SIMULATING MAIZE (*Zea mays* L.) PERFORMANCE USING AQUACROP MODEL UNDER VARYING IRRIGATION SCHEDULES AND WATER DEPLETION LEVELS IN BURA IRRIGATION SCHEME, KENYA

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE **REQUIREMENTS OF THE AWARD OF THE DEGREE OF MASTER OF SCIENCE IN AGRICULTURAL RESOURCE MANAGEMENT FROM THE UNIVERSITY OF NAIROBI, FACULTY OF AGRICULTURE, DEPARTMENT OF PLANT SCIENCE AND CROP PROTECTION**

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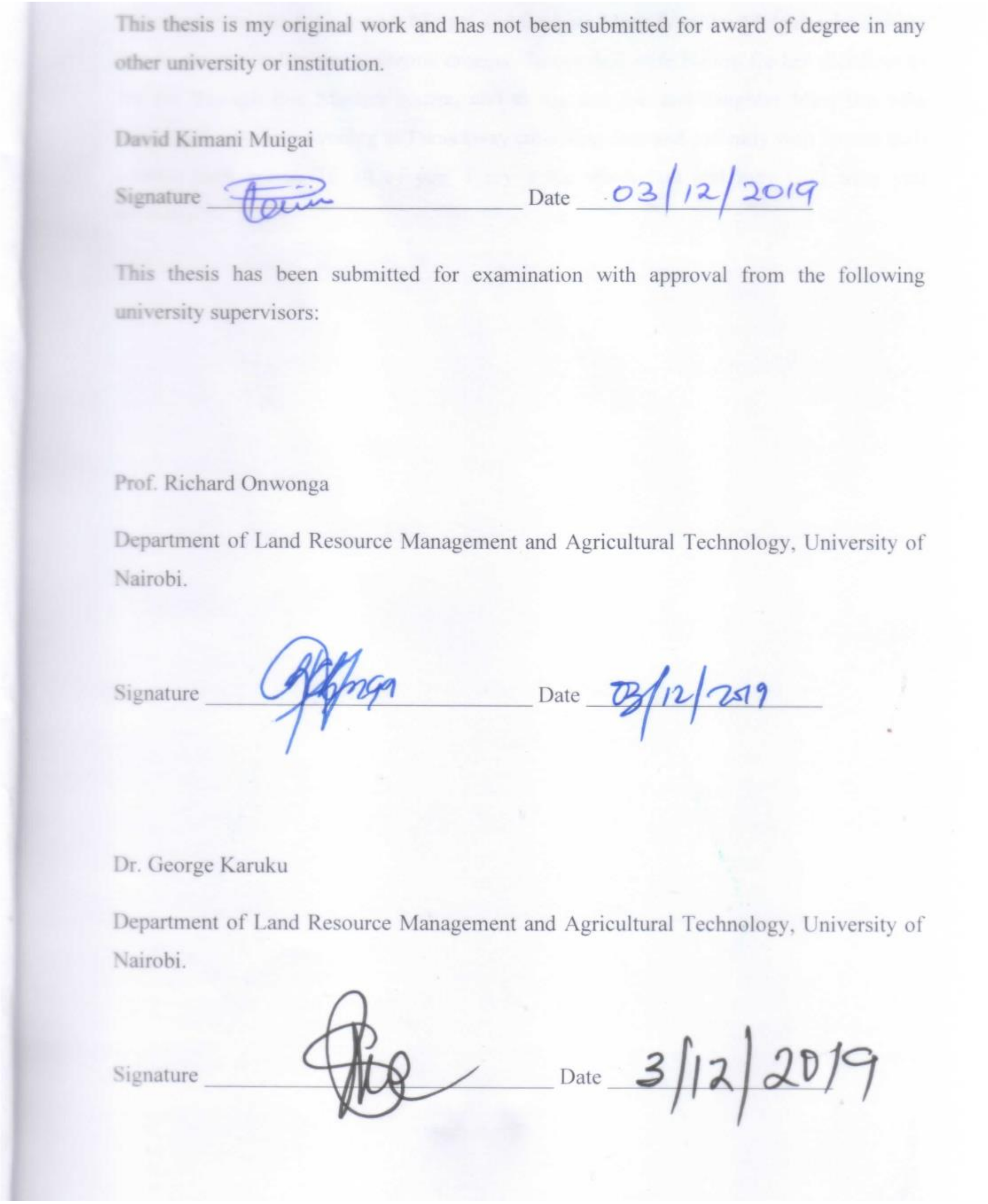
DECLARATION



This thesis is my original work and has not been submitted for award of degree in any other university or institution.

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DEDICATION

To my parents, the Late Joseph Muigai and the Late Mary Wanjiku Muigai, who did not live to see me realize my academic dreams. To my dear wife Naomi for her sacrifices to see me through this Masters course, and to my son Joe and daughter MaryAnn who would call me every evening as I was away collecting data and patiently wait for me until I came back home. To all of you, I say a big thank you and may God bless you abundantly.

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ACRONYMS AND ABBREVIATIONS

ASALs – Arid and Simi-Arid Lands

Asl – Above sea level

BADEA – Arab Bank for Economic Development in Africa

BISS – Bura Irrigation Settlement Scheme

RCBD – Randomized Complete Block Design

ET – Evapotranspiration

Eta – Actual Evapotranspiration

ILRI – International Livestock Research Institute

IWUA – Irrigation Water Users Association

Mg – Mega grams

MIS - Mwea Irrigation Scheme

NIB – National Irrigation Board

OFID – OPEC Fund for International Development

AWC – Available Water Capacity

RCMRD – Regional Center for Mapping and Resource Development

RMSE – Root Mean Square Error

SSA – Sub-Sahara Africa

UNCED – United Nations Conference on Environment and Development

USDA – United States Department of Agriculture

WRB – World Reference Base for Soil Resources

WRMA – Water Resources Management Authority

WUE – Water Use Efficiency

GENERAL ABSTRACT

Supplemental irrigation is an important practice in sustaining soil moisture for optimal crop yield especially in ASAL regions, where during the growing season, potential evapotranspiration exceeds precipitation and the available soil water content. To investigate this, two parallel field experiments were done during the 2015 short rain (October - December) and 2016 long rain (April - July) at Bura Irrigation Scheme, Tana River County, to model maize growth and yield, under seven irrigation treatments. Effect of four irrigation schedules of daily (Td), weekly (Tw), bi-weekly (Tbw) and tri-weekly (Ttw) and three levels of depletion of available water capacity (AWC) at 75% (T75), 50% (T50) and 25% (T25) were tested on maize (*Zea mays L.)* variety PH4. Percentage canopy covers, above ground biomass and grain yield were the parameters used to gauge maize performance. From the results, Tw and Tbw treatments gave 13.9 and 13.7 Tonha^{-1} of above ground biomass, respectively, which were significantly higher ($P \leq 0.05$) compared to Td and Ttw, which gave 7.2, and 8.8 Tonha^{-1} of above ground biomass, respectively. Grain yield for Tw was significantly higher ($P \leq 0.05$) at 5.9 Tonha^{-1} compared to Tbw at 5.7 Tonha^{-1}. Compared to the other irrigation schedule treatments, Td and Ttw had significantly lower ($P \leq 0.05$) grain yield of 2.0 and 2.6 Tonha^{-1}, respectively. T75and T50 treatments gave the highest above ground biomass of 15.8and 15.5 Tonha^{-1} and grain yield of 6.2 and 6.1 Tonha^{-1}, respectively. This was significantly higher ($P \leq 0.05$) compared to T25, which gave 6.2 and 2.7 Tonha^{-1} of above ground biomass and grain yield, respectively. Irrigation scheduling treatments gave lower grain yield and water use efficiency compared to water depletion level treatments. The lowest (3.21 kgmm^{-1}ha^{-1}) and the highest (13.6 kgmm^{-1}ha^{-1}) water use efficiency were recorded under T75 and Td treatments, respectively. Treatments Tw, Tbw, T75 and T50 were found worth of consideration for testing under the soil and weather conditions of the study area. Aquacrop model was hence used to simulate and predict attainable yield in the irrigation scheme for these four treatments. There was agreement between the model's simulated and observed canopy cover, biomass yield and soil water content giving r^2 values of between 0.90 - 1.00, 0.94 - 1.00 and 0.84 – 0.98 ($P \leq 0.05$), respectively. The model predicted higher above ground biomass and grain yield than what was attained in the field, an indication that yields in the farm can further be improved.

Keywords: ASALs, Irrigation schedule, water depletion levels and WUE

CHAPTER ONE

1.0 GENERAL INTRODUCTION

1.1 Background

Globally, maize is ranked third among the popularly grown crops after wheat and rice (Abdolreza, 2006). The Top five producers are United States, China, Brazil and Mexico (Ranum *et al*., 2014), which produced 749 million tons of the 2016 global production of 1060 million tons. In SSA, maize is the principal staple crop where top producing countries are South Africa as the major producer, with 12 million tons of grain annually. It is followed by Nigeria (10.1 million), Ethiopia (7.2 million) Tanzania (6.7 million) and Kenya at seventh position with 3.3 million tons (FAO, 2016). In Kenya, mainly small-scale holders grow it in a wide range of ecological conditions that range from the humid highlands to the ASALs and humid coastal lowlands. These farmers produce maize for domestic consumption as well as feed for livestock as silage or crop residue. Industrially, maize is used for starch and oil extraction (Ambika *et al*., 2012). The grain is consumed in many forms such as *ugali*, mixed with legumes and boiled-*githeri*, porridge and as a local brew-*busaa* (UNESCO, 2013). Green maize is eaten on the cob roasted or boiled.

Maize is cultivated through rain-fed systems or through full or supplemental irrigation. Early maturity grain varieties take 80 - 110 days to mature while medium varieties take 110 - 140 days. For germination and optimum growth and development, the maize crop requires a daily temperature of 18 – 20^{o}C and 450 - 800 mm of water for the growing period depending on variety and climate (Jaetzold *et al*., 2009). Under limited rainfall, two to five supplemental irrigation applications are required (Allen *et al*., 1998) for the growing period. However, due to water scarcity, which has been aggravated by weather change, maize production especially in SSA has been on the downward trend with yields as low as 1.5 Tonha^{-1} (Alexandratos *et al*., 2012). This downward trend points to future food insecurity worsened by population rise, (Beintema *et al*., 2006) that is expected to hit 8.7 billion by 2030. Reports by FAO (2011) attest to the fact that population pressure in developing countries is among the causes of chronic malnutrition for almost 800 million people.

To meet the growing food demand, Alexandratos *et al.* (2012) suggested that agricultural production should increase by 2.4% per annum though this also faces challenges which include among others, dependence on rain fed agriculture, poor soils that cannot support healthy crops, maize diseases such as maize streak virus and the dreaded maize lethal necrosis. Pests and weeds such as the parasitic *Striga hermonthica* are also major challenges to maize production (Roger, 2017). In addition, political conflicts, endemic poverty, poor dissemination of agricultural information pose challenges (world Bank, 2006). Most farmers in SSA and even in ASALs rely on rain fed agriculture, which has been aggravated by climate change (Aseng *et al.*, 2011, Schlenker *et al.*, 2009). Under such uncertainties, crop growth models come in handy to predict attainable yields under such scenarios. The situation is not any different in Kenya because the country experiences variable spatial and temporal availability of rainfall (Clark & King, 2004). This calls for the improvement of Kenya's agricultural water resource management to conserve water and improve production and hence the reason for this study. Modeling allowed the researcher to gauge the level of production at the scheme, aimed at improving water use and increased production.

1.2 Statement of the problem

The potential for increasing maize production in SSA is huge but production is still low. One of the major contributing factors to this poor performance is water availability and efficient use, especially at farm level. The resource is inadequate both in time and space and even where it is deemed adequate, irrigation efficiency especially in large-scale irrigation schemes is quite low. The result is high cost of irrigation water and its unequal distribution where sections of the farm receive more while tail end users receive less. The changing climate has compounded the water problem and made it harder for the management to make the right decision under numerous probable scenarios, hence the importance of use of tools that can assist in decision making and predictions. These tools come in form of crop growth models.

1.3 Objectives

1.3.1 Overall objective

To model Maize crop performance in Bura Irrigation Scheme under different irrigation schedules and water depletion levels.

1.3.2 Specific objectives

i. Evaluate the effects of irrigation schedules on maize growth and yield.
ii. Evaluate the effects of varying water depletion levels on maize growth and yield.
iii. Model maize water requirement and irrigation schedule for Bura Irrigation Scheme using AquaCrop.

1.4 Hypotheses

i. Different irrigation schedules have no significant effect on maize growth and yield.
ii. Varying soil moisture levels have no significant effect on maize growth and yield.
iii. Aquacrop model cannot be used to give the best time for optimal application of irrigation water.

1.5 Justification

As demand for food and water increases, it raises serious environmental concerns and there is need for prudent use of irrigation water by reducing wastage. This will lead to reduction in energy needed to supply the water while maximizing crop yields and profit. Maize yield at Bura Irrigation Scheme currently average 3.5 Tonha^{-1} for commercial farms and 4.4 Tonha^{-1} for seed maize farm. This production is well below the global average and possible attainable yields of 4.9 and 6.0Tonha^{-1}, respectively. It needs to be emphasized that increasing production needs to be achieved by improving yield rather than cultivating more land. This will mean cultivating the same land and using the same amount of water if not less to produce more crops. If less water is used, more water will be available for future agricultural expansion such as the recently initiated one million acre project - Galana-Kulalu. Farmers will make more profit due to reduction in water charges and higher crop yield will be assured. More land will also be available for other competing uses. This can only be done after an empirical determination of maize water requirement and development of a water distribution plan for the scheme. However the Scheme lacks appropriate quantitative and quantitative indicators to gauge water-use efficiency despite its importance in the area. Since efficiency is an important factor of sustainability, the improved productivity of the current and future irrigation activities lies in the efficient utilization of the available water. Because the conditions under which production takes place are ever changing, the farm management needs a tool that will assist in making the proper decision on planting dates, fertilizer application and irrigation timing. Maize was selected as the crop of study because it is the main crop grown in the scheme.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Maize production

Maize (*Zea Mays*) is an annual plant and according to Assem (2015), it has its origins in Central America. Also known as corn, mainly in the United States, it is the third most grown crop after wheat and rice and an important cereal both as human and animal feed. Usually, it is categorized into two groups subject to its colour: yellow and white. Yellow maize epitomizes the vastness of total world maize production and is cultivated in most northern hemisphere countries for animal feed (FAOSTAT, 2014). The crop does well in climatic conditions ranging from temperate to tropical. Different varieties do well in different agro-ecological zones and as such, high yields depend on the right choice of varieties suited for a particular climate (Jaetzold *et al*., 2009). It does well on well-drained and well-aerated soils because the crop is sensitive to waterlogging. Heavy dense clayey and sandy soils are not suitable (Ranum *et al*., 2014). Maize is also moderately sensitive to salinity such that soils of electrical conductivity of 2.5 mmhos/cm or more may decrease yields by up to 10% (Shahid *et al*., 2018, Blaine *et al*., 2006, Jan *et al*., 2000)

Though maize is relatively tolerant to water deficits during the vegetative and maturity stages, irrigation depth and frequency has a significant effect on yield. For optimal production, water requirement ranges between 500 to 800mm during its growing period (Hsiao, 2012). The highest decrease in grain yields occurs when the crop suffers moisture stress during the critical growth periods, which include tasselling, silking and pollination (Rhoads, 2000; Zain, 2014).

2.2 Constraints in maize production

Constraints in maize production include biotic, abiotic and socio-economic factors. The latter include competition from cheap imports that negatively influence domestic production, yet decline in maize production while population increases rapidly has made importation inevitable. The rapid population increase in Kenya has led to subdivision of land to small uneconomic units, which are cultivated continuously allowing no fallow periods. This leads to rapid depletion of soil nutrients, decrease in yields and environmental degradation (Tenaw *et al*., 2009). For the most part, farmers do not use fertilizers and even when they do, they use far below the recommended organic and inorganic fertilizer application rates, leading to reduced yields

(Bationo*et al*., 2012). Rapid decline in soil fertility in Sub Saharan Africa and in Kenya is of particular concern to maize production that has resulted in negative nutrient balances in most smallholder farming systems (Jaetzold *et al*, 2009).

One other factor that causes severe problems for maize production from time to time is the occurrence of climate extremes. One such event is the La Niña phenomenon, the direct opposite of El Niño. La Niña event are responsible for decline in yields in countries such as Kenya (Jeremy, 2017) due to drop in rain. Climate change impacts are already noticeable in Kenya with extreme events becoming a common occurrence. As Chichongue *et al.* (2015) observes, rain seasons have become shorter while dry seasons longer. Change in food production can attest to this. For example, in 2015/2016 periods, Kenya's annual maize production dropped from 3.33 million tons to 2.52 million tons (FAOSTAT, 2016), against the country requirement of 3.6 million tons.

Invasion of weeds such as *Striga hermonthica* (Vanlauwe *et al*., 2005) commonly known as the "witch weed" (a parasitic weed) also causes huge farm losses. Unfortunately, soil fertility depletion (common to SSA) increases the occurrence of this weed; further aggravating maize yields (Gethi *et al*., 2005). Mohamed *et al.*, (2001) described 28 weed species of which six subspecies are indigenous to Africa and causes huge crop loss. Pests also, such as fall armyworm (*Spodoptera frugiperda)* caused destruction of large acres of maize crop in the 2016/2017-production year in Kenya that saw an estimated 7 million bags of maize lost (FAO, 2017).

Water availability happens to be one of the most important single factors of agricultural production in ASALs (Schneekloth *et al*., 2012). Unfortunately, with the current climate change, this is imminent and understanding the crop water balance is critical in developing technological options for sustainable management of soil and water resources (Kinama *et al.,* 2005). This means that to grow healthy crops, it is becoming increasingly important to use irrigation. Industrial and municipal water demand is however on the rise with the rising population. This means that less water is available for agriculture (Ali *et al*., 2006). This leaves the agriculture sector with a great challenge of increasing crop water productivity (Zwart *et al*., 2004) such as efficient irrigation scheduling (Kirda, 2002). If this happens, it will increase WUE and save on this scarce resource. Knowledge gaps in surface irrigation persist and were emphasized by Burton (2016). He advocated for increased focus on improving water use in a series of measures ranging from strengthening Water Users Associations to improving water application at the farm level; and which could see yields increase by 40% and WUE by 60 to 87%. Kenya faces similar problems of dwindling erratic rain especially in ASALs (WCRP, 2010). In 2015 for example, farmers in Bura irrigation scheme suffered maize crop failure due to insufficient irrigation water (Scheme Management, 2015).

Diminishing land sizes due to the tenure systems in Kenya also affect the area under maize production (Ogechi *et al.*, 2014). Land reform professionals assert that, the major drawback to increased agricultural output is population pressure, which leads to shortage of land. Structure of land tenure, lack of suitable land ownership and improved agricultural technology and the current climate change all compound the problem (Shimelles, 2009). Uncertain land tenure or the lack of land ownership also limits the farmers' access to credit facilities, crucial for better land practices (Tenaw *et al*., 2009). Other notable challanges facing maize production include limited access to extension services, which leads to farmers using out-dated technology and lack of access to market.

2.3 Irrigation scheduling

This is a process of determining the correct frequency and duration of watering crops. Proper knowledge of the soil water status, crop water needs, crop water stress status, and possible yield reduction under water stressed situations is necessary for proper scheduling (Yadvinder *et al*., 2014). The rate of soil water depletion is the chief deciding factor for the frequency of irrigation (Nair, 2010), which is essentially determined by either water balance or direct measurement of soil moisture (Marshall, 2007). Gimenez *et al*. (2005) indicate that plant water status is a better determinant of irrigation scheduling.

Various methods have been used in irrigation scheduling. They include plant indicators such as wilting, soil water monitoring or estimation of evapotranspiration (ET) (Gimenez *et al.*, 2005). Plant water indicators are suitable for defining when to irrigate but not the amount of water to apply (Gimenez *et al*., 2005). Many models that have been validated in different regions and climates are available for scheduling. The user is only required to determine the soil moisture deficit, usually expressed as depth of net amount of water lost (Marshall, 2007). In most irrigation schemes, irrigation managers adopt a fixed irrigation depth and interval because it is confusing for the farmers to keep changing the schedule all the time (FAO, 1986). This could lead to over-abstraction, reduced river flows, diminishing ground water levels, and increased risk of pollution, all of which lead to increasing cost of water worldwide. In turn, it may lead to creation of new legislation to restrict the amount of water to be abstracted. This brings about another level of water management at the catchment scale and its consequences on land use. While some of these concerns are not likely to involve farmers directly, the decisions have impact such as which type of crop that can be cultivated (Marshall, 2007; (Nair, 2010). Where rainfall is low and irrigation water supply is restricted, scheduling should be geared towards ensuring that crops don't suffer moisture stress during the critical periods such as flowering and yield formation (Ranum *et al*., 2014).

2.4 Water depletion levels/deficit irrigation.

2.4.1 Crop growth simulation models

Efforts in predicting crop growth and yield using models started way back in the1960s by several research groups among them de Wit and co-workers in 1969. Their efforts led to the development of more superior models such as CERES (Jones and Kiniry, 1986), APSIM (Agricultural Production Systems Simulator), DSSAT (Decision Support System for Agro technology Transfer), WOFOST (World Food Studies crop growth model) (Sarangi, 2012) CropWat, and CropSyst (Crop System Model)(Vote *et al.*, 2015). Msongaleli *et al*., (2014) generally summarizes use of models in agricultural systems as: -

(i) Better understanding of water-food-climate change relations, and

(ii) Investigating options to increase agricultural production now and in future climates.

Various studies have been conducted on use of growth models to optimize agricultural systems under changing environmental conditions because of their user-friendly interface (Sarangi *et al*., 2012, Vote *et al.*, 2015; Buerkert, 2001; Sinaj *et al.*, 2001). Models are simplified mathematical representations of reality that can compute experimental outcomes without having to perform trials. One such model is Aquacrop.

Aquacrop is FAO's crop water productivity simulation model that morphed from amendment of Irrigation and drainage Paper No. 33 (Doorenbos, 1977). The model's simplicity and minimal data requirement in comparison to other models such as APSIM, DSSAT, CERES, CropSyst and WOFOST made it the model of choice in this study. (Sarangi, 2012; Vote *et al.*, 2015; Steduto *et al.*, 2009). The model has been used extensively the world over to simulate different scenarios with a high degree of prediction. For instance Hunink and Droogers (2011) using Aquacrop model to replicate wheat growth and yield observed statistically similar observed versus simulated yields, proving the model's accuracy. A study by Mhiza (2010) in the maize belt of Zimbabwe for two growing seasons using AquaCrop showed the model performed satisfactorily giving Nash-Sutcliffe model efficiency parameter of 0.81, RMSE of 15% and R^2 of 0.86 upon validation. The closer the EF and R^2 are to 1, and RMSE closer to zero, the higher the level of model accuracy. The calibrated and validated model by Mhiza (2010) was subsequently used to develop sowing guidelines for rain-fed maize in Zimbabwe's local environment. Salem *et al.* (2011) found out that AquaCrop provided excellent simulations validated with RMSE, R^2 and Nash-Sutcliffe model efficiency parameterfor canopy cover, grain yield and water productivity of wheat crop in central Iran for three growing seasons under 40% deficit irrigation. Other researchers include Kiptum *et al*., 2013 and Mbindah *et al*., 2017,

Despite various studies being carried out in the region on overall agricultural productivity among smallholder farmers in the study area, much of these findings have not been adopted due to various reasons. These include weakness of extension services, lack of funds for implementation and a wide diversity of agricultural production systems. Heterogeneous agricultural systems make growth models particularly important because such findings may not be generally implemented across the region but models will simulate for any set of agricultural conditions. Site-specific scenario consideration and information on soil characteristics and agro-climatic variables need to be done. This study therefore sought to address some of these gaps with the main aim of evaluating the scheme water requirement and consequence of different levels of irrigation and its effects on maize productivity and WUE considering long-term influence of site-specific variables through modeling.

CHAPTER THREE

3.0 GENERAL MATERIALS AND METHODS

3.1 Study Site Description

Bura Irrigation Scheme is located in the Tana River Basin, Tana River County 50km North of Hola town and about 400 kilometers North of Mombasa city at latitude of $10^{o}8'$S and longitude $39^{o}45'$ E and elevation of 110m asl. The scheme lies in agro-ecological zone V (semi-arid to arid) and experiences a bimodal mean annual rainfall of about 400mm. Long rains occur in March to May while short rains occur in November to December (Jaetzold *et al*., 2009). High Temperatures are experienced all year round with little seasonal variation with mean maximum temperatures $\geq 31°C$ and average minimum temperatures above 20°C. February and March are the hottest months where temperature range between 29.2 and $30.5^{o}C$ (Muchena, 1987). The mean measured annual evaporation using US Weather Bureau Class A evaporation pans for Garissa and Hola is 2,712 and 2,490 mm, respectively, giving an average annual value of 2601 mm. The scheme is situated between the Garissa and Hola meteorological stations and on average records a daily evaporation of about 6.4 mm day^{-1} and r/ETo of 0.15. Soils in the study area are a combination of Vertisols and Verticfluvisols according to WRB (2014) classification system (Wamicha *et al*., 2000), which are characterized with swelling and forming ponds during wet seasons due to low infiltration rates caused by sealing caused by high clay content (Koech *et al*., 2014). The scheme has shallow sandy clay loams and heavy cracking clays overlying saline and alkaline sub-soils of low permeability (Mwatha *et al*., 2000). Land suitability evaluation indicates that the soils are marginally suitable to not suitable for arable farming. They land is best suited for livestock, pasture and forages (Muchena, 1987).

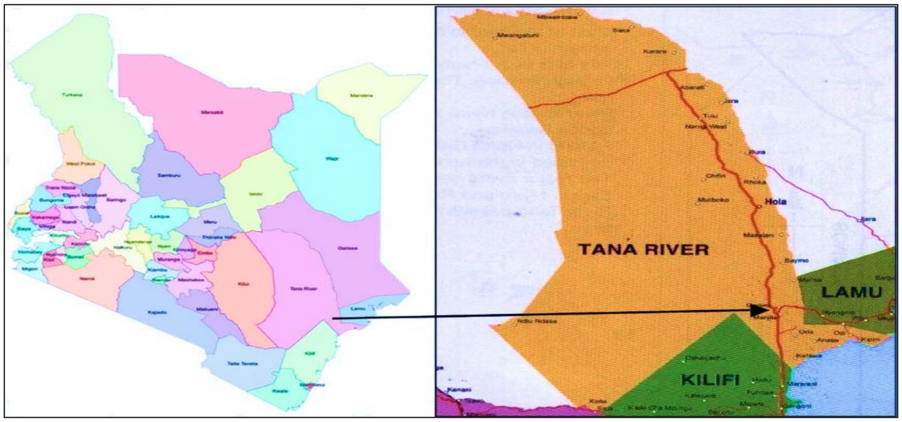


Figure 1: Location of Tana River County and Bura in Kenya.
Source: Department of Geography University of Nairobi

3.2 Experimental Design, Treatments and Layout

Experimental design was Complete Randomized Block Design with seven treatments replicated five times in 4m x 4.5m plots to give a total of 35 experimental plots. The study was carried out during 2015 short rains (October - December) and 2016 long rains (March–May) cropping seasons. The experiment was purposely made to coincide with the farmers' cropping season so that the research findings could reflect and be adopted by farmers with minimum or no adjustments. After 90% emergence, four irrigation scheduling treatments namely:

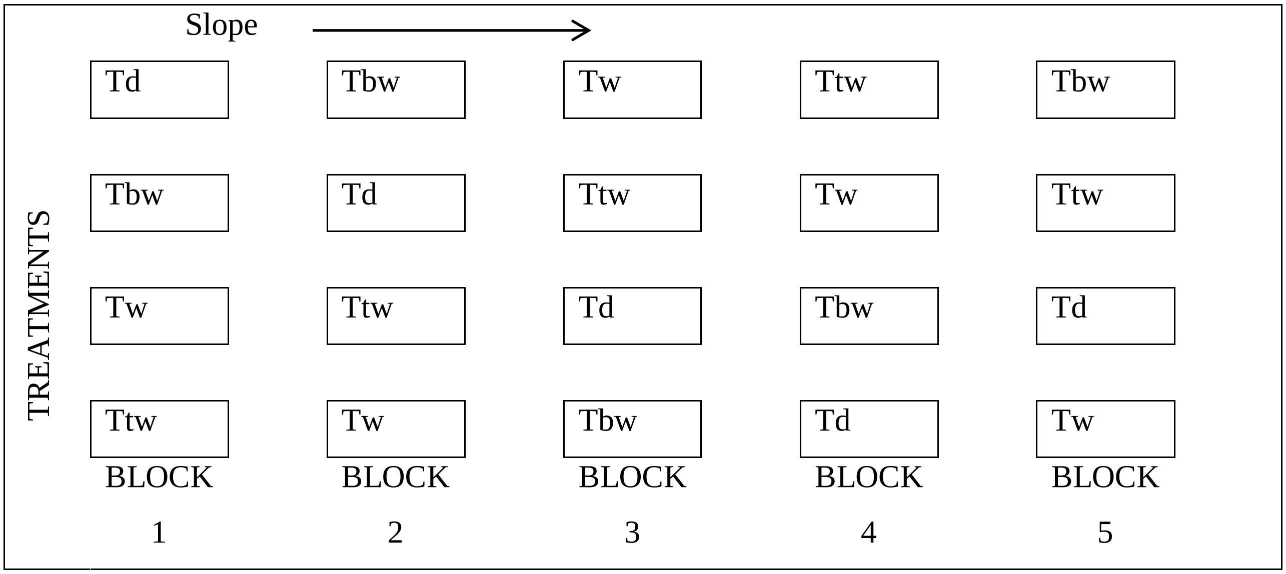
1) Td – Irrigation water was applied every day,
2) Tw – Irrigation to near or field capacity after 7 days,
3) Tbw – Irrigation to near or field capacity after 14 days,
4) Ttw – Irrigation to near or field capacity after 21 days,

And three water depletion level treatments namely:

1) T75 – irrigation to near or field capacity when 25% of plant available water (AWC) is depleted,
2) T50 – irrigation to near or field capacity when 50% of AWC is depleted,
3) T25 – irrigation to near or field capacity when 75% of AWC is depleted,

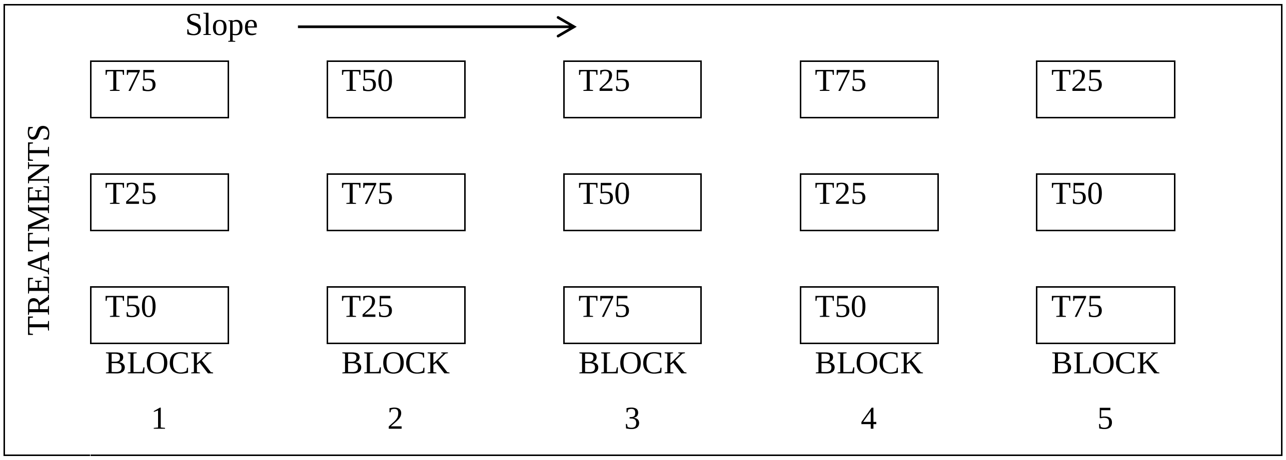
Were used to test their effect on maize crop development and grain yield.

Tbw treatment was the control.



BLOCK 1	BLOCK 2	BLOCK 3	BLOCK 4	BLOCK 5
Td	Tbw	Tw	Ttw	Tbw
Tbw	Td	Ttw	Tw	Ttw
Tw	Ttw	Td	Tbw	Td
Ttw	Tw	Tbw	Td	Tw

Figure 2. Irrigation schedules layout



BLOCK 1	BLOCK 2	BLOCK 3	BLOCK 4	BLOCK 5
T75	T50	T25	T75	T25
T25	T75	T50	T25	T50
T50	T25	T75	T50	T75

Figure: 3. Water depletion levels layout.

3.3 Soil moisture measurement

An Extech Soil Moisture Meter with an 8-inch Stainless steel probe was used to monitor soil water to determine how much to irrigate and when. Equation 1 was used to estimate the amount of irrigation water to apply.

Amount to be applied = water deficit (mm/m) x irrigation depth x area…………………Eq 1

To prevent lateral moisture movement, water was fed directly into furrows in the plots using pipes. A 2m guard rows were made round each plot as an added measure to prevent the likelihood of water from one plot feeding into another. Water was drawn from the feeder canal using the similar siphons used by farmers. Irrigation using pipes enabled the quantification of the amount of water added during the maize growing period. Water was applied to the plots in the evening since it was cooler; atmospheric evaporative demand was lower so that more water infiltrated to the soil and less lost by direct surface evaporation.

3.4 Soil sampling and analysis

Soil auger (600cm^3) was used to collect undisturbed core samples for physical and chemical analysis. Saturated hydraulic conductivity (Ksat) and water content at saturation (θs), field capacity (θf) and permanent wilting point (θpwp) were determined based on the method by Hinga *et al*. (1980). Soil pH was determined with a pH meter in a ratio of 1:2.5 soil/water suspension while electrical conductivity (EC) was determined on a soil paste using an EC meter. Soil texture was by hydrometer method as described by Glendon and Doni (2002). CEC (cation exchange capacity) was determined in an ammonium acetate (NH_4OAc) solution at pH7 and

NH_4-N concentration in the solution determined by micro-Kjeldhal distillation followed by titration with hydrochloric acid. Exchangeable bases (Ca, Mg, Na and K) were extracted from the soil - NH_4OAc leachate and determined using Atomic Absorption Spectrometry (ASS). Organic carbon in soil and manure samples was determined following the Walkley and Black (1934) method as described by Nelson and Sommers (1996). Total N was determined by micro-Kjeldhal distillation method as described by Bremner (1996). The Bray II method was used to determine available P according to Bartlett *et al*. (1994)

3.5 Agronomic practices

The land was ploughed using a disc plough. For uniformity, furrows were made in the entire block before dividing it into plots. The furrows ran parallel to the shorter side of the plot on an east west orientation. Maize seeds of variety PH4 were treated with Thiamethoxam at a rate of 10g per kg of maize seed prior to planting to protect them from insect pests. Planting was done at a depth of 5cm by hand at a spacing of 25 cm between plant and 75cm between rows to give a density of 53,333 plants ha^{-1}. Diammonium Phosphate (DAP) fertilizer was incorporated into the soil during planting at the recommended rate of 175 kgha^{-1}. All plots were irrigated to near field capacity after planting to enhance germination. A pre-emergent weed killer, Atrazine and S-Metolachlor (Primagram) was applied after the first irrigation at a rate of 2500ml ha^{-1}. Weeds that sprouted immediately after were uprooted by hand or weeded by hand hoe. Top dressing at the recommended rate of 250 kg urea ha^{-1} was applied using hands at the base of each plant 40 days after crop emergence. Spraying with 1000mlha^{-1} of Deltamethrin 60 days after crop emergence controlled pests such as stalk borer. No mulch was added in order to replicate farmers' practice.

3.6 Data collection

3.6.1 Above ground biomass (AGB)

AGB was determined bi-weekly by destructively harvesting two randomly selected plants from each of the four middle rows and then drying them in an oven at 60^{o}C for 72 hours, then weighed on a digital balance with precision of ±0.002 grams. The obtained weights were averaged and extrapolated to biomass in Tonha^{-1} at a cropping density of 53,333 plants ha^{-1}.

3.6.2 Canopy cover (CC)

Maize crop CC was determined using the meter stick method according to Miller (1969) between 11.30am and 12.30pm after every two weeks starting from crop emergence. Three sites were selected at random and marked in each plot. Canopy cover was determined from these specific points throughout the growing period. A meter rule was placed on flat ground at midday and the % CC estimated by taking the sum of centimeters covered by the canopy shade on the meter rule. The meter rule was then rotated and the same procedure repeated over an angle of 45^{o}, 90^{o} and 135^{o}. The four readings were averaged to get the percentage canopy cover for that spot. The readings obtained from the three spots in a plot were averaged to get the percentage canopy cover for the plot.

3.6.3 Grain yield (GY)

Grain yield was determined by randomly harvesting all cobs from three plants in each of the six rows after crop physiological maturity. The number ears per plant and the number of rows per ear and the grains per row from each plant were determined. This data was used to obtain the average number of ears per plant, average number of rows per ear and the average number of grains per row. The cobs were shelled and units of 1000 grains weighed to obtain the average weight of grain at 13.5% moisture content. The data obtained was used to estimate grain yield per hectare using Equation 2 and 3.

Grains per ear = Rows of grains x number of gains per row……………………………….………......Eq. 2

Mass of grain per hectare = number of ears per hectare x grains per ear x average mass of grain………....……………………………………………………………………………………….….. Eq 3

3.6.4 Water use efficiency (WUE)

WUE was computed using the Cooper *et al*. (1988) method as used by Karuku *et al*. (2014) and Koech *et al*. (2015)

$$WUE\ (kgha^{-1}mm^{-1}) = \frac{Yield\ (kgha^{-1})}{ETm\ (mm)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad Eq4$$

Where WUE is the crop water use efficiency, yield refers to the crop economic yield and ETm is maize evapotranspiration for that season.

3.6.5 Harvest index (HI)

This is the ratio of economical yield to biological yield, and is calculated from Equation 5.

$$HI = \frac{Y}{B} \quad \text{……………………………………………………………………………………} \textit{Eq.5}$$

Where HI is harvest index, Y is grain yield and B is total biomass

3.7 Statistical Analysis

Data collected was summarized in Microsoft Excel spread sheets and subjected to analysis of variance using Statistical Analysis System (SAS) version 9.1. Post hoc analysis to separate the means was carried out using LSD at $P \leq 0.05$ to determine the sources of differences.

CHAPTER FOUR

4.0 EFFECT OF IRRIGATION SCHEDULES ON MAIZE (*Zea mays L.*) GROWTH AND YIELD

Abstract

Maize accounts for almost a third of annual global grain production. The demand for the grain is on the rise because it is used as human food, feed for livestock and also used to produce biofuel. This increase in demand is putting pressure on land and the available water. Measures to improve WUE in maize production therefore cannot be overemphasized. On this light, a field study was done in Bura irrigation scheme, Tana River County to establish the effect of irrigation schedules on maize yield. Four treatments of daily (Td), weekly (Tw), bi-weekly (Tbw) and tri-weekly (Ttw) irrigation intervals were used. Except Td where AWC never went below FC, the other three treatments were irrigated to field capacity during each irrigation exercise. Canopy covers, above ground biomass and grain yield were used to compare performance of the treatments. Tw had the highest AGB of 13.9 Tonha^{-1} followed by Tbw at 13.7 Tonha^{-1}, Ttw with 8.8 Tonha^{-1} and Td at 7.2 Tonha^{-1}. Tw had significantly higher ($P \leq 0.05$) grain yield of 5.9 Tonha^{-1} compared to Tbw at 5.7 Tonha^{-1} with the lowest grain yield of 2.0 Tonha^{-1} recorded in Td. Ttw gave grain yield of 2.6 Tonha^{-1}. Canopy cover ranged from 72.8% in Tbw, which was significantly higher ($P \leq 0.05$) compared to Tw, Td and Ttw treatments, which had 70.8%, 59.3% and 43.6%, respectively. Data indicated that too much irrigation water negatively affected maize yields, just like deficit.

Key words: Above ground biomass, canopy cover, irrigation schedules, yield

4.1 Introduction

Irrigation provides 60% of cereal produced and uses over 70% of freshwater supplies. Future food and fibre requirement is expected to rise and so does irrigation water demand (FAO, 2003). Meeting this demand does not necessarily mean increasing irrigation water but in improving efficiency of utilising the available water. With the future expected expansion on irrigated land and water scarcity especially in ASALs due to climate change, every available drop of water needs to be prudently used to increase crop production. This will include among other measures increased attention to water management comprising monitoring and measurement of water use at all stages of the irrigation value chain. Water conservation practices have become the focus of renewed research to maximize on irrigation water for crop uptake and subsequent optimal yields. Sustainable water management practices will reduce the irrigation demand for water and spare some for use in the other competing sectors, or expansion of irrigated land (OECD, 2010).

Bura Irrigation Scheme totals 5,360 ha but only 3,340 ha are currently under irrigation due to inadequate water supply. However, the available water could be enhanced to irrigate more land and increase maize production, which is low. The scheme maize production currently stands at 3.5 Tonha^{-1} for commercial and 4.4 Tonha^{-1} for seed maize). This falls below the global average of 4.9 Tonha^{-1}. However, this is well below the attainable yield of 6Tonha^{-1}or more in the region when use of hybrid maize varieties and application of recommended fertilizer rates by small-scale maize producers is adopted (Republic of Kenya, 1997; 2004; Kang'ethe, 2004).

Quantifying the scheme irrigation water requirement is a prerequisite before remedial measures are taken. For optimal production, maize crop needs between 500 to 800 mm of water during its growing cycle (Tekwal *et al*., 2011). The study area receives on average 400 mm per annum. The rain is bimodal hence the amount received per season is far below the maize water requirement. Irrigation is therefore an inevitable practice in the area. However, planting during the short rain season (September-December) takes advantage of the more rain than received in the long rain (April-July) season. The 2015 short rain season received over 250 mm, a trend observed over 2005-2016 (Bura Research Station data). Planting during this season saves irrigation water to be used during flowering and grain filling, growth stages when maize is sensitive to moisture stress. The crop is comparatively tolerant to water shortages during the other stages of growth (Rhoads, 2000; Zain, 2014) hence there may be little need to irrigate during these stages. Water saved will be used for expansion of irrigation or for other uses. It is on this account that this study was undertaken to quantify the scheme water requirement and come up with an irrigation schedule that would optimise use of the available water and increase maize production in the scheme.

4.2 Results and Discussion

4.2.1 Soil characterization of the study site

The amount of clay in the soil increased with depth from 30% at 0-30 cm to 35% at 31-60 cm and 44% at 61-120 cm depths (table 1). This could probably be due to leaching of the fine clay particles by water down the profile, leaving the coarse sand particles at the top. Gul *et al*., (2011) and Adugna *et al*., (2011) reported similar findings. Clay is considered a mobile component in the soil (Charles 1977). According to FAO World Soil Resources Reports (2001), eluviation will occur when water percolates through the soil carrying with it clay as well as metals, humus and other colloidal or dissolved substances and deposit them in lower depths through illuviation process (Gemma *et al*., 2017).

Table 1: Salient soil characteristics of the study site

Profile	Soil texture			Texture class	PWP	FC	AWC	Ksat
cm	Sand (%)	Silt (%)	Clay (%)	(USDA)	--------- Vol. % --------			cm hr^{-1}
0-30	50	20	30	Sandy clay loam	25.13	36.85	11.75	2.27
31-60	40	25	35	Clay loam	14.74	32.85	18.11	0.882
61-120	38	28	44	Clay	25.61	39.47	14.86	0.461

Legend: PWP – permanent wilting point, FC – field capacity, AWC – available water capacity, Ksat – saturated hydraulic conductivity.

Amount of water that can be held in the soil profile is of great importance because soil is a major water reservoir. Water retention of the top horizon (0-30 cm) was lowest compared to the horizons below. It was highest in the middle horizon (31-60 cm), which then decreased in the 61-120 cm horizon (Table 1). The low available water capacity in the topsoil probably was due to high sand content that reduced available water capacity because water in sand's large pores is subject to free drainage under gravity. As the soil particles size decrease, the pores become finer and hold more water against free drainage, increasing water-holding capacity as was seen with the second profile. A fine textured soil therefore holds more water than a coarse textured one because small pores have higher matrix potential than large pores (Jon, 2015). The bottom layer (61-120 cm) had the highest clay content (44%) in comparison to the horizons above but in contrast, available water capacity of this horizon was found to be lower. This could be because clay creates a complex soil matrix of much smaller pores, which makes it hold more water, but the water is held at greater suction pressure leading to increased permanent wilting point, hence reducing the amount of available water. According to Nathalie *et al*. (2001), although clay soils can hold 280 mm of water per metre depth, only 70 mm of it is available to plants. The rest of water is held so tightly and unavailable for use by crops. This is also in agreement with findings by Jeff (2001), O'Geen (2013), Ministry of Agriculture – British Columbia (2015) and Zachary (2016).

The observed high Ksat values in the study indicate high rate of water movement. These Ksat values were found to decrease with depth, as the amount of clay content increased (table 1). This is an indication of increasing resistance to water movement down the profile. Ksat is important in the study of soil infiltration and drainage, aspects that are vital in irrigation water management (Tayfun, 2005) and in the study of nutrient movement in the soil (Philip *et al*., 2014). The value is also important as it dictates the plant type to be grown in a soil, spacing and erosion control. Behzad (2015) also says that Ksat is important in modelling flow and contaminant transport in the soil. Others such as Lin (2003) and West *et al*. (2008) talk of importance of Ksat in modelling and determination of water budget, soil leaching potential and its suitability for agriculture. The notable drop in Ksat value between the surface 0-30cm and the horizons below could be an indicator of compaction. This low Ksat in the lower horizon will cause resistance to plant root penetration and water percolation, which is likely to cause ponding and runoff during rain or irrigation. Ponding indicates saturated soils and most crops don't do well in waterlogged soils due to anaerobic conditions. Since Ksat in agricultural lands is influenced by, among other factors, cropping and tillage practices (Das *et al*., 2010), farmers can correct this by using better farming methods such as deep tillage to loosen the soil and application of manure that will improve soil structure.

4.2.2 Effect of irrigation schedules on performance and grain yield

Weekly (Tw) and Bi-weekly (Tbw) irrigation schedules had significantly ($P \leq 0.05$) higher AGB of 13.9 and 13.7 Tonha^{-1}, respectively compared to the other treatments (Table 2). This was probably due to higher soil moisture content available in Tw and Tbw treatments, which ensured crops didn't suffer moisture stress hence optimal crop growth. Yazar *et al*. (2002)

had similar findings when he obtained highest average maize yield of 12Tonha^{-1} from a schedule of six-day irrigation intervals, and which was 55% higher than a tri-weekly irrigation schedule in field. Daily (Td) irrigation schedule had the lowest AGB of 7.2 Tonha^{-1}. The low yield could have been due to excess water in the soil that created anaerobic conditions consequently leading to poor root respiration and development and hence poor crop establishment. Excess water in Td could also have led to leaching of nutrients below plants root zone due to high water percolation in the sandy soils. Mukhtar *et al*., (1990) had similar results on susceptibility of maize growth in poorly drained soils with high water table, where excess soil water significantly reduced maize yield. Jin *et al*. (1999) also found that over-irrigation reduced both the maize grain yield and dry matter production while Saut & William (2007) reported that over irrigation led to Nitrogen leaching and runoff, disturbed oxygen balance, increased potential for root diseases among other impacts that negatively affect yield in flood irrigation systems.

Tbw irrigation schedule had significantly ($P \leq 0.05$) higher canopy cover compared to the other treatments. This was probably due to maintenance of a sufficient soil moisture content that enabled the crop extract water and nutrients for growth. This compares to the results of Hayrettin and Osman (2009) who observed that if enough water was supplied during vegetative and flowering stages, crop canopy development and dry matter yield were not adversely affected. The least canopy cover was recorded in Ttw treatment probably due to moisture stress. There was significant reduction in soil moisture content before the next irrigation exercise. On the other hand, daily irrigation probably caused anaerobic conditions in the soil and leached nutrients away from the reach of the plant roots. The anaerobic conditions created caused poor root development hence the plant could not absorb nutrients and water for development of the canopy.

Tw recorded significantly ($P \leq 0.05$) higher grain yield of 5.94 Tonha^{-1} compared to Tbw, with 5.68 Tonha^{-1}. Tri-weekly (Ttw) treatment had a low grain yield of 2.69 Tonha^{-1} probably due to water scarcity that inhibited nutrient uptake by the crop for carbohydrate manufacture. Osman (2009) found that dry matter yield of maize significantly reduced due to soil water deficit especially when it occured at the critical growth stages. Igbadun *et al*. (2008) also observed that water stress at any stage of maize crop growth led to decline in biomass and grain yield. Moisture stress could have occurred throughout the entire growing period in Ttw treatment, hence the low yield. Experimental findings showed that, yield decreased with increase or decrease in soil water content above or below the optimal. Karam*et al*. (2003), Pandey *et al*. (2000), Panda *et al*. (2004), Oktem (2008) and Ozgurel (2008) had similar findings.

Table 2: Means for biomass, canopy cover, harvest index, stover and grain yield

Treatment	AGB(Tonha^{-1})	CC (%)	HI (%)	STY(Tonha^{-1})	GY(Tonha^{-1})
Td	7.2^c	59.3^c	27.8^c	5.23^c	2.01^d
Tw	13.9^a	70.8^b	42.8^a	7.9^a	5.94^a
Tbw	13.7^a	76.2^a	41.5^a	8.0^a	5.68^b
Ttw	8.9^b	43.6^d	30.2^b	6.2^b	2.69^c
Means	10.9	62.5	35.4	6.84	4.08
P	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
LSD	0.382	1.34	1.74	0.391	0.175
r^2	0.996	0.979	0.979	0.97	0.996
CV	2.54	1.44	3.54	4.15	3.11

Legend: Td – daily irrigation treatment, Tw – 7 days interval irrigation treatment, Tbw – 14 days interval irrigation treatment, Ttw – 21 days interval irrigation treatment, LSD – least significant difference, CV – coefficient of variation, mean figures followed by same letter down the columns are not significantly different at $P \leq 0.05$

4.2.3 Effect of irrigation schedules on water use efficiency (WUE)

WUE of maize is yield (Tonha^{-1} of grain) per unit of crop water use (Cooper *et al*., 1988). Bi-weekly (Tbw) treatment gave the highest water use efficiency (WUE) of 1.2 kgm^{-3} in comparison to the daily treatment (Td) with 0.32; Weekly (Tw) at 0.81 and Tri-weekly (Tw) had 0.63 kgm^{-3} (Fig. 2). This is probably due to the reason that Tbw provided irrigation water to the maize crop at the right interval and amount, avoiding non-productive water use. Wang (2017) supports this assertion by indicating that scheduling and quantity of irrigation water supply are two most crucial aspects for improving crop WUE based on results of field experiments on wheat under supplemental irrigation in China. The observed highest average WUE of 1.2 kgm^{-3} falls within the accepted 1.1 and 2.7 range of irrigated maize (Zwart and Bastiaanssen, 2004). The low WUE for Td treatment was probably due to non-productive water application, explaining the fact that WUE is negatively correlated to irrigation water volume. Higher grain yield and biomass production is associated with higher irrigation water applied, up to the optimal amount (Fig. 2).

Extra irrigation water above optimal does not lead to increase in biomass yield but may even cause decline in yield as a result of leaching of nutrients and oxygen deprivation to the roots. Chen *et al*. (2009) observed that water required for maximum WUE was much lower than that needed to achieve maximum crop yield.

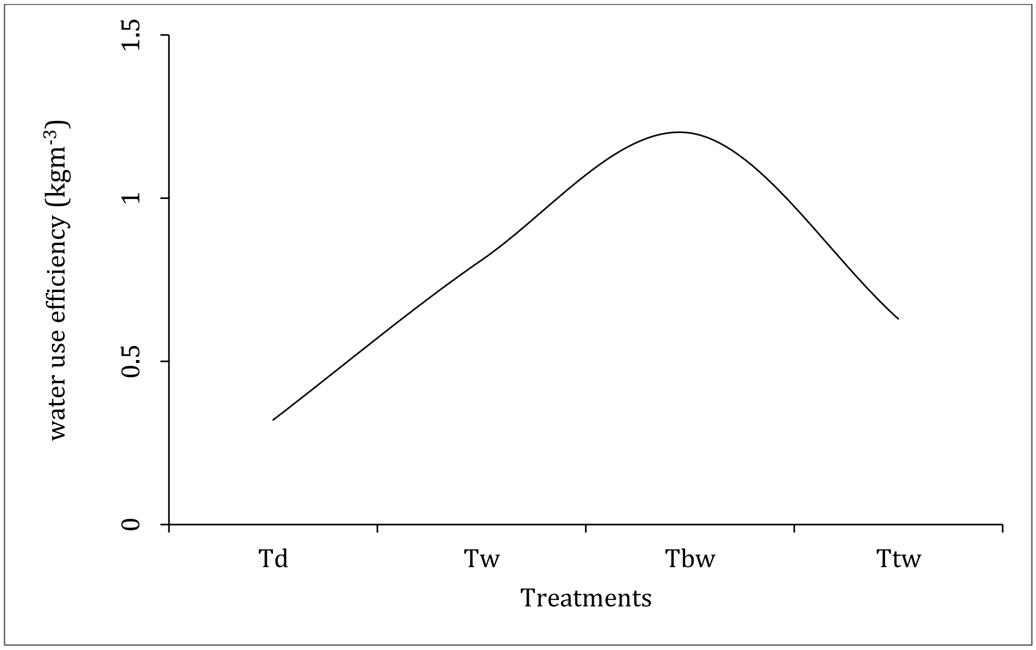


Figure 4: WUE for irrigation schedules

Legend: Td – daily irrigation treatment, Tw – 7 days interval irrigation treatment, Tbw – 14 days interval irrigation treatment, Ttw – 21 days interval irrigation treatment

4.3 Conclusion

Irrigation scheduling is critical to maize performance and yield. Yields from daily and tri-weekly irrigation schedules were low. Too much water applied in the daily irrigation schedule led to low yield probably due to leaching and water logging. Applications of non-productive water also lead to low WUE. Tri-weekly schedule subjected crops to water stress that negatively affect yields and should not be considered. Though weekly and bi-weekly irrigation schedules gave similar performance indicators of above ground biomass, stover yield and harvest index, yields were slightly lower in biweekly than weekly irrigation probably as a result of slight water stress caused by depleted soil moisture before the next scheduled irrigation exercise, especially during very dry days. The lower WUE of weekly irrigation schedule and the slight difference in yield between weekly and bi-weekly irrigation schedules supports the use of the current bi-weekly irrigation schedule in the scheme.

CHAPTER FIVE

5.0 EFFECT OF WATER ON DEPLETION LEVELS ABOVE GROUND DRY BIOMASS, CANOPY COVER AND MAIZE (*Zea mays* L.) GRAIN YIELD.

Abstract

Sufficient soil moisture in the root zone is critical for optimal crop development. Excess or deficit water leads to reduced crop performance and yields. A field study was done to determine the effect of available water on performance of PH4 maize variety on sandy clay loam soil at Bura Irrigation Scheme, eastern Kenya. Three water depletion level treatments T75, T50 and T25 laid in RCBD were used during 2015 long rain (March to June) and 2016 short rain (October to December) seasons. Irrigation was undertaken when 25% (T75), 50% (T50) and 75% (T25) of available water capacity (AWC) was depleted, respectively. Canopy cover, above ground biomass and grain yield was used as indicators of maize performance. Treatments T75 and T50 had no significance difference among them but both had significantly ($P \leq 0.05$) higher above ground biomass, canopy cover, stover and grain yield compared to T25. Maize performance showed a positive linear relationship with the quantity of irrigation water applied up to a certain optimal quantity. Additional irrigation water used in T75 treatment gave slightly higher yields though statistically insignificant compared to T50 treatment. Higher WUE was recorded in T75 than T50. Supplemental irrigation at 50% AWC is recommended for the scheme as it gives high yields and is safe on water compared to T75.

Key words: Above ground biomass, canopy cover, water depletion levels, and yield.

5.1 Introduction

Maize (*Zea mays L.*) is the main staple food in Africa. This is an annual plant, rich in carbohydrates and high productivity, giving a HI of about 50%. It enjoys excellent geographic adaptability, a significant property that has aided its cultivation to spread throughout the world. For optimal growth and development, maize requires temperature range of 15 – 25^{o}C and yearly rainfall of between 500 and 800 mm (Tekwal *et al*., 2011) on well-drained and well-aerated soils. Under such conditions, yield of 6 to 9 Tonha^{-1} can be achieved (Jaetzold *et al*., 2009).

Globally, irrigation provides 60% of cereal produced and uses over 70% of global fresh water (FAO, 2003). With the expected future global increase in food and fibre demands and water scarcity, more pressure will be put on the available fresh water resources. Every available drop of water therefore needs to be prudently used to increase crop production (UN, 2016). The potential for increasing maize production in SSA is huge but unfortunately, maize production has been on the decline, getting as low as 1.5 Tonha^{-1} (You *et al*., 2012). Challenges in water availability and efficient use especially at farm level have immensely contributed to the low yields. This is the situation replicated in the study area and in many other irrigation schemes in Kenya (Ali, 2012, Koech, 2014). For instance, irrigation land in the Scheme totals 5,360ha though only 3,340ha are currently under irrigation due to inadequate water supply (Scheme Management-2015). Improvement of WUE in the scheme would mean possible use of less water or the same amount of available water to produce more food by irrigating more land. Maize production in the scheme currently stands at 3.5 Tonha^{-1} for commercial farm and 4.4 Tonha^{-1} for seed maize. This falls below the global average of 4.9 Tonha^{-1} (Edgerton, 2009). It is also well below the attainable yield of 6 Tonha^{-1} or more with hybrid maize varieties and application of recommended fertilizer rates (Kang'ethe, 2004; Republic of Kenya, 1997; 2004). To change this trend and produce more food with less water, increased attention to water management comprising monitoring and measurement at all stages of the irrigation value chain is key. This means that water conservation practices will become the focus of renewed research to maximize on irrigation water. Sustainable water management practices may in future reduce the irrigation demand for water and spare some for use in expansion of irrigated land and other competing sectors. It is in this light that this study was carried out to improve Kenya's agricultural water resource management through understanding yield potentials and exploiting gaps in present irrigated maize (*Zea mays* L.) production.

5.2 Results and Discussion

5.2.1 Effect of water depletion on maize performance

Treatments T75 and T50 had no significance difference between them on above ground biomass (15.6 and 15.5 Tonha^{-1}, respectively), canopy cover (67.6% and 64.7%, respectively) and grain yield (6.3 and 6.2 Tonha^{-1}, respectively). The two treatments however had statistically ($P \leq 0.05$) higher above ground biomass, canopy cover and grain yield as compared to T25 (6.5 Tonha^{-1}, 50.5% and 2.74 Tonha^{-1}, respectively) (Table 3). The good performance of treatments T75 and T50 was probably because the two treatments didn't suffer moisture stress because the available water capacity (AWC) didn't fall below 50%, the critical point for crops such as maize (Thomas *et al*., 2019).

Table 3: Means of above ground biomass, canopy cover, harvest index, stover and grain yield.

Treatments	AGB(Tonha^{-1})	CC (%)	HI (%)	STY(Tonha^{-1})	GY(Tonha^{-1})
T75	15.6^{a}	67^{a}	40.6^{b}	9.2^{a}	6.3^{a}
T50	15.5^{a}	64.7^{a}	40.3^{b}	9.2^{a}	6.2^{a}
T25	6.5^{b}	50.5^{b}	42.0^{a}	3.8^{b}	2.7^{b}
means	12.5	60.9	41.0	7.4	5.1
P	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
LSD	0.42	4.62	1.13	0.39	0.14
R^{2}	0.99	0.92	0.77	0.99	0.99
CV	2.3	5.2	1.89	3.63	1.84

Legend: T75 – irrigation to field capacity when 25% of available water capacity (AWC) is depleted, – irrigation to field capacity when 50% of AWC is depleted, T25 – irrigation to field capacity when 75% of AWC is depleted, AGB-above ground biomass, CC-canopy cover, HI-harvest index, SY-stover yield and GY-grain yield.

'Water engine' model (Yang *et al*., 2004) suggests that there is a linear relationship between yield to amount of water transpired and that enough water led to high rate of photosynthesis hence higher vegetative growth. Treatment T25 received 305 mm of supplemental irrigation water against an evaporative demand of 523mm for the growing season, giving an r/ETo ration of 0.58 while that of T50 and T75 were 0.83 and 1.05, respectively; this is an indication that treatments T75 and T50 received enough water for crop growth while water supplied to T25 could not meet the crop water requirement. Consequently, the treatment gave significantly (P≤0.05) low grain yield, canopy cover and aboveground biomass as compared to T50 and T75, which received 435 and 549 mm, respectively of irrigation water. Grain yield for treatment T25 was 55 and 56% lower compared to that attained in T50 and T75 treatments, respectively (table 3). When moisture fell to 25% of AWC, plants showed signs of moisture stress such as curling of leaves (figure 5) as it became harder for plant roots to extract water because it was held at higher tension in the soil matrix.

Figure 5: Curled maize leaves as an indicator of moisture stress.

Water shortage is a major abiotic factor that limits agricultural crop production (Geoff, 2002; Nemeth *et al*., 2002; Chaves and Oliveria, 2004; Lea *et al*., 2004; Ramachandra *et al*., 2004; Seghatoleslami *et al*., 2008; Jaleel *et al*., 2009 and Golbashy *et al*., 2010). Inadequate water to crops leads to inhibited cell expansion and reduced dry matter accumulation due to decrease in chlorophyll content, which reduces the amount of food produced in the plant (Lack *et al*., 2014, Libing *et al*., 2016, Jain *et al*., 2019). As irrigation water increased, crop production also increased significantly. For instance, grain yield increased from 2.8 in T25 to 6.2 and 6.3 Tonha^{-1} mm in T50 and T75, respectively as irrigation water increased from 305 mm in T25 to 435 and 549 mm in T50 and T75, respectively of irrigation water during the growing period (Table 3). Hayrettin *et al*. (2013) observed that, as seasonal ET increased from 305 mm for the non-irrigated treatment to 1133 mm of irrigation water, grain yield also increased. For most crops grown under irrigated conditions, the allowable soil moisture deficit is 50% of the available moisture during critical growth stages, and up to 65% during stages of anthesis and grain filling (Thomas *et al*., 2019; Zhandong *et al*., 2014). Below 50% PAW, the crop is considered in danger of undergoing enough stress to suffer a reduction in yield. Yenesew and Tilahun (2009) had similar findings where they observed that, stressing crop by 75% resulted in the highest yield reduction. According to Cakir (2004), water stress leads to reduced leaf area, lower crop growth rate, and reduced plant height and shoot dry matter. Farshad *et al*. (2008) showed that silking stage is the most sensitive. Further, Westgate (1994) observed that water shortages may prolong the time from silking to pollen shed and limit the grain filling period severely, lowering grain yield. Pandey *et al*. (2000) observed yield reduction of 22 to 26% caused by decrease in leaf area as a result of water stress. Decreased leaf area reduces the fraction of photosynthetic active radiation (PAR) absorbed by the green vegetation hence decreasing net primary production. The result is reduction in grain number and weight.

5.2.2 Effect of water depletion on water use efficiency

The water use efficiency (WUE) for all treatments were significantly ($P \leq 0.05$) different with the highest recorded in T75 (1.4 kgm-3) while the lowest (0.6 kgm^{-3}) was recorded in T25. Treatment T50 recorded 1.3 kgm^{-3} (Table 4) though it used less irrigation water (435 mm) compared to T75 (549 mm). Stress caused by a 25% and 50% reduction in applied water in treatments T50 and T25, respectively could have caused reduction in yield and WUE significantly. Mahdi *et al*. (2004) obtained the highest WUE for maize irrigated at 85% while Kannan *et al*. (2009) obtained at 70% of crop water application, which had no significant difference with treatments receiving 85% of crop water. Shammout *et al*. (2016) obtained highest WUE when irrigating at 80% AWC and recommended irrigation at 80%. Hailu *et al*. (2015) obtained highest WUE with 100% irrigation, though the treatment used 39.75% more water than treatment irrigated at 75% ET.

Supplemental irrigation water for optimal growth for T50 treatment was estimated to be 420 mm for the growing season (planting to physiological maturity), though the figure may vary depending on seasonal rain received. This gave a mean daily crop evapotranspiration (ETc) of 4.6mm against a daily ETo of 5.2 mm, obtained from the weather station in the research center. The average evapotranspiration of the crop rose from 1.085 mm for the initial stage to 8.4 mmday^{-1} during the middle stage when the crop had highest evaporative demand due to fully established canopy. Irrigation and rainfall were the only source of crop water because underground water was found to be below 2m. Variation in soil water content was presumed to be due to evapotranspiration because it was assumed that deep percolation below 1m depths of soil was negligible and, no water was lost through runoff either.

Table 4: Grain yield, biomass and WUE

Treatment	Grain yield (Tonha^{-1})	Water use efficiency (kgm^{-3})
T75	6.3^{a}	1.4^{a}
T50	6.2^{a}	1.3^{b}
T25	2.8^{b}	0.6^{c}
Means	5.11	1.1
P-value	<0.0001	<0.0001
LSD (0.05)	0.40	0.08
CV (%)	5.01	4.96

Legend: T75 – irrigation to or near field capacity when 25% of available water capacity (AWC) is depleted, T50 – irrigation to or near field capacity when 50% of AWC is depleted, T25 – irrigation to or near field capacity when 75% of AWC is depleted.

5.3 Conclusion and recommendation

The results of this study show that the quantity of irrigation water used has a positive impact on maize output in the scheme. The impact is significant at 95% confidence level and there was sufficient evidence to reject the null hypothesis. Supplemental irrigation is important in ASAL regions when rain received during the growing season is not sufficient to support a healthy crop. However, due to serious water shortage and high cost of water abstraction, where either diesel or electricity are used to pump, water saving farming and improvement of its efficient use at farm level are crucial. The researchers found that supplemental irrigation at 50% saved on irrigation water and didn't lead to significant reduction in yields. From the findings, the researcher made the following recommendations

- Supplemental irrigation at 50% AWC is recommended for the scheme. It uses less water and yet yields have no significant difference with irrigation at 75% AWC, which uses more water. T25 should not be recommended for adoption in the study area.
- Grain yield of over 6.0 Tonha^{-1} is attainable in the scheme with proper irrigation practices. The experiment attained 6.3 and 6.2 Tonha^{-1} for T75 and T50 treatments, respectively.
- Short rain is the recommended cropping season as opposed to long rain. The season receives much of the rain in the year. This is based on the 2005-2016 average (figure 3). Cropping during this season will mean that less irrigation water will be needed to make up for the moisture deficit.

CHAPTER SIX

6.0 USE OF AQUACROP MODEL TO PREDICT MAIZE WATER REQUIREMENT AND YIELDS

Abstract

Water is the major factor in agricultural production systems. However, it has become scarce in quality, quantity and distribution, a situation that has been aggravated by climate change especially in ASALs. Under these unpredictable weather patterns, farmers, scheme managers and policy makers are finding it difficult to make decisions impacting on the daily, monthly, seasonal or annual operations. Of great concern is that these changes will impact different ecological zones differently. In order to predict the effect these changes will have on food production and possibly mitigate their negative effects, many researchers agree that use of crop growth models is the way to go. It is in this light that two parallel field experiments were conducted at Bura Irrigation Scheme research center in Tana River County during the 2015 short rains (October – December) and 2016 long rains (March – July) seasons. The data obtained was used to calibrate and validate FAO AquaCrop growth model (V5.0) that was then used to simulate maize production and water use under four irrigation schedules and three water depletion levels. Root mean square error (RMSE), Wilmot's index of agreement (d), Nash &Sutcliffe coefficient (E) and coefficient of determination (r^2) were used to test the model's ability to predict maize yields and water use. Overall, there was agreement between the model's simulated and observed canopy cover that gave r^2 values of between 0.90 and 1.00, 0.94 and 1.00 for biomass yield and 0.82 and 0.98 for soil water content. Further, the model predicted grain yields of 7.72, 7.04, 6.5 and 6.4 Tonha^{-1} for T50, T75, Tw and Tbw treatments, respectively (Table 12) for short rain and 6.42, 6.32, 6.16 and 6.46 Tonha^{-1}, respectively, for long rain (Table 13). The short rain season (October -December) depicted better performance probably due to more rain received during the season as compared to long rain (March-July) season. The model was found to be a valuable decision making tool in irrigation water management and in predicting crop productivity under different conditions of weather and water availability.

Keywords: Calibration, simulation, crop water requirement (CWR) and yields.

6.1 Introduction

Agricultural production in ASALs is characterized by risks and uncertainties due to inadequate rain, needed to maintain soil moisture for plant growth. Soils in these regions are normally desiccated due to high rate of evaporation, which exceeds the rate of natural water supply (Elias *et al*., 2012). Globally, climate change and weather variability have increased the risks in agricultural production systems as rains may have a false or late start and/or may cease early before crops attain physiological maturity (Jones, 2003). ASALs are the most vulnerable making it increasingly impossible to predict weather or produce healthy crops unless the water deficit is supplemented through irrigation. It is becoming more challenging to apportion fresh water among competing sectors (Geerts *et al*., 2009) of which, the agricultural sector consumes over 70%. New planning and management strategies of available water resources especially at farm level are critical (Sarangi, 2010) as indicated by Saadati *et al.* (2011) that, improving water productivity was key to future water shortage and food security. To achieve this goal, there is a need to predict possible future water availability and weather patterns understand plant response to these and put in place mechanisms of handling future scenarios. Though field experiments can be done to establish this, they are limited by time and cost effectiveness. Cropping models give an alternative solution to this complex scenario by identifying optimal management strategies under varying weather conditions (Geerts *et al.*, 2010). The Water Division of FAO has developed one of such a tool, the AquaCrop model tool that predicts yield response to water for different crops at different levels of irrigation management and varying climatic conditions. The model's ability to simulate growth of crops under limited and non-limited irrigation has made it an important tool in allotting available fresh water for agriculture in the most prudent way and predicting possible agricultural output under future weather.

AquaCrop was chosen for this study because, according to Steduto *et al*. (2009) and Sarangi (2012), it is simple and practitioner oriented in terms of performance. The model needs a comparatively small number of parameters (Hsiao *et al.*, 2009). The model has water-driven growth module whose biomass production is obtained by converting transpired water through a water productivity parameter. CropSyst on the other hand calculates production based on water transpired and solar radiation while WOFOST simulates growth using carbon driven approach and captured solar energy (Todorovic *et al*., 2009). Various scholars have used AquaCrop model in studying different irrigation water levels (Farahani*et al*., 2009; Hsiao *et al*., 2009; Araya *et al*., 2010; Khoshravesh *et al*., 2013; Ng'etich *et al*., 2011) and on farm irrigation water management (Heng *et al*., 2009; Kiptum *et al*., 2012; Onyango *et al*., 2012; Mbindah *et al*., 2017) and found the model satisfactory.

6.2 Aquacrop model

6.2.1 Model description

AquaCrop is a crop growth model developed by the land and water division of FAO (Raes, 2012). The model simulates conceivable crop yields under rain fed, supplemental, deficit and full irrigation settings. According to Steduto *et al.* (2009), the model computes daily water balance and splits evapotranspiration into evaporation and transpiration. Transpiration is related to canopy cover while evaporation is proportional to the exposed area of soil. The model relates its soil-crop-atmosphere components and field management to biomass production and harvestable yield. In the model, daily transpiration is converted to biomass. Harvestable yield (Y) is a product of biomass (B) and harvest index (HI).

6.2.2 Model data requirements,

The FAO Aqua Crop model Version 5.0 was used to simulate AGB production, canopy cover and grain yield, as a measure of performance and Water Use Efficiency (WUE). Input data consisted of climate, crop, soil and management data. The simulation period and initial conditions at the start of the simulation period were also entered before a simulation run.

Climate data: Minimum and maximum temperature (^{o}C), rainfall (mm), relative humidity (%), wind speed (ms^{-1}) at 2 m above ground, and sunshine hours for the study period were obtained from the weather station situated at the research center in the scheme. The data was entered into the model and used to calculate Reference Crop Evapotranspiration (ETo) using 41FAO-ETo calculator version 3.2, which utilizes the Penman-Monteith method (Allen *et al.*, 1998). Monthly mean CO_2 concentration data (Table 6.1) was obtained from the Mauna Loa observatory in Hawaii (NOAA, 2016) (Table 5).

Table 5: Monthly mean CO_2 concentration during the experimental period

Year 2015		Year 2016
Month	CO_2 (ppm)	CO_2 (ppm)
January	399.74	402.28
February	399.47	403.22
March	399.97	403.26
April	400.38	404.52
May	400.55	404.30
June	400.47	404.48
July	400.89	403.97
August	400.81	404.13
September	401.18	404.57
October	401.67	404.95
November	402.24	405.62
December	401.63	405.20

Crop data: The study had crop type as grain producing crop. Parameters for the selected crop were then displayed in the model for adjustments. Four-growth stages namely initial (crop establishment), development (also called vegetative stage where the crop undergoes rapid vegetative growth), mid-season (flowering and grain filling) and late season (maturity and ripening) were considered. Other information collected included time from planting to emergence, planting to flowering, planting to full canopy cover and planting to harvesting. Cropping density (53,333 plants per hectare), initial canopy cover, maximum crop canopy cover and maximum rooting depth were the other parameters that were specified in the model's crop file. Canopy cover (%) and above ground biomass (Tonha^{-1}) were collected every 2 weeks after 90% emergence. Grain yield was determined according to equations 2 and 3.

Soil file: Few soil characteristics were specified in creating this file in the model. These included soil type, depth and water content (table 1). The effect of soil fertility on yield was not addressed because adequate amount of fertilizer was applied as per the recommended agronomic practices in the study area under all situations to ensure achievement of full genetic potential. The soil of the study site was found to be sandy clay loam.

Irrigation schedule: The user created an irrigation schedule by specifying irrigation time interval (for irrigation scheduling treatments) or the allowable depletion of AWC (for water depletion levels treatments), respectively, for every treatment.

6.3 Model Calibration and validation

Observed soil data (appendix 1), climate data, irrigation and season one observed crop yield and canopy growth data were entered into the model and its parameters adjusted as per values in table 6 for season I and table 7 for season II so that its predictions could be as close as possible to observed values. Output data included crop development, soil water balance, irrigation requirement, biomass, grain yield, and water productivity. The model performance and accuracy in predicting maize canopy cover, AGB and grain yield was tested by means of Root Mean Square Error (RMSE) (Eq. 6), index of agreement (d) as described by Wilmot *et al.* (1982) (Eq. 7), and coefficient of efficiency (E) according to Nash and Sutcliffe (1970) (Eq. 8). The closer the RMSE value is to zero, the higher the model accuracy while Wilmot index and Nash and Sutcliffe coefficient take values between 0.0 and 1.0, where 1.0 implies high model precision in prediction.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(s_i - o_i)^2}{n}} \quad \text{……..…………….….……………………………….….………… (6)}$$

$$d = 1 - \frac{\sum_{i=1}^{n}(o_i - s_i)^2}{\sum_{i=1}^{n}\left(\left(o_i - \bar{o}\right) + \left(s_i - \bar{o}\right)\right)^2} \quad \text{…………………………..…………………......……..........……... (7)}$$

$$E = 1 - \frac{\sum_{i=1}^{n}(s_i - o_i)^2}{\sum_{i=1}^{n}\left(o_i - \bar{o}\right)^2} \quad \text{…..…………….…………….…………………………...…..… (8)}$$

Where S_i and O_i are predicted and observed data, respectively. ō is the mean value of O_i, and n is the number of observations.

Pearson correlation coefficient (r) (Eq. 9) was used to test the model accuracy in simulating observed crop data.

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

where x and y are observed and simulated crop data points, respectively; while n is the number of observations.

Table 6: Parameters used to calibrate the AquaCrop model for season I

Description	T_d	Tw	T_{bw}	T_{tw}	T_{75}	T_{50}	T_{25}	Units or meaning
Planting density	5,333	5,333	5,333	5,333	5,333	5,333	5,333	Ha^{-1}
Sowing to emergence	5	5	5	5	5	5	5	Days
Initial canopy cover CCo	0.27	0.27	0.27	0.27	0.27	0.27	0.27	cm^2
Canopy growth coefficient (CGC)	0.7%	1.4%	1.3%	1.1%	1.4%	1.4%	1.0%	Increase in CC relative to existing CC per GDD
Canopy decline coefficient (CDC)	0.3	0.3	0.4	0.4	0.3	0.3	0.42	% decrease in CC relative to CCx per GDD
Maximum canopy cover CC_x	77	77	77	77	77	77	77	Function of plant density (%)
Water productivity, (WP) as calibrated	32	32	32	32	32	32	32	$g\ m^{-2}$
Canopy expansion growth threshold (P_{upper})	0.25	0.25	0.25	0.25	0.25	0.25	0.25	As fraction of TAW, below this leaf growth is inhibited
Canopy expansion growth threshold (P_{lower})	0.5	0.5	0.5	0.5	0.5	0.5	0.5	As fraction of TAW, below this leaf growth is enhanced
Stomatal closure threshold (P_{upper})	0.50	0.50	0.50	0.50	0.50	0.50	0.50	Above this stomata begin to close
Early canopy senescence stress coefficient (P_{upper})	0.75	0.75	0.75	0.75	0.75	0.75	0.75	Above this early canopy senescence begins
Shape factor for soil-water stress	3.0	3.0	3.0	3.0	3.0	3.0	3.0	Moderately convex curve
Reference harvest index (HI_0)	32	40	41	29	40	40	29	%

Legend: CC – canopy cover, GDD – growing degree days; TAW – total available water,

Table 7: Parameters used to adjust the AquaCrop model for season II

Description	T_d	Tw	T_{bw}	T_{tw}	T_{75}	T_{50}	T_{25}	Units or meaning
Planting density	5,333	5,333	5,333	5,333	5,333	5,333	5,333	Ha^{-1}
Sowing to emergence	5	5	5	5	5	5	5	Days
Initial canopy cover CCo	0.27	0.27	0.27	0.27	0.27	0.27	0.27	cm^2
Canopy growth coefficient (CGC)	0.7%	1.4%	1.3%	1.1%	1.4%	1.4%	1.0%	Increase in CC relative to existing CC per GDD
Canopy decline coefficient (CDC)	0.44	0.4	0.4	0.45	0.3	0.3	0.42	% decrease in CC relative to CCx per GDD
Maximum canopy cover CC_x	77	77	77	77	77	77	77	Function of plant density (%)
Water productivity, (WP) as calibrated	32	32	32	32	32	32	32	g m^{-2}
Canopy expansion growth threshold (P_{upper})	0.25	0.25	0.25	0.25	0.25	0.25	0.25	As fraction of TAW, below this leaf growth is inhibited
Canopy expansion growth threshold (P_{lower})	0.5	0.5	0.5	0.5	0.5	0.5	0.5	As fraction of TAW, below this leaf growth is enhanced
Stomatal closure threshold (P_{upper})	0.50	0.50	0.50	0.50	0.50	0.50	0.50	Above this stomata begin to close
Early canopy senescence stress coefficient (P_{upper})	0.55	0.55	0.55	0.55	0.55	0.55	0.55	Above this early canopy senescence begins
Shape factor for soil-water stress	3.0	3.0	3.0	3.0	3.0	3.0	3.0	Moderately convex curve
Reference harvest index (HI_0)	32	40	41	29	40	40	30	%

6.4 Results and Discussion

6.4.1 Validation and simulation of yields by Aquacrop model

The model predicted canopy cover with a high degree of accuracy giving R^{-2} values of between 1.00 and 0.90 (table 8). RMSE values ranged between 2.4 and 9.7, while NRMSE from 6.4 to 20.2% and E ranged between 0.88 and 0.98. Wilmot's Index of Agreement (d) was found to be 0.99 indicating a high degree of agreement between the model's simulated canopy cover and the observed values. The model predicted canopy cover correctly for 64% of all the observations with the highest accuracy occurring in the Tw treatment at 86%.

Table 8: Validation of Canopy Cover

	Treatments						
	T25	T50	T75	Td	Tw	Tbw	Ttw
Average observed canopy cover (%)	23.7	56.1	61.1	25.4	58.1	57.0	19.5
Average simulated canopy cover (%)	24.8	59.8	58.8	27.4	56.0	60.5	20.4
|O-S|	1.1	3.7	2.3	2.0	2.1	3.5	0.9
Coefficient of determination (R^2)	0.98	0.97	0.99	1.00	0.98	0.90	0.95
Root Mean Square Error (RMSE)	2.4	6.2	3.9	2.4	4.4	9.7	3.9
Normalized Root Mean Error (NRMSE)	10	11.0	6.4	9.5	7.6	17.0	20.2
Nash &Sutcliffe Model Efficiency Coefficient (E)	0.97	0.94	0.98	0.96	0.97	0.88	0.94
Wilmot's index of agreement (d)	0.99	0.99	0.99	0.99	0.99	0.97	0.99

Comparison between observed and simulated mean canopy cover against days to physiological maturity shows that Pearson correlation coefficient (r) on average equaled 0.97 (Figure 6). The R-values were close to one, indicating a high degree of accuracy by the model to simulated canopy cover. Pearson correlation coefficient takes on values between +1 and -1, where values equal or close to +1 indicate a high positive model precision, as was the case in this study. Kiptum *et al*. (2013) also noted a strong relationship (r = 0.94) between observed and simulated canopy cover when using Aquacrop.

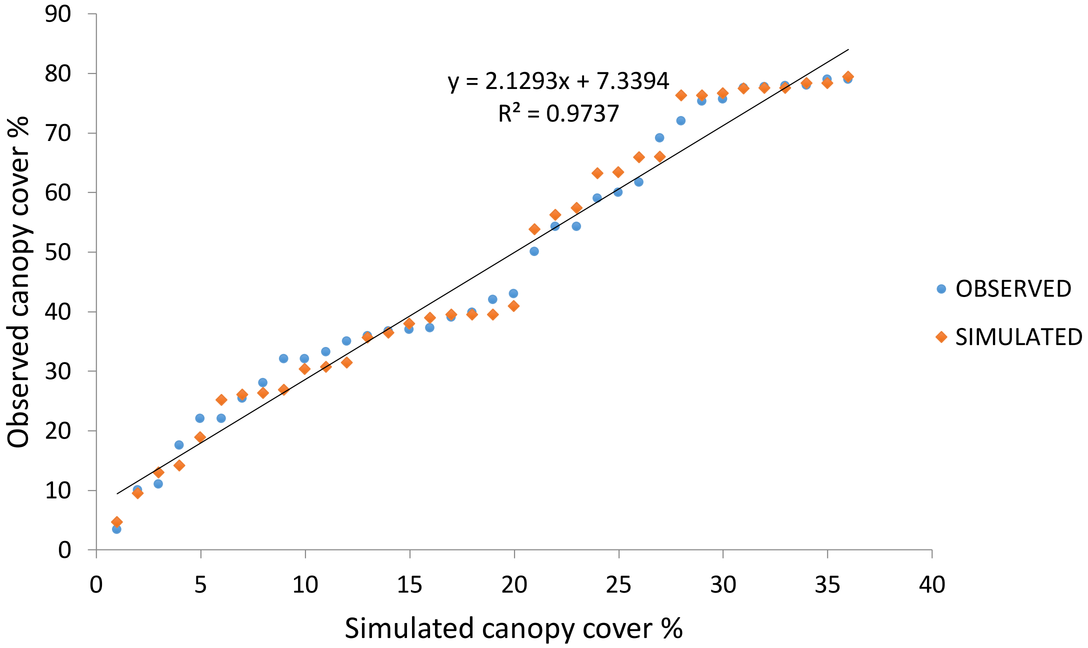


Figure 6. Simulated versus measured canopy cover for various treatments.

6.3.1 Biomass prediction

The model predicted biomass with a high degree of accuracy (Table 9) giving R^2 values of between 1.00 and 0.94, RMSE between 0.154 and 1.037Ton ha^{-1}, NRMSE between 2.4 and 9%. E between 0.85 and 0.99 while d varied between 0.97 and 1.00. This indicated the model performed well because observed values agreed with simulated values. The few inconsistencies in biomass prediction might have been caused by error in measured data and/or the approach in which the model simulated crop development. Essentially, Wilmot index and Nash and Sutcliffe coefficient are dimensionless and may assume values ranging from –∞ to +1, but the closer they are to +1, the better the model simulation performance. Hence, d, E as well as RMSE values obtained in the two indicated that AquaCrop model satisfactorily simulated maize yields in the study area. Similar findings have been reported elsewhere, for instance Agbemabiese, (2015) found a RMSE of 0.09, Wilmot's index of 0.99 and Nash-Sutcliffe efficiency of 0.96 while simulating onions yields under different irrigation regimes in Ghana. Similarly, Kiptum *et al*. (2013) found a RMSE of 0.38 while simulating cabbages (*Brassica oleracea*) biomass in Kenya.

Table 9: Validation of biomass yield.

	Treatments						
	T25	T50	T75	Td	Tw	Tbw	Ttw
Av observed biomass production (Ton ha^{-1})	4.489	7.248	7.299	2.436	5.769	7.544	4.358
Av simulated biomass production (Ton ha^{-1})	4.198	7.290	7.252	2.434	6.878	7.600	4.113
|O-S|	0.291	0.042	0.047	0.002	1.109	0.054	0.245
Coefficient of determination (R^2)	1.00	0.99	0.99	0.99	0.99	0.99	0.94
Root Mean Square Error (RMSE) Ton ha^{-1}	0.370	0.424	0.429	0.154	1.520	0.535	1.037
Normalized Root Mean Error (NRMSE) %	8.2	5.8	5.9	6.3	26.3	7.1	23.8
Nash & Sutcliffe Efficiency Coefficient (E)	0.99	0.99	0.99	0.99	0.89	0.99	0.85
Wilmot's index of agreement (d)	1.00	1.00	1.00	1.00	0.98	1.00	0.97

Legend: T75 – irrigation to field capacity when 75% of AWC is depleted, T50 – irrigation to field capacity when 50% of AWC is depleted, T25 – irrigation to field capacity when 25% of AWC is depleted, Td – daily irrigation treatment, Tw – 7 days interval irrigation treatment, Tbw – 14 days interval irrigation treatment, Ttw – 21 days interval irrigation treatment

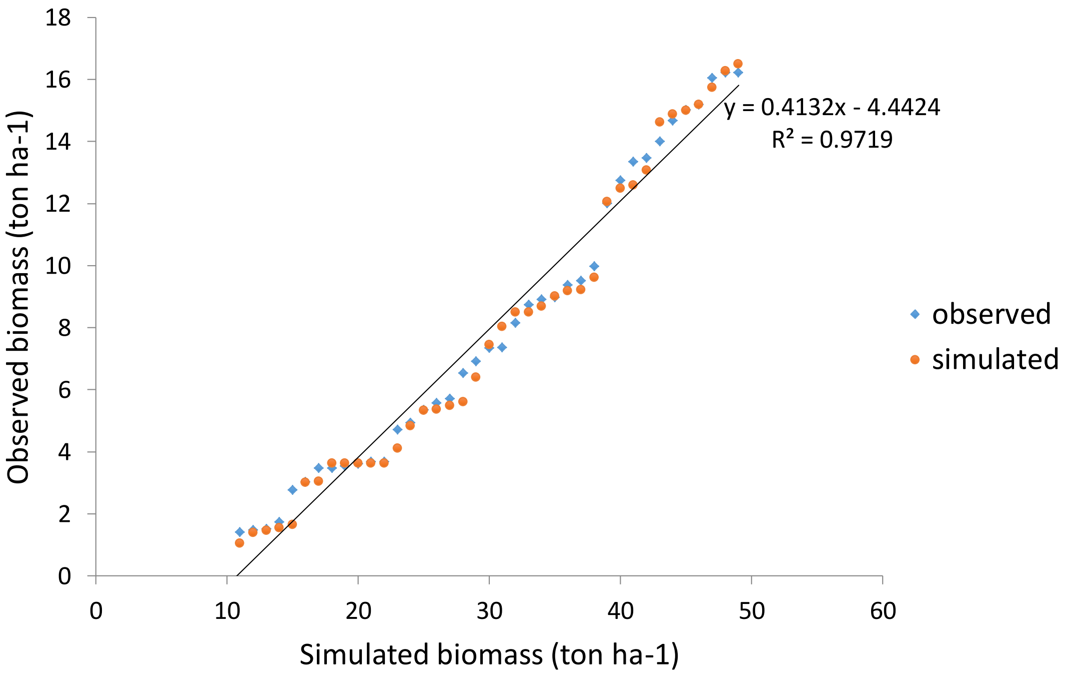


Figure 7. Simulated versus simulated biomass for various treatments

6.3.2 Soil water content prediction

The model was able to predict soil water content with acceptable degree of accuracy. R^2values ranged between 0.82 and 0.98 while E values ranged from 0.70 to 0.92. RMSE showed the model's prediction of the soil water content was not very accurate because in some treatments, like Td, it gave a value of 38.8 (table 10)

Table 10: Validation of Soil Water Content

	Treatments						
	T25	T50	T75	Td	Tw	Tbw	Ttw
Average of observed Soil water content (mm)	325.7	338.8	452.1	540.8	428.3	453.4	347.1
Average of simulated Soil water content (mm)	330.9	336.3	449.0	563.4	426.4	446.7	348.3
|O-S|	5.2	2.5	3.1	22.6	1.9	6.7	1.2
Coefficient of determination (R^2)	0.93	0.89	0.93	0.98	0.82	0.88	0.91
Root Mean Square Error (RMSE) mm	6.9	6.9	10.0	38.8	16.3	10.6	8.9
Normalized Root Mean Error (NRMSE) %	2.1	2.0	2.2	7.2	3.8	2.3	2.6
Nash and Sutcliffe Efficiency Coefficient (E)	0.82	0.86	0.92	0.76	0.70	0.78	0.84
Wilmot's index of agreement (d)	0.95	0.96	0.98	0.91	0.94	0.93	0.97

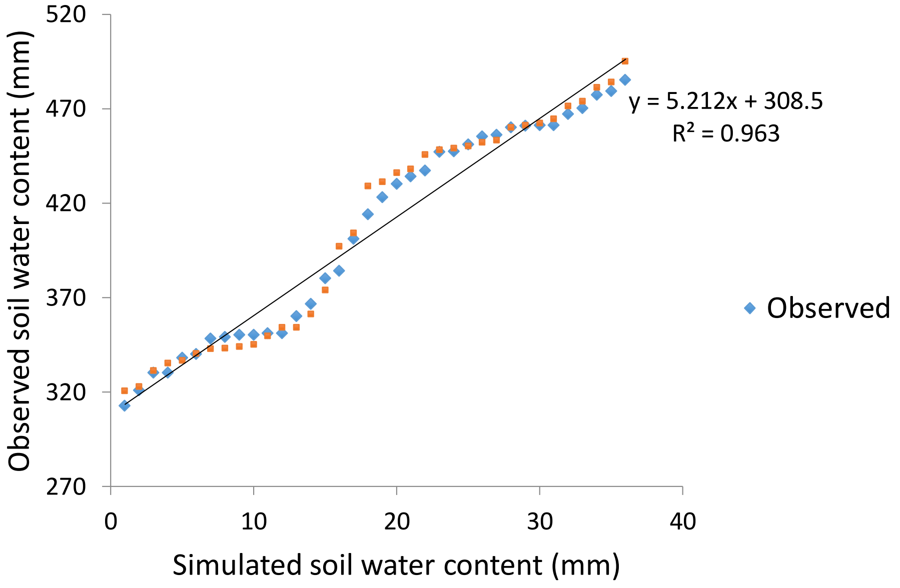


Figure 8. Simulated versus simulated soil water content

6.4 Maize growth and yield prediction

The model was used to predict attainable grain yield, biomass, water productivity and irrigation water requirement for T75, T50, Tw and Tbw treatments for both short and long rain seasons. The highest biomass was predicted from T50 treatment in both seasons (18.4 and 16.04 Tonha^{-1}, respectively) while the lowest was predicted in Tbw treatment in short rain (16.03 Tonha^{-1}). Grain yield was highest in T75 for season short rain (7.7 Tonha^{-1}) and highest in Tbw treatment for long rain season (6.5 Tonha^{-1}). The predicted grain yield was found to be 8, 13, 3 and 3% higher for Tw, Tbw, T75 and T50 treatments, respectively, than the observed in season two (long rains). T50 treatment gave the highest water productivity (1.80 kgm^{-3}) in the short rain season (Table 11).

The model predicted irrigation water requirement to range from 183mm for T75 treatment to 405mm for Tw treatment in season one (short rain) (Table11) and from 410mm in T50 to 680mm in T75 treatment in season two (long rain) (Table 12). Irrigation water requirement was found to be between 67 and 124% higher in the long rain compared to short rain. The low irrigation water requirement for short rain season is due to the high amount of rain received during short rain as compared to long rain (Figure 2). Total ETo for the growth period was 480 and 601 mm for season short rain and long rain, respectively. This gave a daily average ETo of 5.3 for short rain and 6.7 mmday^{-1} for long rain season. The model predicted better performance during short rains than long rains. The higher water requirement for long rain (April – July) agreed with the experimental findings where short rain season (October – December) needed less irrigation water because it received more rain than the long rain season. The research findings indicated high and direct relationship between the amounts of rain and crop performance. The October – December season was found to do better for maize growing for the research area. Water use efficiency was also high for this season probably due to predictability of the rains.

Table 11: Predicted maize yield in season 1 (short rain)

Treatment	GDD ^{o}C.day	Irri (mm)	Infil. (mm)	Runoff (mm)	Drain (mm)	E (mm)	E/Ex (mm)	Biomass Tonha^{-1}	HI %	Yield Tonha^{-1}	WPet kgm^{-3}
T50	1869	194	478	0	47	128	53	18.390	42.0	7.724	1.80
T75	1869	183	467	0	30	86	45	16.210	40.0	7.043	1.65
Tw	1869	405	434	0	1	109	59	16.112	40.1	6.461	1.66
Tbw	1869	365	393	0	0	88	43	15.869	40.4	6.411	1.74

Legend: T75 – irrigationto field capacity when 75% of AWC isdepleted, T50 – irrigation to field capacity when 50% of AWC is depleted, T25 – irrigation to field capacity when 25% of AWC is depleted, Td – daily irrigation treatment, Tw – 7 days interval irrigation treatment, Tbw – 14 days interval irrigation treatment, Ttw – 21 days interval irrigation treatment

Table 12: Predicted maize yield in season II (long rain)

GDD ^{o}C.day	Rain (mm)	Irri (mm)	Infil. (mm)	Runoff (mm)	Drain (mm)	E (mm)	E/Ex (mm)	Biomass Tonha^{-1}	HI %	Yield Tonha^{-1}	WPet Kgm^{-3}
1726	28	435	439	0	111	80	38	16.039	40.0	6.419	1.42
1726	28	549	708	0	0	143	74	15.786	40.0	6.315	1.24
1726	28	479	643	0	0	103	62	15.401	40.0	6.162	1.34
1726	28	417	440	0	0	79	43	16.031	40.3	6.460	1.43

Legend: T75 – irrigation to field capacity when 75% of AWC is depleted, T50 – irrigation to field capacity when 50% of AWC is depleted, T25 – irrigation to field capacity when 25% of AWC is depleted, Td – daily irrigation treatment, Tw – 7 days interval irrigation treatment, Tbw – 14 days interval irrigation treatment, Ttw – 21 days interval irrigation treatment

6.5 Bura Irrigation Scheme water requirement

AquaCrop model was then used to generate irrigation schedule for the two seasons for treatments T75, T50, Tw and Tbw (appendices 6 and 7), based on the 11 years (2006 to 2016) average rain (appendix 8). According to the Scheme’s management, majority of farmers plant during the short rain (October - December) season. Research results showed that supplemental irrigation water requirement ranged from 300mm for Tbw treatment to 430mm for T75 treatment for the October-December season. This translated to between 3,000 m^{3} and 4,300 m^{3}ha^{-1} for the growing season. A total of 1092 ha (971 ha under maize seed and 121 ha under commercial maize) during 2016 short rain season were under irrigation. The scheme water requirement for the season ranged between 3,276,000 and 4, 695, 600 m^3.

6.6 Predicted near future (2020-2039) agro-climate changes and the effect on maize yield

Future maize production is uncertain due to the vagaries of weather change. Regions that depend entirely on rain-fed crop production like Kenya (Karuku *et al.,* 2014b) will be severely impacted by the climate change. It is therefore important to seek ways of predicting future climate change, its effect on crop production and put in place necessary future mitigation and adaptation measures, for continued crop production. To do this, Historic/baseline (years 1986-2005) climate data were sourced from the World Bank Climate Change Knowledge Portal (CCKP). The current climate data was derived from Community Climate System Model version 4 (CCSM4) while future (2020 - 2039) climate data was obtained from global circulation models (GCMs) used by the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report as it gave a high R^2 value of 0.91 when compared to historical mean monthly temperature, and a moderately high correlation (R^2 = 0.70) for mean monthly rainfall compared to the other Coupled Model Intercomparison Project (CMIP5). The relationship between the past and future climates and possible impact on maize yield was assessed and possible adaptation options recommended. Assumption made was that sunshine hours for the region as well as wind speed would remain the same even in the future.

Future climate projections were considered under representative concentration pathway (RCP) 4.5 and RCP8.5 whose CO_2 files are available by default in AquaCrop version 5.0. The RCPs take into account different combinations of economic, technological, demographic, policy and institutional futures (Moss *et al.*, 2010; van Vuuren *et al.*, 2011; Rogelj *et al.*, 2012). RCP4.5 scenario corresponds to a future with some form of climate policy where CO_2 concentration stabilizes at 650 ppm equivalent after the year 2100, whereas RCP8.5 is a ‘business as usual’ future scenario translating into high severity climate change impacts with CO_2 concentration soaring to 1,370 ppm and rising in 2100. Baseline annual CO_2 concentration was from the global average based on marine boundary layer air data for years1980 to 2007, available in AquaCrop model (table 13).

Table 13: monthly average climate data for baseline and future periods generated form IPSL CM5A MR Global Circulation Model for the study area.

Month	Baseline				Future (2020-2039) RCP 4.5				Future (2020-2039) RCP 8.5			
	T_{max} °C	T_{min} °C	Rain Mm/month	ETo	Tmax °C	Tmin °C	Rain Mm/month	ETo	Tmax °C	Tmin °C	Rain Mm/month	ETo
Jan	31.64	24.13	30.56	5.5	32.96	25.16	22.26	5.0	34.40	25.57	49.80	6.5
Feb	32.43	24.45	33.04	8.5	34.46	26.08	8.08	6.0	35.89	26.45	13.16	7.0
March	31.22	23.28	20.94	6.0	34.92	26.22	24.06	6.5	36.35	27.08	21.35	7.0
April	30.58	23.68	33.54	6.5	33.88	25.58	44.06	6.0	35.38	26.40	32.45	6.5
May	30.80	23.93	29.03	6.5	31.97	24.66	58.67	5.0	33.32	25.71	35.60	6.0
Jun	29.88	24.12	28.11	6.0	30.90	23.94	33.11	4.5	31.63	24.44	36.87	5.0
Jul	25.81	23.28	23.86	5.0	30.97	23.00	20.48	5.0	31.43	23.73	26.56	5.5
Aug	30.43	24.94	11.23	7.0	31.33	23.04	18.69	5.5	31.22	24.50	17.75	6.5
Sept	31.88	24.12	34.54	7.0	31.08	23.94	45.96	5.0	31.59	25.02	32.61	6.0
Oct	32.76	24.44	107.01	6.5	30.54	25.52	113.06	6.5	30.80	25.62	114.35	4.5
Nov	33.63	24.98	111.43	5.0	30.21	24.59	115.80	5.5	29.43	25.56	201.35	4.5
Dec	32.00	25.52	77.48	4.5	32.14	24.74	92.99	6.0	31.89	25.65	90.33	5.5

Rain is predicted to increase in the study area from 453mm (annual average for the period 2005 - 2016) to 606mm pa (figure 9) by 2035, a trend that is likely to be witnessed in most parts of East Africa (Thorntorn *et al*., 2005) and over the same period, atmospheric CO_2 concentration will increase to 440.55 ppm (Mauna Loa observatory in Hawaii). Though FAO (2001) has predicted negative impact of future climate change, the simulated future yields indicated marginal increase in maize production under irrigation. This could probably be due to increase in rain and carbon IV oxide concentration which will lead to increased rate of photosynthesis and increased soil water content for plant use. Nyandiko *et al.* (2015) also found that between the years 1979 and 2009, Mutomo and Mwingi meteorological stations recorded increase in rain by up to 7.3 mm pa. According to David *et al*. (2012), carbon dioxide trends are likely to increase global crop production by up to 1.8% per decade. Increased rain is also likely to lead to runoff and likely erosion of topsoil and nutrients. The disclaimer is that the increase in yield will only occur if necessary measures to cushion the situations where improved stresses are likely to occur are implemented (Thorn Mg *et al*., 2008). Challinor *et al.* (2014) observed that the decrease in crop production would be due to climate change without adaptation. Rainwater harvesting and growing of early maturing crops are some mitigation measures that can be adopted in areas that will experience erratic rain (Oseni *et al*., 2011). Others will include development of varieties that tolerate water stress and early planting (Nyandiko *et al*., 2015)

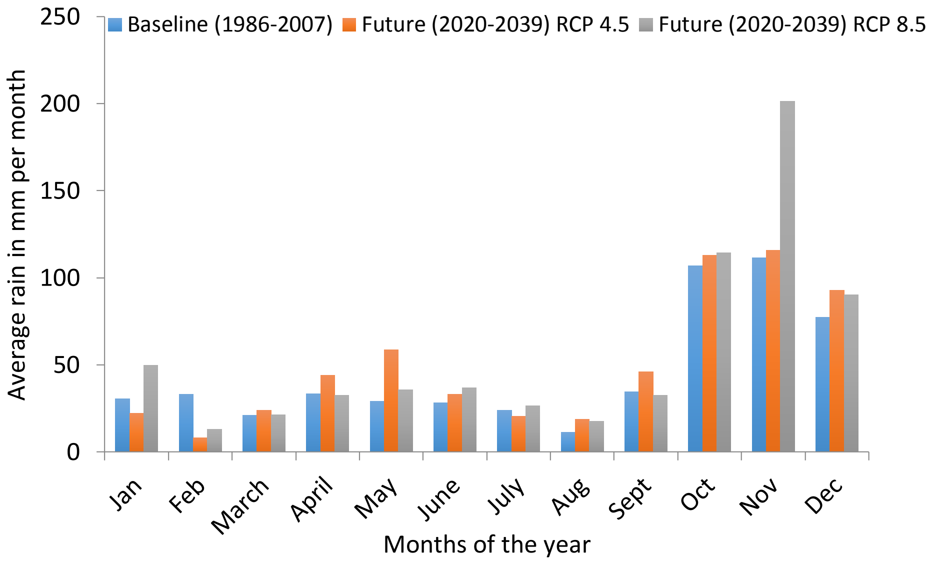


Figure 9. Mean monthly rain for 1986-2007 (baseline) and future (2020-2039) at RCP 4.5 and 8.5

Future (2020-2039) climate change in the research region indicates there will be increase in average temperature by 1.025 (RCP 4.5) and 1.69^{o}C (RCP 8.5) from the baseline period with months of February and march remaining as the hottest (Figure 10). Raised temperature is likely to lead to decreased maize production due to heat stress and reduced growth period as a result of faster accumulation of growing degree-day (Chen *et al*., 2014; Prasad *et al*., 2018; Abera *et al*., 2018). This could also be caused by soil water deficit due to high rate of evaporation that will be caused by increased temperature.

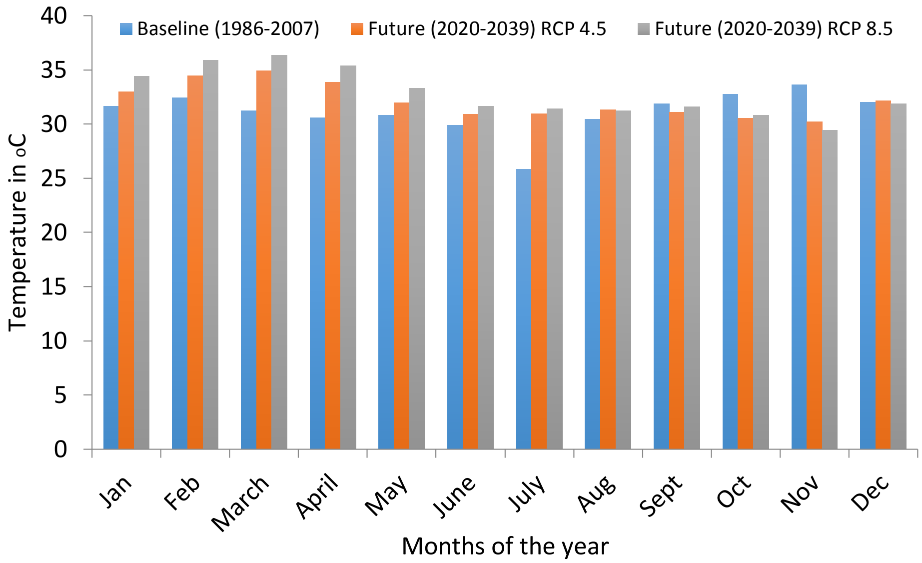


Figure 10. Mean monthly temperature for 1986-2007 (baseline) and at RCP 4.5 and 8.5

CHAPTER SEVEN

7.0 General discussion, conclusion and recommendation

7.1 General discussion

Many irrigation farms in developing world use irrigation scheduling as opposed to water depletion levels. Though the two approaches have their merits and demerits, water depletion level is only applicable to farms subject to availability of soil water monitoring equipment and the technical knowhow of the farmers to interpret these measurements. On the other hand, irrigation scheduling at fixed time interval is less demanding in terms of finances and technology. This makes the latter strategy to be the first choice by most farms. Risks of crop water stress and consequently yield reduction are therefore imminent. Addressing these issues through more research and adoption of the findings will be of great benefit.

In terms of growth indicators used, maize performed better in October – December season (short rains) than in April – June season (long rain) (Figure 11) probably due to more rain that was received in the short rain season (263 mm) in comparison to long rain season (28 mm) (Appendix 18). The rains supplied water to the crops and therefore the crops suffered less from the effects of water stress. Irrigation water requirement for the scheme is also low during the short rain season (October – December). The scheme management has realized this and they have scheduled this as the cropping season for the scheme. They should however take advantage of the wettest month – November as per recommendation 2.

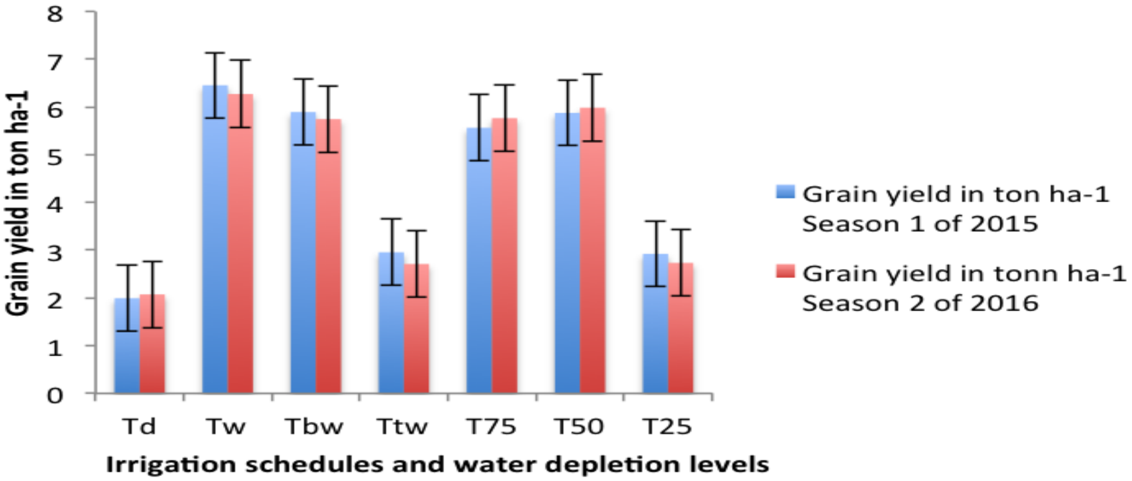


Figure 11: Grain yield from season one and two

Legend: Td - daily irrigation, Tw – weekly irrigation to or near field capacity, Tbw – bi-weekly irrigation to or near field capacity, Ttw – tri-weekly irrigation to or near field capacity, T75 – irrigation to or near field capacity when 25% of available water capacity (AWC) is depleted, T50 – irrigation to or near field capacity when 50% of AWC is depleted, T25 – irrigation to or near field capacity when 75% of AWC is depleted.

The bi-weekly irrigation schedule in the scheme was found to be economically sound. For the four treatments recommended as worth consideration, T75, T50, Tw and Tbw, yield was generally found to have no significance difference but the amount of irrigation water used in Tbw found to be the lowest among the four treatments. It is essential to note that, from the two parallel experiments, irrigation water requirement for Tbw was found to be slightly lower than but almost the same as that of T50. During the April – June long rain, irrigation water used for T50 was higher that of Tbw by 4% while Tw and T75 used 13 and 23% more water. The trend was the same even when using the 2005 – 2016 average rain, where Aquacrop model showed that whereas T50 would use 9% more of the irrigation water than Tbw, Tw while T75 would use 19 and 23% more. Though much could not be done within the limited research time, from the research results, it can be conclude that Tbw is best irrigation schedule recommended for the scheme. Its water supply to the crop is found to be similar to what most other research recommend, where crop performance is found to be optimal and WUE high if AWC does not fall below the critical 50% of the AWC.

7.2 Conclusion

From the study, several conclusions can be made. First, the current bi-weekly irrigation is the suitable for the scheme and there is no need to adopt a different schedule because a 7 days irrigation schedule lead to increased water use with no significant increase in yield. Longer irrigation interval leads to reduced WUE and decrease in yield caused by moisture stress. Secondly, there is inefficiency in water use in the scheme leading to low WUE. Thirdly, Aquacrop model was able to predict maize output under various scenarios and hence a useful management tool in the scheme. Due to its high degree of accuracy in predicting crop performance under different scenarios, the model is useful to compare the achievable against actual yields, and as a benchmarking tool to identify the constraints restraining crop production and water output so as to take corrective measures. Whereas these results are commensurate with similar results elsewhere in the world, Kenya's fast-increasing water poverty and the critical role of irrigation in revitalizing its agriculture warrant serious remedial measures. The results showed that there is room for enhancing water productivity in the Scheme through better water management.

Measures to mitigate effect of climate change on maize production need to be put into place if the current grain production is to be maintained or even improved.

7.3 Recommendations

In order to improve water use efficiency, increase crop yield in the scheme and mitigate future negative effects of climate change, the following recommendations are proposed.

- The best cropping season is the short rain (October – December) because it receives more rain then the long rain season (April - July). Planting dates need to be scheduled to coincide with the onset of the rains to save on irrigation water. Of more importance is timing such that the most water sensitive maize growth stage (anthesis to grain filling) are made to coincide with the onset of the wettest month in the region (November-based on 1986-2005 average, research period and projected 2020-2039). This will reduce the risk of water stress during these moisture sensitive maize growth stages and the negative impacts this would have on yields.

- Water abstracted from the river to be quantified at two levels: At abstraction point and at the farm level. This will enable the scheme management to quantify the amount of water used by community in the area and in several villages where the canal passes through and more important, the amount used for irrigation and possibly losses. This calls for installation of necessary tools for water measurement that will enable scheme management to make sound decision on scheme water management and monitor fluctuations in water demand with seasons. Such data will be useful even in future for planning purposes.
- Having established that the bi-weekly irrigation schedule is suitable for the scheme, more research should be carried out in the farm on deficit irrigation. This will be aimed at establishing how much of the irrigation water can be saved without compromising on yields.
- Further studies and use of crop growth models need to be done to establish the actual interaction between future elevated temperature and increased atmospheric carbon dioxide and other many changes at smaller scale that could be of great relevance to irrigation and food security in the region.
- There is a big discrepancy between the scheme's maize yield and the research findings. The scheme potential has therefore not been exploited and there is still a big room to improve the scheme production. With change in water management, the research has proofed that a yield of over 6 ton per hectare is attainable in the region. The region can therefore be food secure with change in the mode of water management in irrigation. This need be implemented without delay, as this will assure the region of food security and more income besides saving water for other competing uses.
- There's need to develop maize varieties that are tolerant to heat stress especially in areas that will experience a high rise in temperature.
- Flood control mechanisms to be provided in areas that are likely to have elevated rain.
- Public should be made aware of climate change and the expected effect and ways of alleviating.

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APPENDICES

Appendix 1:Soil chemical properties of the experimental plot

pH	%OC	cmol/kg Na	cmol/kg K	Texture	Bulk density	Ksat(cm/hr)	Rate
8.32 (high)	0.64 (1.1% OM) low	0.56 (CEC1.6%)	1.20	Sandy clay loam	1.05	15.25	Very rapid
8.41 (high)	0.62 (1.1%OM) low	0.68	1.30	Sandy clay loam	1.08	11.35	Very rapid
8.46 (high)	0.9% (low)	0.68	1.3	Sandy clay	1.17	8.55	Rapid

Appendix 2: N, P and K in plant tissue

Sample Description	%N	ppm P	ppm K
Plant sample	1.89	3850	9500

Appendix 3: growth stages and estimated Kc, ETo and ETc

Date	T max	Tmin	Growth stage	Kc	ETo mmd^{-1}	ETc mmd^{-1}
17-Sep	27	25	VE	0.31	3.2	0.992
19-Sep	30	27		0.31	3.5	1.085
29-Sep	27	26	V6	0.6	6	3.6
6-Oct	29.5	28	V10	0.9	5.5	4.95
15-Oct	27.5	24	V14	1.2	7	8.4
23-Oct	29	25.5	VT	1.2	7	8.4
27-Oct	30	26.5	Silking	1.2	6.5	7.8
12-Nov	29	25.5	R4 dough stage	1.2	3.5	4.2
7-Dec	30	27.5	R6 phys. maturity	0.4	4	1.6

Legend; VE – crop emergence growth stage, V6 – Sixth leaf collar growth stage, V10 - Tenth leaf collar growth stage, V14 – Fourteenth leaf collar growth stage, VT – Tasseling, R4 – Dough stage, R6 – Maturity.

Appendix 3:Phenological observations of maize crop in the study area (season I)

Growth stage	Growing degree-days	Calendar days	DATE
Emergence	84	5	17/9/2015
V2	122	7	19/9/2015
V6 (tassel initiation)	291	17	29/9/2015
V10	427	24	06/10/2015
V14	582	33	15/10/2015
VT (tassel emergence)	722	41	23/10/2015
Silking	795	45	27/10/2015
R4 (dough stage)	1086	61	12/11/2015
R5 (dent stage)	1369	77	28/11/2015
R6 (physiological maturity)	1529	86	07/12/2015

Appendix 5: irrigation water requirement - long rain season 2016

Date	April				May				June				July			
	T75	T50	Tw	Ttw	T75	T50	Tw	Ttw	T75	T50	Tw	Ttw	T75	T50	Tw	Ttw
1																
2											46.3					
3									22.6							
4					20.9								24			
5							26.1			45						
6														44.5		
7									28.1						36	69
8					21.5											
9						38.4					53	96	25			
10									24.4							
11					20.4											
12							36.1	49.8								
13										48						
14					21				24						27	
15	25	25	25	25												
16						42.5					45		23			
17	8.3	10.2			23.1				23.1							
18																
19							51			45						
20					22.6				22							
21			17.2													
22	8.6					41.7										
23					22.3						44.5	87				
24	10.7															
25																
26	10.9						41.7	88	31							
27					23.5					49						
28			19.1	27.9												
29	15.1	24.1														
30						47.1			23		36					
31					25.4											
TOTAL RAIN (mm)				28				28				28				28
IRRIGATION (mm)				549				435				479				417
TOTAL (mm)				**577**				**463**				**507**				**445**
Treatment				**T75**				**T50**				**Tw**				**Tbw**

Appendix 6: Irrigation events for short rain season based on 11 years average

Date	September				October				November				December			
	T75	T50	Tw	Ttw	T75	T50	Tw	Ttw	T75	T50	Tw	Ttw	T75	T50	Tw	Ttw
1					11.9								21			
2											40.5					
3					12.4	28.5										
4									18.8							
5					12.5		28.1									
6													19.1			
7					13.2										27	39
8																
9					13.8						19.5	59.9				
10																
11					14	36.7			18.9							
12							38.2	42.7								
13					16.7											
14															15	
15					16											
16	14.3	14.3									14.9					
17	4.9				16.1	47										
18	6.4	10.1														
19	6.6				16.1		54.3									
20	6.5															
21	6.4	15.9	29		15.3				19.6							
22	6.4															
23	6.7										13.9	26.4				
24	6.6				21.5	21.5										
25	6.9	20.3								55.4						
26							51	97								
27	11.6				21.2											
28			25.6	34.8												
29	11.9															
30					20.7						13.3					
31						48.5										
TOTAL RAIN (mm)				263				263				263				263
IRRIGATION (mm)				433				329				370				300
TOTAL (mm)				**696**				**592**				**633**				**563**

Appendix 7: Rainfall for the years 2006 to 2016

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
2006	0	0	62.4	71.8	32.4	3.5	10	13.2	18.1	82.6	414.7	106.6
2007	3.2	0	0	21.3	47.5	18.7	0	21.3	60.6	0.6	190.3	54.6
2008	0	6.9	100.5	65.9	32.2	56.9	0	24	21	17.8	113.2	0
2009	35	0	0	14.4	7	39.1	0	15	11.5	85.2	3.7	43
2010	0	2.6	105	110	23.2	1.3	2.9	0	0	16	34.5	47
2011	17.3	6.7	4.6	66.9	17.8	0	1.8	4.1	24.9	142	267.8	20.2
2012	0	0	0	0	0	0	0	0	1.8	52.4	97.8	55.6
2013	44.3	5.3	93.6	199.3	5.5	0	0	0	0	0	0	0
2014	0	0	0	0	0	18.4	8.5	28.6	9.3	1.4	268.1	26.6
2015	17.3	6.7	4.6	71.8	47.5	47	24.5	10	0	6.7	181.3	89.1
2016	5.9	0	0	21.5	9.3	0	0	1.4	1.3	2.5	17.8	31.6
MEAN	12.3	2.82	37.07	71.4	24.711	20.54	5.3	16.5	14.85	40.72	158.92	47.43

Appendix 8: Soil sampling

Appendix 9: Sowing & fertilizer application

Appendix 10: Initial irrigation

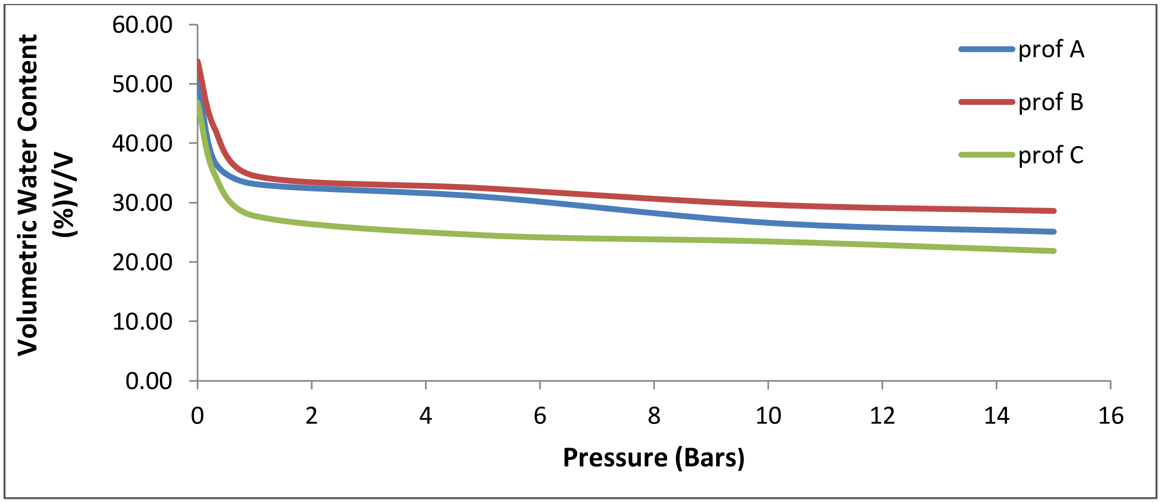
Appendix 11: Appearance of crop in T75

Appendix 12: Early tasseling in Ttw crop

Appendix 13: Estimating canopy cover

Appendix 14: Crop destruction by wild animals

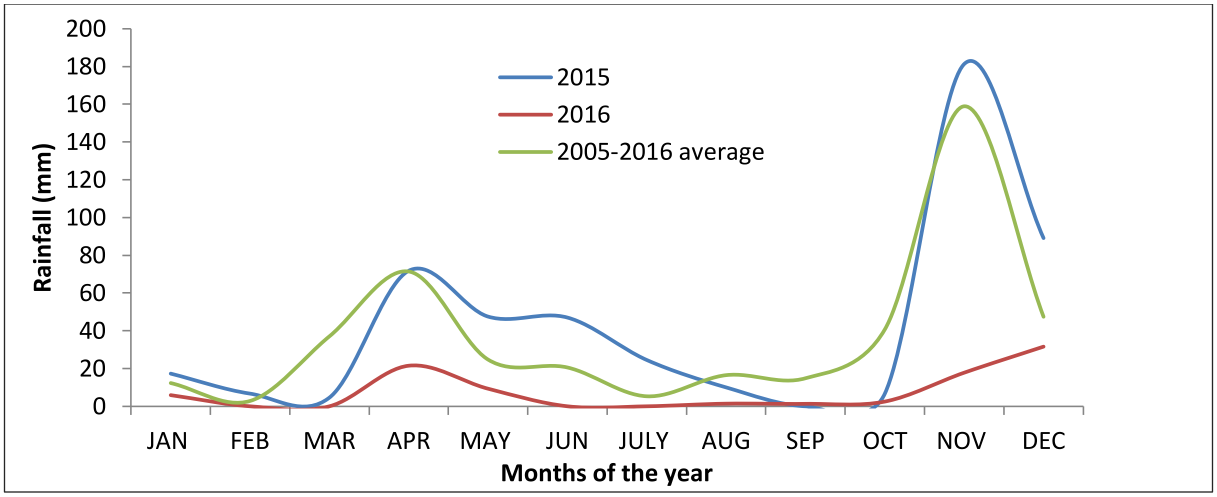
Appendix 15: Determination of rooting depth



Appendix 16: Soil moisture characteristic curves for the study site

Appendix17: Soil water content of the study site

Field Ref.	FC	AW	PWP
Prof A	36.85	31.01	25.1
Prof B	42.47	35.57	28.61
Prof C	34.74	28.3	21.85



Appendix 18. 2005 – 2016 average rain and 2015 and 2016 rain