447.

Ravi, V., and Indira, P. (1999). Crop physiology of sweet potato. Horticultural Review, 23, 277-338.

Ravi, V., Naskar, S. K., Makeshkumar, T., Babu, B., and Krishnan, B. P. (2009). Molecular physiology of storage root formation and development in sweet potato (Ipomoea batatas (L.) Lam.). J Root Crops, 35(1), 1-27.

Raymundo, R., Kleinwechter, U., and Asseng, S. (2014). Virtual potato crop modelling.

Raziei, T., and Pereira, L. S. (2013). Estimation of ETo with Hargreaves–Samani and FAO-PM temperature methods for a wide range of climates in Iran. Agricultural water management, 121, 1-18.

Reynolds, W., Elrick, D., Youngs, E., Amoozegar, A., Booltink, H., and Bouma, J. (2002). 3.4 Saturated and field-saturated water flow parameters. Methods of soil analysis, Part, 4, 797-801.

Richards, L. A., and Weaver, L. R. (1944). Moisture retention by some irrigated soils as related to soil moisture tension. Journal of Agricultural Research, 69(6), 215-235.

Rockström, J. (2003). Water for food and nature in drought–prone tropics: vapour shift in rain–fed agriculture. Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 358(1440), 1997-2009.

Rodiyati, A., Arisoesilaningsih, E., Isagi, Y., and Nakagoshi, N. (2005). Responses of *Cyperus brevifolius* (Rottb.) Hassk. and Cyperus kyllingia Endl. to varying soil water availability. Environmental and experimental botany, 53(3), 259-269.

Salami, A., Kamara, A. B., and Brixiova, Z. (2010). Smallholder agriculture in East Africa: Trends, constraints and opportunities. Tunis: African Development Bank.

Schaap, M. G., and Leij, F. J. (2000). Improved prediction of unsaturated hydraulic conductivity with the Mualem-van Genuchten model. Soil Science Society of America Journal, 64(3), 843-851.

Scher, S. (2018). Toward data-driven weather and climate forecasting: Approximating a simple general circulation model with deep learning. Geophysical Research Letters, 45(22), 12-616.

Schofield, R. K. (1935). The pF of water in soil. In Trans. of the Third International Congress on Soil Science, 2, Plenary Session Papers, 30 July-7 August, 1935 Oxford, UK (pp. 37-48).

Schoonover, J. E., and Crim, J. F. (2015). An introduction to soil concepts and the role of soils in watershed management. Journal of Contemporary Water Research and Education, 154(1), 21-47.

Serraj, R., Krishnamurthy, L., Kashiwagi, J., Kumar, J., Chandra, S., and Crouch, J. H. (2004). Variation in root traits of chickpea (Cicer arietinum L.) grown under terminal drought. Field Crops Research, 88(2-3), 115-127.

Shank, D. B., McClendon, R. W., Paz, J., and Hoogenboom, G. (2008). Ensemble artificial neural networks for prediction of dew point temperature. Applied Artificial Intelligence, 22(6), 523-542.

Shao, H. B., Chu, L. Y., Jaleel, C. A., and Zhao, C. X. (2008). Water-deficit stress-induced anatomical changes in higher plants. Comptes rendus biologies, 331(3), 215-225.

Shwetha, P., and Varija, K. (2015). Soil water retention curve from saturated hydraulic conductivity for sandy loam and loamy sand textured soils. Aquatic Procedia, 4, 1142-1149.

Simonovic, S. P. (2017). Bringing future climatic change into water resources management practice today. Water Resources Management, 31(10), 2933-2950.

Sitienei, R. C., Onwonga, R. N., Lelei, J. J., and Kamoni, P. (2017). Use of Dolichos (Lablab Purpureus L.) and combined fertilizers enhance soil nutrient availability, and maize (Zea Mays L.) yield in farming systems of Kabete Sub County, Kenya. Agricultural Science Research Journal, 7(2), 47-62.

Skirycz, A., and Inzé, D. (2010). More from less: plant growth under limited water. Current Opinion in Biotechnology, 21(2), 197-203.

Smart, R. E., and Coombe, B. G. (1983). Water relations of grapevines [Vitis]. Water deficits and plant growth.

Smith, P., Clark, H., Dong, H., Elsiddig, E. A., Haberl, H., Harper, R., ... and Ravindranath, N. H. (2014). Agriculture, forestry and other land use (AFOLU).

Snyder, R. L., and Melo-Abreu, J. D. (2005). Frost protection: fundamentals, practice and economics. Volume 1. Frost protection: fundamentals, practice and economics, 1, 1-240.

Stagnari, F., Maggio, A., Galieni, A., and Pisante, M. (2017). Multiple benefits of legumes for agriculture sustainability: an overview. Chemical and Biological Technologies in Agriculture, 4(1), 2.

Surendran, U., Sushanth, C. M., Mammen, G., and Joseph, E. J. (2015). Modelling the crop water requirement using FAO-CROPWAT and assessment of water resources for sustainable water resource management: A case study in Palakkad district of humid tropical Kerala, India. *Aquatic Procedia*, *4*, 1211-1219.

Tambussi, E. A., Bort, J., and Araus, J. L. (2007). Water use efficiency in C3 cereals under Mediterranean conditions: a review of physiological aspects. Annals of Applied Biology, 150(3), 307-321.

Taylor, M., and Bhasme, S. (2018). Model farmers, extension networks and the politics of agricultural knowledge transfer. Journal of Rural Studies, 64, 1-10.

Tenge, A. J., Sterk, G., and Okoba, B. O. (2011). Farmers' preferences and physical effectiveness of soil and water conservation measures in the East African Highlands. J. Soc. Sci. (The University of Dodoma), 2, 84-100.

Thompson, P. G., Smittle, D. A., and Hall, M. R. (1992). Relationship of sweet potato yield and quality to amount of irrigation. Hort Science, 27(1), 23-26.

Thorne-Miller, B., Harlin, M. M., Thursby, G. B., Brady-Campbell, M. M., and Dworetzky, B. A. (1983). Variations in the distribution and biomass of submerged macrophytes in five coastal lagoons in Rhode Island, USA. Botanica Marina, 26(5), 231-242.

Tumwegamire, S., Kapinga, R., Zhang, D., Crissman, C., and Agili, S. (2004). Opportunities for promoting orange-fleshed sweet potato as a mechanism for combat vitamin-A deficiency in Sub-Saharan Africa. African Crop Science Journal, 12(3), 241-252.

Van Genuchten, M. V., Leij, F. J., and Yates, S. R. (1991). The RETC code for quantifying the hydraulic functions of unsaturated soils.

Verelst, W., Skirycz, A., and Inzé, D. (2010). Abscisic acid, ethylene, and gibberellic acid act at different developmental stages to instruct the adaptation of young leaves to stress. Plant signaling and behavior, 5(4), 473-475.

Wakrim, R., Wahbi, S., Tahi, H., Aganchich, B., and Serraj, R. (2005). Comparative effects of partial root drying (PRD) and regulated deficit irrigation (RDI) on water relations and water use efficiency in common bean (Phaseolus vulgaris L.). Agriculture, Ecosystems and Environment, 106(2-3), 275-287.

Walker, S., and Ogindo, H. O. (2003). The water budget of rainfed maize and bean intercrop. Physics and Chemistry of the Earth, Parts A/B/C, 28(20-27), 919-926.

Wang, K., Dickinson, R. E., and Liang, S. (2012). Global atmospheric evaporative demand over land from 1973 to 2008. Journal of Climate, 25(23), 8353-8361.

Wayne, G. P. (2014). Representative Concentration Pathways.

Weerarathne, L. V. Y., Marambe, B., and Chauhan, B. S. (2017). Intercropping as an effective component of integrated weed management in tropical root and tuber crops: A review. Crop protection, 95, 89-100.

White, C. J., Tanton, T. W., and Rycroft, D. W. (2014). The impact of climate change on the water resources of the Amu Darya Basin in Central Asia. *Water Resources Management*, *28*(15), 5267-5281.

Wilhite, D.A.; and M.H. Glantz. 1985. Understanding the Drought Phenomenon: The Role of Definitions. Water International 10(3):111–120.

Willey, R. (1985). Evaluation and presentation of intercropping advantages. Experimental Agriculture, 21(2), 119-133.

Wiryawan, A., and Hairiah, K. (1983). Effect of nitrogen and soil water content on the growth and yield of sweet potato (Ipomea batatas POIR). Agrivita (Indonesia).

Wohleb, C. H., Knowles, N. R., and Pavek, M. J. (2014). Plant growth and development. The potato: Botany, production and uses. CABI, Boston, MA, 64-82.

Xoconostle-Cazares, B., Ramirez-Ortega, F. A., Flores-Elenes, L., and Ruiz-Medrano, R. (2010). Drought tolerance in crop plants. American Journal of Plant Physiology, 5(5), 241-256.

Xuan, T. D., Toyama, T., Khanh, T. D., Tawata, S., and Nakagoshi, N. (2012). Allelopathic interference of sweet potato with cogon grass and relevant species. Plant ecology, 213(12), 1955-1961.

Zelitch, I. (1975). Improving the efficiency of photosynthesis. Science, 188(4188), 626-633.

Zhang, G., Liu, C., Xiao, C., Xie, R., Ming, B., Hou, P., ... and Li, S. (2017). Optimizing water use efficiency and economic return of super high yield spring maize under drip irrigation and plastic mulching in arid areas of China. Field Crops Research, 211, 137-146.

Zhou, Z. C., Gan, Z. T., Shangguan, Z. P., and Dong, Z. B. (2010). Effects of grazing on soil physical properties and soil erodibility in semiarid grassland of the Northern Loess Plateau (China). Catena, 82(2), 87-91.

Zwart, S. J., and Bastiaanssen, W. G. (2004). Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. Agricultural water management, 69(2), 115-133.

# 8.0 APPENDICES

**Analysis of variance**

## Appendix i: ANOVA for Bean yield t/ha season (I)

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| BLOCK stratum | 2 | 0.02501 | 0.01250 | 0.68 | |
| BLOCK. *Units* stratum | | | | | |
| TREATMENT | 2 | 0.21461 | 0.10730 | 5.84 | 0.065 |
| Residual | 4 | 0.07356 | 0.01839 | | |
| Total | 8 | 0.31317 | | | |

## Appendix ii. ANOVA for Bean yield t/ha season (II)

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| BLOCK stratum | 2 | 0.18838 | 0.09419 | 3.21 | |
| BLOCK. *Units* stratum | | | | | |
| TREATMENT | 2 | 2.99605 | 1.49802 | 51.06 | 0.001 |
| Residual | 4 | 0.11735 | 0.02934 | | |
| Total | 8 | 3.30178 | | | |

## Appendix iii. ANOVA for % COVER season (I)

Covariate: DAS

| Source of variation | d.f. | s.s. | m.s. | v.r. | cov.ef. | F pr. |
|---|---|---|---|---|---|---|
| BLOCK stratum | 2 | 1362.4 | 681.2 | 3.68 | | |
| BLOCK. *Units* stratum | | | | | | |
| TREATMENTS | 3 | 3200.3 | 1066.8 | 5.77 | 1.00 | <.001 |
| Covariate | 1 | 105866.7 | 105866.7 | 572.41 | | <.001 |
| Residual | 209 | 38654.2 | 184.9 | | 3.72 | |
| Total | 215 | 149083.6 | | | | |

## Appendix iv: ANOVA for % COVER season (II)

Covariate: DAS

| Source of variation | d.f. | s.s. | m.s. | v.r. | cov.ef. | F pr. |
|---|---|---|---|---|---|---|
| BLOCK stratum | 2 | 157.7 | 78.9 | 0.29 | | |
| BLOCK. *Units* stratum | | | | | | |
| TREATMENTS | 3 | 104.9 | 35.0 | 0.13 | 1.00 | 0.944 |
| Covariate | 1 | 49416.4 | 49416.4 | 178.75 | | <.001 |
| Residual | 209 | 57778.9 | 276.5 | | 1.85 | |
| Total | 215 | 107457.9 | | | | |

## Appendix v: ANOVA for Tuber yield t/ha season (I)

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| block stratum | 2 | 20.071 | 10.036 | 3.22 | |
| block. *Units* stratum | | | | | |
| treatment | 3 | 6.219 | 2.073 | 0.67 | 0.603 |
| Residual | 6 | 18.700 | 3.117 | | |
| Total | 11 | 44.991 | | | |

## Appendix vi: ANOVA for Tuber yield t/ha season (II)

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| block stratum | 2 | 54.40 | 27.20 | 1.82 | |
| block. *Units* stratum | | | | | |
| treatment | 3 | 1006.63 | 335.54 | 22.40 | 0.001 |
| Residual | 6 | 89.89 | 14.98 | | |
| Total | 11 | 1150.91 | | | |

## Appendix vii. ANOVA for WUE tuber Season (I)

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| block stratum | 2 | 29.390 | 14.695 | 3.22 | |
| block. *Units* stratum | | | | | |
| treatment | 3 | 9.106 | 3.035 | 0.67 | 0.603 |
| Residual | 6 | 27.382 | 4.564 | | |
| Total | 11 | 65.878 | | | |

## Appendix viii: ANOVA for WUE Tuber Season (II)

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| block stratum | 2 | 87.51 | 43.76 | 1.82 | |
| block. *Units* stratum | | | | | |
| treatment | 3 | 1619.48 | 539.83 | 22.40 | 0.001 |
| Residual | 6 | 144.61 | 24.10 | | |
| Total | 11 | 1851.60 | | | |

## Appendix ix: ANOVA for HI season (I)

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| block stratum | 2 | 107.65 | 53.82 | 0.60 | |
| block. *Units* stratum | | | | | |
| treatment | 3 | 498.37 | 166.12 | 1.86 | 0.237 |
| Residual | 6 | 535.14 | 89.19 | | |
| Total | 11 | 1141.16 | | | |

## Appendix x: ANOVA for HI season (II)

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| block stratum | 2 | 196.14 | 98.07 | 5.95 | |
| block. *Units* stratum | | | | | |
| treatment | 3 | 276.02 | 92.01 | 5.58 | 0.036 |
| Residual | 6 | 98.89 | 16.48 | | |
| Total | 11 | 571.04 | | | |

## Appendix xi: ANOVA for CWP season (I)

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| block stratum | 2 | 0.032005 | 0.016003 | 3.22 | |
| block. *Units* stratum | | | | | |
| treatment | 3 | 0.009917 | 0.003306 | 0.67 | 0.603 |
| Residual | 6 | 0.029819 | 0.004970 | | |
| Total | 11 | 0.071741 | | | |

## Appendix xii: ANOVA for CWP season (II)

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| block stratum | 2 | 0.09530 | 0.04765 | 1.82 | |
| block. *Units* stratum | | | | | |
| treatment | 3 | 1.76361 | 0.58787 | 22.40 | 0.001 |
| Residual | 6 | 0.15748 | 0.02625 | | |
| Total | 11 | 2.01640 | | | |

## Appendix xiii: ANOVA for predicted irrigation water needs at RCP 2.6

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| Stage | 3 | 5773.3 | 1924.4 | 10.15 | 0.001 |
| Residual | 13 | 2465.6 | 189.7 | | |
| Total | 16 | 8238.9 | | | |

## Appendix xiv: ANOVA for predicted irrigation water needs at RCP 8.5

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| Stage | 3 | 5855.9 | 1952.0 | 9.59 | 0.001 |
| Residual | 13 | 2644.8 | 203.4 | | |
| Total | 16 | 8500.7 | | | |

## Appendix xv: ANOVA for irrigation water needs for the baseline period

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| Stage | 3 | 8285.4 | 2761.8 | 18.85 | <.001 |
| Residual | 13 | 1905.0 | 146.5 | | |
| Total | 16 | 10190.5 | | | |

## Appendix xvi: Soil moisture characteristics

| ***pF*** | Soil water content (cm$^{-3}$ cm$^{-3}$) | | | |
|---|---|---|---|---|
| | θ 15cm | θ 30cm | θ 45cm | θ 60cm |
| 0 | 0.3896 | 0.4143 | 0.4398 | 0.4697 |
| 0.1 | 0.3894 | 0.4141 | 0.4397 | 0.4695 |
| 0.2 | 0.3891 | 0.4138 | 0.4394 | 0.4692 |
| 0.3 | 0.3886 | 0.4135 | 0.4391 | 0.4688 |
| 0.4 | 0.3880 | 0.4130 | 0.4386 | 0.4683 |
| 0.5 | 0.3872 | 0.4123 | 0.4380 | 0.4676 |
| 0.6 | 0.3861 | 0.4114 | 0.4371 | 0.4666 |
| 0.7 | 0.3846 | 0.4101 | 0.4360 | 0.4653 |
| 0.8 | 0.3825 | 0.4084 | 0.4344 | 0.4635 |
| 0.9 | 0.3797 | 0.4061 | 0.4322 | 0.4611 |
| 1 | 0.3760 | 0.4031 | 0.4294 | 0.4580 |
| 1.1 | 0.3711 | 0.3991 | 0.4256 | 0.4538 |
| 1.2 | 0.3649 | 0.3940 | 0.4206 | 0.4484 |
| 1.3 | 0.3570 | 0.3875 | 0.4142 | 0.4415 |
| 1.4 | 0.3474 | 0.3794 | 0.4062 | 0.4330 |
| 1.5 | 0.3361 | 0.3696 | 0.3964 | 0.4226 |
| 1.6 | 0.3230 | 0.3581 | 0.3848 | 0.4103 |
| 1.7 | 0.3085 | 0.3451 | 0.3713 | 0.3963 |
| 1.8 | 0.2930 | 0.3308 | 0.3564 | 0.3808 |
| 1.9 | 0.2769 | 0.3155 | 0.3402 | 0.3641 |
| 2 | 0.2606 | 0.2997 | 0.3233 | 0.3467 |
| 2.1 | 0.2446 | 0.2838 | 0.3061 | 0.3290 |
| 2.2 | 0.2292 | 0.2681 | 0.2890 | 0.3115 |
| 2.3 | 0.2144 | 0.2529 | 0.2723 | 0.2944 |
| 2.4 | 0.2006 | 0.2383 | 0.2564 | 0.2780 |
| 2.5 | 0.1878 | 0.2246 | 0.2412 | 0.2624 |
| 2.6 | 0.1759 | 0.2117 | 0.2271 | 0.2478 |
| 2.7 | 0.1649 | 0.1997 | 0.2139 | 0.2341 |
| 2.8 | 0.1549 | 0.1886 | 0.2017 | 0.2214 |
| 2.9 | 0.1458 | 0.1783 | 0.1904 | 0.2096 |
| 3 | 0.1374 | 0.1689 | 0.1800 | 0.1988 |
| 3.1 | 0.1298 | 0.1602 | 0.1706 | 0.1888 |
| 3.2 | 0.1229 | 0.1522 | 0.1619 | 0.1796 |
| 3.3 | 0.1166 | 0.1449 | 0.1539 | 0.1712 |
| 3.4 | 0.1109 | 0.1382 | 0.1466 | 0.1635 |
| 3.5 | 0.1058 | 0.1321 | 0.1400 | 0.1564 |
| 3.6 | 0.1011 | 0.1265 | 0.1339 | 0.1499 |
| 3.7 | 0.0968 | 0.1214 | 0.1284 | 0.1439 |
| 3.8 | 0.0930 | 0.1167 | 0.1234 | 0.1384 |
| 3.9 | 0.0894 | 0.1124 | 0.1188 | 0.1334 |
| 4 | 0.0863 | 0.1085 | 0.1146 | 0.1289 |
| 4.1 | 0.0834 | 0.1049 | 0.1107 | 0.1247 |
| 4.2 | 0.0808 | 0.1016 | 0.1072 | 0.1208 |