MODELING OPTIMAL YIELD OF MAIZE UNDER DEFICIT IRRIGATION AND NUTRIENTS LEVELS IN UASIN GISHU COUNTY, KENYA.

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DECLARATION

Declaration by the Candidate

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This research thesis has been submitted for examination with our approval as University Supervisors.

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DEDICATION

I wish to dedicate my successful completion of doctorate research to the support of my dear wife Florence C.K. Langat, children and grandchildren for their cheerful encouragement and togetherness.

ABSTRACT

Agriculture uses the largest volume of water which is a scarce natural resource and equally demanded for both industrial and domestic requirements. Increasing demand in agricultural production for food and industrial products necessitates careful management of the limited resources. High uses of agricultural chemicals and diminishing production levels have continued stressing livelihoods with a basis on the environment. Mitigation measures of the challenges facing agricultural development require a policy shift that adopts research tools on productivity and limit the gaps generated by poor practices. The current research investigated the relationship between the levels of nutrient fertilizer and amount of water applied to achieve optimum yields for maize crop grown under deficit irrigation. Field trials were applied to achieve the following research objectives: (1) to establish the response of maize yields to various levels of moisture and fertilizer, (2) to determine and correlate residual soil nutrient levels in the soil at harvest as function of moisture and fertilizer treatments, (3) calibrate and validate AquaCrop model using data from field trials of deficit irrigation and fertilizer application levels, and (4) use AquaCrop model to predict maize yield gaps as a result of water and fertilizer stress in Uasin Gishu County. The results were subjected to AquaCrop model for water productivity simulation and have clearly shown that the use of high nutrients in the soil does not translate into high yields in maize. Deficit irrigation has led to a lot of water saving and increased area put under maize production. Optimum yield of maize requires application of about 65% of the conventional rates of nitrogenous fertilizer and 80% of moisture requirements of maize crop in Uasin Gishu County. Model prediction of maize yields and the prevailing yield gaps supported the level of moisture and had higher than the non-stressed conditions of 100% moisture applications. Statistical analysis results were supported by the model and recommend that application of fertilizer in crop production need to be re-considered to control the negative impacts on the environment.

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LIST OF ABBREVIATIONS/ACRONYMS

FAO	Food and Agriculture Organization of the United Nations
IPCC	Intergovernmental Panel on Climate Change
ICRISAT	International Crops Research Institute for Semi-Arid Tropics
MWI	Ministry of Water and Irrigation
NPK	Nitrogen, Phosphorus and Potassium (Chemical fertilizer ratio)

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CHAPTER ONE

INTRODUCTION

1.1 Background to the Problem

The world water environment is experiencing continuous drop in its capacity to assimilate inputs from anthropogenic activities that include agricultural developments. This is attributed to increased demand for both industrial and domestic water requirements in addition to increased pollutant levels entering the water masses. The physical constraint of fresh water scarcity is further threatened by the inefficiency in its use and management.

Agricultural development uses the largest volume of water and depends on availability of adequate rainfall or reliable surface water sources for irrigation and regulation of micro climate environments. The sector is faced with the challenge of producing food and fiber to satisfy the growing world population (*Raes et al, 2009*) majorly because of water scarcity which is the main environmental factor limiting crop production and a barrier to food production in the future (*Carter et al.2001*, *Chaves et al*, 2003 and *Flexas et al* 2006). Water use in agriculture accounts for about 75% of all usages in developing countries, and FAO predicted a 14% net increase in use to meet the food demands by the year 2030 as compared to the year 2000 (FAO, 2008). The scenario demands judicious management that enhances crop water productivity and nutrient fertilizer levels that maintain optimal growing conditions throughout the season with acceptable yields and conserve the environment.

The traditional practice of agricultural production applies the strategy of full irrigation with intent to maximize yield and/or profit. Full irrigation implies water is applied and maintained at field capacity level to meet the crop consumptive use, the amount required to leach the salts below the root zone and an extra amount to even out non-uniformities during the irrigation process. The ultimate result is application of water above the irrigation requirement level and leads to nutrient loss into sub-zones of the soil profile and may also cause surface runoff if not carefully monitored. Crops readily use water in the soil when the moisture level is above 60% of the available regime (between permanent wilting point and field capacity). Economical use of water in an irrigation system should consider the amount of water used for a unit production of the crop yield and compare with the value of the amount conserved as an opportunity cost of yield reduction. Limited reduction of irrigation water such as applied in deficit irrigation is a more sustainable alternative as a demand management strategy (Kjne 2003; Farahani, 2006). Strategic reduction of irrigation water is considered for crop stages that do not cause drastic decline in both the yield and monetary gain but instead more area is put under production using conserved water and ultimately lead to a conserved environment.

1.2 Statement of the Problem

The regime of moisture in the soil porous media is critical for balancing the demands of a stress free crop growth. The water is imbibed by the crop and creates an environment in the root zone and a microclimate on the soil surface that is conducive for optimal crop production. Application of plant nutrients into the soil requires moisture to regulate its concentration levels to allow assimilation process. Soil moisture potential generated in the root zone controls the ability of plants to abstract the water and therefore a stress free amount needs to be estimated. Conventional irrigation methods are designed to apply full amount of the crop water requirement to recharge the soil moisture content to field capacity according to what a particular soil can hold without consideration of the existing complex processes in the soil environment.

The levels of application of nutrient fertilizers used in agricultural production are based on the gross levels recommended by the agricultural extension workers and also the advice obtained from the agricultural inputs (retailers/stockiest) in the market. Such rates are recommended with the assumption that water availability through rain-fed agriculture is above normal levels for the various crop water requirements. Under normal circumstances, the rates of fertilizer application are never consistent and do not necessarily apply what exactly the crop requires. The limitation is further challenged by the available amount of soil moisture that is not always maintained at the field capacity level due to inconsistent rainfall patterns. The rates could be above or below the recommended amounts and does not match the amount of water (or rainfall) availability at any one particular time.

The use of fertilizer dispensing hoppers is calibrated before use but does not consistently dispense uniform amounts throughout the area applied. This is because of several variations prevailing in the farm and normal malfunctioning of the equipment. The net effect of the fertilizer application rates lead to amounts above the recommended rates and yet rainfall is never controlled to match the amounts sufficient for the nutrient absorption by the crops. Non use of excess nutrient fertilizers applied often lead to build up of residual amounts after crop maturity. Occurrence of excess rainfall result in surface water runoff that leads to soil erosion that carries the crop nutrient loading into the open water masses. Increase in nutrients mainly Phosphorous and Nitrogen entering water masses, cause the growth of water vegetations such as water Hyacinth and the Algae blooms that lead to public health risks and aquatic ecosystem failure. This lead to the imbalance of the important oxygen in water masses because it gets consumed by both harmful algae blooms under limited light, and bacterial decomposers of dead organisms. Water from such sources are reused for irrigation and also consumed directly without treatment by majority of the population who are living below the poverty line. Polluted water sources carry lethal contents that cause the consumers to risk contracting water related diseases such as Cholera and Typhoid, contrary to the requirement of safe and potable drinking water as vital to human dignity, health, productivity, economic and social development (Water Act, 2016). This scenario has persisted and continues to increase without any viable solutions to mitigate damage to the environmental resources which form the livelihood base of the biota. There is need to regulate the amounts of moisture and nutrient fertilizer that a crop utilizes for optimal yields and limit any excess that would remain in the soil profile.

Available research on deficit irrigation and water productivity have considered crop yield levels as influenced by only the moisture available in the soil and assume the applied nutrient fertilizer levels are not limiting. Current research assumes that nutrients play a key role in the growth and yield levels of crops. In addition, crops ability to absorb the nutrients is dependent on the amount of moisture in the soil for dissolving and transport of mineral elements.

The research design elaborates on the influence of both water and nutrients level for optimum yield level of the crops. The solution of the problem involves modeling water productivity and optimal crop yields. In the past, simple equations were used in evaluating crop response to water but more sophisticated simulation models have been developed in the recent decades (Uehara and Tsuji, 1998). Under optimized irrigation water for enhanced sustainability and profitable production, crop yield is conveniently predicted using AquaCrop model *(Farahani et al, 2009)*. The model assesses the effect of the environment and management changes on crop development, develop deficit irrigation strategies and simulate expected yields and water use efficiency in a given soil-field-climate environment (Farahani, 2009). Current research aims at providing solutions for achieving optimum production of maize at acceptable yields level through reduction in irrigation water use and nutrients application level. Through the research investigation of resource use efficiency is maximized and damage to the environment caused by excess amounts is highlighted.

1.3 Purpose of the Study

The main purpose of the study was to investigate the effect of application of moisture and nutrient fertilizer on the water productivity of maize crop. The study aimed at achieving optimal application levels of both the soil moisture and plant nutrients to obtain optimum maize yields and to limit uneconomical use of excess amounts that alter the environment of soil and ultimately get transported into large water masses. Use of demonstration plot designs of maize production was adopted to obtain actual field production of maize and the necessary data used in calibration and prediction by the AquaCrop model. The research explored further the effect of residual nutrients left in the soil after crop maturity to explain their contribution to non-point source pollutant loading of the water masses and result in environmental degradation. The study utilized correlation of the levels of nutrients uptake by maize crop with deficit irrigation amount of water available for assimilation process and developed yield gap production levels to be used as a management tool.

1.4 Research Objectives

1.4.1 General Objective

Simulate using FAO AquaCrop model the optimum yield level of maize under deficit irrigation and different levels of nutrient fertilizer application.

1.4.2 Specific Objectives

The following specific objectives are addressed by the research:

(1) To establish the response of maize yield to various levels of both deficit irrigation and nutrient fertilizer application.

(2) To determine and correlate residual nutrient levels in the soil at harvest as function of various deficit irrigation and fertilizer treatments.

(3) To calibrate and validate FAO AquaCrop model based on field trials of deficit irrigation and nutrient fertilizer application levels.

(4) To predict maize yield gaps using AquaCrop model as a result of water and fertilizer stress prevailing in Uasin Gishu County.

1.5 Research Questions

The study aims at answering the following research questions:

(i) How does maize yield respond to various levels of deficit irrigation and nutrient fertilizer application?

(ii) How does the amount of residual nutrient levels in the soil at harvest correlate to various deficit irrigation and fertilizer treatments?

(iii) How AquaCrop model is calibrated and validated using field trials data of deficit irrigation and nutrient fertilizer application?

(iv) How can AquaCrop model be used in simulating yield gaps and generating guidelines for management of maize crops in Uasin Gishu County?

1.6 Research Hypothesis

Null Hypothesis: H_O: Maize crop yield is a function of both the amount of moisture content (irrigation water) and nutrient fertilizer applied.

Alternative Hypothesis: H_A: Maize crop yield is independent of the amount of moisture content (irrigation water) and nutrient fertilizer applied.

1.7 Significance/Justification of the Study

The profile of crop production function is used as a tool in predicting yield response to irrigation water. The main features of the function indicate that as the crop yield attained its maximum, the slope of the trend plot decreases and approaches zero as the amount of moisture applied increases. The relationship shows that there is a direct correlation between yield and the amount of irrigation water applied and the correlation diminishes as the yield attains its maximum. The function implies that the rate of return by additional amount of irrigation water to cause a unit increase in yield progressively become uneconomical and therefore it is preferable to operate at a deficit irrigation level than full irrigation strategy. The saved water can be used to irrigate another crop.

Irrigation infrastructure is expensive and demands that it should be a well designed and managed system utilized for production of high value crops. Irrigated agricultural production therefore should be managed as a business and the economic returns are justified when the profit margins are wider. Application of deficit irrigation strategy will allow unutilized water saving considered for increased production area and reduced wastage into the environment. Crop assimilation of nutrients must be in the solution form that is easily absorbed. Reduced amounts of water and increased level of nutrients may result in the concentration imbalance which may not allow plants to absorb the nutrients easily. This implies that concentration levels need to be evaluated and appropriate levels determined for given amount of moisture available in the soil. An optimal level of yield obtained maximizes on the appropriate maximum levels of both the moisture and nutrient fertilizer application. In addition, excess amounts of fertilizer left in the soil leads to acid conditions which cause the environment to deteriorate and may not continue to support a balanced ecosystem. It is also important to regulate and minimize wastage of the amounts of nutrient fertilizer used because the commodity is the most expensive component in crop production to allow crop production practiced at maximum economic returns possible.

1.8 Scope of the Study

The research varied the amounts of water application for deficit irrigation and the amounts of nutrient fertilizer at sowing (N:P:K) and top dressing (C:A:N) used to feed the maize crop for optimum results in yield. Five levels of water application were combined with five levels of nutrient fertilizer applications to generate a matrix and for three replicas giving a total of 75 sub-plots. Soil analysis was undertaken to determine the levels of crop nutrients at the beginning before maize crop sowing and at the time of harvesting to determine the amount of residual nutrient levels left in the soil after crop maturity. Climatic data was recorded at the site using installed mini meteorological station and long term data obtained from the nearby Kapsoya meteorological station. AquaCrop model was calibrated and validated using the demonstration field data and used to simulate optimal yields of maize crop under deficit irrigation from the 75 plots.

1.9 Assumptions of the Study

The following assumptions were considered in the current study: (i) only drip irrigation provided water required by the maize crop and the rainout shelter eliminated any precipitation water from entering the plots, (ii) the maize crop adopted its normal physiological growth and was not influenced by the modification of the site and use of rainout shelter, (iii) air borne diseases did not affect the normal performance of the maize crop growth, (iv) the results obtained from the sub-plots were sample representation and give similar outcome as the larger population of the farm.

1.10 Limitations and Delimitations of the Study

The capacity to research on a larger area was limited by availability of both financial and human resources. The research was set up at Saroiyot farm with its unique conditions and micro-climate and may not be representative of other regions. The maize crop was tested for one growing season which may be different from any other season and data may not be replicated in future trials. The seeds and nutrient fertilizer used were supplied by the seed processers/suppliers and their viability and vigour may not be known at the farm level.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Agricultural productivity is a primary function in which Biomass/Organic matter is produced per unit area over a time period by plants (crops) during photosynthesis. The process of productivity involves using solar energy as a basic requirement to capture and store chemical energy during conversion of carbon dioxide and water used for biomass production from inorganic substances found in the soil in a given length of time.

Appropriate quality and affordable water is required yet it is the main cause of agricultural droughts that limit agricultural productivity because it is a limiting resource that is demanded in both the biotic and abiotic spheres of an ecological system. To sustain productivity under the conditions of limiting water resources, there is need to have full knowledge on how plants interact with the environment and the rate of growth under optimized irrigation application as an alternative strategy of management.

Water is finite in the environment and a resource which require conservation and an elaborate means of use in crop production in order to realize profitable levels and enhanced environmental protection. Seasonal plant water use is governed by the prevailing climatic conditions, stage of maturity, soil fertility and water availability. Application of less water than the full amount that the crop demands during the growing stages is one of the strategies of crop production that aim at achieving a desired quantity and quality of the production and increased utilization of the available land area. Reduced water application is made in such a way that avoids unbalanced/limited water condition that causes plants to stop normal metabolic functions but create an ideal balance between the available moisture and amount of oxygen in the rhizosphere. Available water in the soil dissolves plant nutrient ions and allows the process of absorption at the root surface. Transport of nutrient ions to plant roots is a diffusion movement process aided by transpiration by causing mass flow of nutrients to the roots and the physical contact as a result of root growth. The inorganic substances used in the biomass production are a function of the amount of water required during the assimilation process.

Crop water demands suffer reduced water condition during periods of irregular rainfall patterns and when irrigation water is limited. Seasonal availability of water and nutrient levels need to be synchronized and develop appropriate application levels of the inorganic fertilizers to avoid crop susceptibility to drought. Excess application of the inorganic fertilizers may lead to an increase in the residual levels, alter the salinity levels and consequently leach in the soil and eventually spread into the environment during periods of high moisture conditions and in turn contributes to eutrophication of water masses (FAO, 2006).

2.2 Crop Response to Water

Crop sensitivity to water stress is explained by considering the change in crop yield with the amount of water available for its productivity. Evaluation of the production function indicates that at the beginning the slope is relatively high showing that water is efficiently used to increase production (a small increase in applied water results in a significant increase in yield). Further increase in water levels applied lead to a decrease in the relative yield for the same amount of water applied and a zero slope is attained at maximum yield. Any increase of water applied for yields beyond the plateau level of the function decreases the yield achieved because the moisture level in the soil is beyond field capacity and start to inhibit normal gas transfer within the root zone. Considering the trend of the consumptive use of water (Evapotranspiration) versus the amount of moisture in the soil also indicate a steep slope at the beginning but start to diminish at a critical value of the soil moisture.

Crops respond to the available moisture and maximize on abstraction for consumptive use when the available moisture in the soil is less than the maximum possible and in the process economically save on unnecessary use of excess water for irrigation. This implies that all water at low soil moisture level is converted into biomass growth and Evapotranspiration but less conversion occurs when soil moisture is increased and lead to the excess water stored or lost through drainage causing leaching of nutrients below the active root zone and inhibit soil aeration. However frequent irrigation of less amounts reduce the water application efficiency due to accumulated amount of water lost during each application event. The two scenarios indicate that carrying out full irrigation by supplying all the crop water requirement lead to maximum yields with maximum water losses not utilized by the crops (*Steduto et al., 2012)* and consequently affect the environment. Average water consumption, the extent of induced stress and production loss in plants is traced to the sensitivity to crop growth stages of initial growth, development, mid-season growth, ripening and harvest (senescence) and allow different apportionment levels of application.

Young plants during the initial growth stage have shallow rooting zone and need small depths of water access for transpiration that is applied more frequently and the ground surface is prone to increased evaporation. However moisture must be available in the eventual root profile to assure good root development. Timing of crop water use and differential application in the four growth stages is necessary to minimize yield losses and optimize yield per unit of water applied. Amount of water demanded by the maize crop during mid-season growth stage (tasseling and flowering) is important to supply and facilitate pollination process to minimize reduction of grains yield. The mature plants with developed rooting system and much higher storage capacity has canopy cover over 80%, highly sensitive to water shortage and the demand for water is high (FAO, 2002).

Controlled water application that does not recharge the complete root zone in both development and maturity/ripening stages do not adversely affect the ultimate grain yield. Evaporation of moisture on the soil surface and Transpiration through the plant leaf surfaces are two components of crop water use that are governed by the ambient temperature, humidity, wind, solar radiation and total leaf area of the crop and when combined is referred to as Evapotranspiration (FAO, 2018). Economical irrigation system reduces the amounts of applied water (deficit irrigation) to a level that does not drastically reduce the yields and eventually the cost of production saving is higher than the loss of the crop yields.

Yield responses to irrigation and to Evapotranspiration deficit have shown that biomass production and yield of many crops are linearly related to transpiration and evapotranspiration respectively (*Stewart et al, 1990* and *Fereres et al, 2003*). Factors influencing the response include the location, stress patterns, cultivars, and planting dates. The yield response varies depending on the crop sensitivity when water deficit occurs during a specific crop development period. The response formulation according to Vanx and Pruitt (1983) is summarized by the relationship between Y_a, Y_m, ET_a, ET_m, to the yield response factor, K_y in Eqn. (2.1):

$$1 - \frac{Ya}{Ym} = K_y \left(1 - \frac{ETa}{ETm}\right) \tag{2.1}$$

Where, Y_a is the actual yield (kg/ha), Y_m is the maximum yield (kg/ha), ET_a is the actual evapotranspiration (mm), ET_m is the maximum evapotranspiration (mm) and K_y is the yield response factor (depend on species, variety, irrigation method and management, and growth stage when deficit irrigation is imposed). The term $(1 - \frac{Ya}{Ym})$ represent yield depression, while $(1 - \frac{ETa}{ETm})$ is the Evapotranspiration deficit. The two terms form a linear relationship with the yield response factor (K_y) as the slope (Doorembos and Kasssan, 1986). The crop yield response factor gives an indication of whether the crop is tolerant to water stress. Value of K_y greater than unity indicates that the expected relative yield decrease for a given Evapotranspiration deficit is proportionately greater than the relative decrease in Evapotranspiration (Kirda et al, 1999). As crop yield response factor increases, field water use efficiency ($E_c = \frac{Ya}{ETa}$) decreases which in turn imply that benefit from deficit irrigation is unlikely. Crops response to water stress as shown by negative production signs generates complex mechanisms that allow crops to adapt to the water shortage. Several crops and genotypes have developed different degrees of drought tolerance, drought resistance, or compensatory growth to deal with periods of stress (FAO, 2000). The mechanism has shown that water stress applied during vegetative growth stage may have a favourable effect on the root growth, contributing to more effective water use from deeper layers. During irrigation scheduling, maize sensitivity to water is categorized into medium to high and critical during the flowering and grain filling periods.

2.3 Deficit Irrigation

Deficit irrigation is an on-farm strategy of applying less water than the full amount of irrigation requirement of a crop. Irrigation requirement refer to the total amount of water that must be applied by irrigation to a disease free crop, growing in a large field with adequate soil water and fertility, and achieving full production potential under the given growing environment (Doorenbos and Pruitt, 1977). Water for the irrigation requirement supplies the crop consumptive use, maintains a favourable salt balance within the root zone, and overcomes non-uniformity and inefficiencies of irrigation.

Deficit irrigation aims at saving on irrigation water without affecting both the quality and quantity of the crop yield. Water is applied below full irrigation and production costs decreases faster than revenue decline (Larry, 1988) and is justified by the relatively zero slope of the production functions in the vicinity of full irrigation. Various techniques of deficit irrigation strategies are applied to balance the production of a crop while maximizing the use of the limited water resources. The strategy of deficit irrigation justifies the applications of accurate water management and soil water monitoring to attain the level of increased water use efficiency. Other definitions of deficit irrigation have been published depending on the perspective of the respective authors and considers either crop growth stages or in terms of drought stress. *Kipkorir et al*, (2001) considered deficit irrigation as an incomplete supplemental irrigation or regulated deficit irrigation. The definition was modified by Greets and Raes, (2009) to refer to an on-farm strategy to maximize crop water productivity in dry areas.

Deficit irrigation is a crop sensitivity response to yield formation when crop water requirement is reduced below critical levels. Where water is limiting, it is more important and profitable to maximize crop water productivity than maximizing the harvest per unit of land (Fereres and Soriano, 2007). This involves allowing regulated plant drought stress and the crop increases its water use efficiency that leads to reduced cost of the water used and prevents loss of crop yield associated with lower water use efficiency. The success of deficit irrigation strategy is influenced by specific crops response to water stress.

Water needed by plants is stored in the soil and held in the voids by the matric forces. The maximum limit of soil water available to plants occurs at field capacity, a level when the forces (matric potential) holding significant amounts of water which plants can remove and use is about 1/3 bar for most soils (Larry, 1988). Permanent wilting point marks the lower limit of soil water that is available to plants and is a function of both the crop and stage of growth. Half (50%) of the soil water content between field capacity and permanent wilting point is defined by the critical soil water content that marks the lower limit of readily available water or allowable depletion to plants. Water holding capacities of different types of soils influence the amounts of irrigation demand daily. Course textured sandy soils stores less water and irrigation requirement is higher and more frequent than fine-grained clayey soils. The Agricultural Research Services of the USA reported that early application of deficit irrigation on peanut plants maintained sufficient yields and was attributed to the plant physiologically adapting to the stressful drought environment. However, maize crop sensitivity to drought stress is low during vegetative/development stage compared to high values during flowering and yield formation (NeSmith and Ritchie, 1992).

2.3.1 Deficit Irrigation Management

Deficit irrigation increases the water use efficiency of a crop by eliminating irrigation water application that has little impact on the yield. The resulting yield reduction may be small compared with the benefits gained through irrigating more land. The impact of deficit irrigation management practices is quantified through the crop water use efficiency and its implementation requires knowledge of crop yield response to water stress, either during defined growth stages or throughout the whole season (Kirda and Kanber, 1999).

The crop growth status depends on the availability and distribution of the moisture in the root zone and to attain the optimum yield levels the crop must save and store energy as yield by easily abstracting moisture from the soil. This scenario occurs when the soil moisture is within the readily available range. Stressed plant condition is a sign that roots have difficulty in extracting moisture and result in the decrease in leaf area growth, limit the ability to transpire water and consequently result in less crop yield (*Mthandi et al*, 2013). The amount of water required to grow a crop defined by the crop water use efficiency must meet the threshold for leaf expansion that realizes the acceptable yields.

This management practice is clarified through understanding irrigation water use efficiency a term used to correlate with the amount of water applied. The efficiency refers to the fraction of the amount of water required to grow a crop to the total amount of irrigation water applied.

The amount of water required by the crop is applied to meet the demands for evapotranspiration, leaching requirement for salinity control and water for management of no-uniformities. A more concise description of the agronomic water use efficiency is to view in terms of the amount of yield produced by a unit volume of water used. This is referred to as the Water Productivity (WP) defined as the ratio of unit of yield produced to a unit volume of water used to produce the yield and both irrigation water use efficiency (IWUE, kg/m^3) and crop water use efficiency (CWUE, kg/m^3) are defined as follows (*Irmak et al, 2012*);

$$\text{Crop water use efficiency (CWUE)} = \frac{\text{grain yield (g/m2)}}{\text{ETc (mm)}} \tag{2.2}$$

$$\text{Irrigation water use efficiency (IWUE)} = \frac{\text{grain yield (g/m2)}}{\text{total irrigation applied(mm)}} \tag{2.3}$$

where ET_c = Crop evapotranspiration.

When moisture is depleted from the soil by the plant roots, a critical range of between 50% - 60% depletion level of available soil moisture is reached that correspond to the threshold for leaf expansion, beyond which yields reduce. When water is limited by the short supply, WP realizes acceptable yields under deficit irrigation.

FAO (1979) report showed that high yielding varieties are more sensitive to water stress than low yielding varieties and yields of new varieties of maize were adversely affected than those of traditional varieties. Deficit irrigation was found to favour crops with short growing season and tolerant of drought (Stewart and Musick, 1982). Soil properties contributed to the sensitivity of the crops to water stress. Low plastic sandy soils cause plants to undergo water stress more quickly under deficit irrigation than deep soils of fine texture which hold more moisture and allow plants to adjust to change in soil matric potential as moisture stress develops and therefore remain unaffected by low levels of water content *(Katerji et al., 2010)*. In addition to crop success in fine textured soils, influence of agronomic practices such as reduced plant population, less application of fertilizer, synchronized planting dates and using shorter season varieties help the crops to survive under reduced irrigation water regimes.

2.4 Availability of residual plant nutrients in the soil

Residual nutrients found in the soil are considered as soil fertility and depending on the amount available can provide sufficient plant needs without any external addition. Sources of the nutrients include; decomposed organic matter, exchangeable nutrients, soluble chemical compounds, and the soil mineral fraction (Maaz, T., and Pan, W. 2017). The available fertility in the soil changes when the nutrient carriers are added or removed from the site.

Plants require 16 essential elements (three from the atmospheric air and thirteen from the soils) as nutrients for growth and development. The three from air are Carbon (CO_2), Hydrogen (H_2O) and Oxygen (O_2) and form the sugars and starches in the plant tissues.

The elements from the soil are; Phosphorus (P), Potassium (K), Nitrogen (N), Sulphur (S), Calcium (Ca), Iron (Fe), Magnesium (Mg), Boron (B), Manganese (Mn), Copper (Cu), Zinc (Zn), Molybdenum (Mo) and Chlorine (Cl). Release of these nutrients and their availability for plant abstraction is influenced by the prevailing environmental conditions that include, temperature, soil moisture, aeration, soil pH and tillage method (*Saweda et al., 2017*).

Reduced agricultural productivity and soil test results are used to establish the level of fertility in soils. Inorganic fertilizers are added into the soil when essential plant nutrients are insufficient for optimum yields or imbalance of nutrients exists.

2.4.1 Maize production and applied nutrient fertilizer

Maize (*Zea mays L.*) is the leading cereal crop produced worldwide (*Carter et al., 2016*) and a stable primary food eaten by majority of communities in the world. The crop is a source of carbohydrate used in livestock diet, textile industry and pharmaceutical industry (*Usman et al.*, 2015). It grows in a large range of ecological zones in Kenya having altitudes from 100 – 2900m above sea level and soil pH of 5.8 – 7.0. Maize does well in areas with average seasonal rainfall between 400 – 1200mm, received during the first 30 days (initial growth stage) after sowing and well distributed throughout the cropping period and sufficient amount during flowering and grain filling period.

Planting of maize is recommended to take place during the onset of rains with spacing of 75 cm between the rows by 25 cm between the plants along the row. One seed is planted per hole and using N:P:K formulation of 18:46:0, Di-Ammonium Phosphate (DAP) fertilizer at the rate of one table spoon per hole. The three elements; Nitrogen, Phosphorus and Potassium in the inorganic fertilizer are essential at the initial growth stage in maize production (Sangwon and Scott, 2011). Potassium is not applied from the inorganic fertilizer (K = 0) because it is found in sufficient quantities in the soil. Nitrogen mostly is limiting in the soil but essential in the growth of leaves and obtaining maximum yield and quality. The organic matter in the soil releases nitrogen during mineralization and contribute to the required amount for plant use. Phosphorus is required for root growth and the development of growing tips in plants. Potassium helps to keep plant tissues rigid and regulates the amount of water content in plants.

Maize crop demand for the nutrients is high to meet the requirements of its production of dry matter yields. At knee high, maize crop is top dressed at the same rate as the planting fertilizer using Calcium Ammonium Nitrate (C:A:N) to boost the amount of nitrogen in the soil.

2.4.2 Effect of Soil moisture and Nutrient fertilizer on Maize production

Soil moisture dissolves and facilitates transport of the available nutrient fertilizer for imbibing by plants. The amount of moisture available in the soil influences plant root growth and the vigour at which plants abstract soil nutrients for growth and development. *Kipkorir et al*., 2007 recommended that initial soil water reserve from previous season can influence early establishment of the crop and contribute to water use and yield during the cropping season. Lateral roots are responsible for water uptake into plants while the main seminal and nodal roots distribute the laterals in the soil. Low moisture in the soil cause root proliferation highly restricted in the upper part of the soil profile (*Rudnick, et* *al.*, 2017), and result in deep penetration in search of moisture. Deep roots of the un-watered plants exhibit very high water depletion rates per unit root length.

Plants react to negative imbalance of water in the tissues and all organs respond to remove the stress effect. To maintain turgidity of the plant cells, the leaves inhibit transpiration while the roots increase water uptake and maintain the hydraulic xylem conductivity (Grzesiak, 1999). Sustained water drought in the soil results in deficit water to plants and lead to variations in dry matter and maize grain yields. Maize grain yield is a function of the rate and duration of grain filling that occur when the crop demands maximum water requirements. Irrigation of maize crop provides controlled mitigation against detrimental effects of depleted soil moisture.

Maize crop is a strong exhauster of plant nutrients in the soil and poor yields are realized in low fertility soils. Demonstrations by *Stefano et al., 2004* on nutrient influence on growing conditions and quality of cherry concluded that inorganic fertilizer has a strong influence on plant growth, development and yield. This is manifested by the vigour in the crop growth and high production of dry matter yield.

2.5 Models and Crop Simulation Modeling

2.5.1 Introduction

A model is a representation of phenomenon under investigation and provides simplified information of aspects that are complex to visualize. Models provide information on physical systems, apply concepts and ideas (conceptual) and/or describe a system using variables and equations. Simulation models describe objects using different size scales specified as smaller, same size or larger than the prototype. Field observations and experimental results of real systems utilize models in testing and predicting constraints that help to understand the physical condition involved and achieving better interpretations.

Modeling refers to the use of mathematical expressions to represent the physical processes in nature. The current research utilizes the Food and Agricultural Organization developed AquaCrop model (FAO, 2017) to simulate the results of determining optimal yield of maize under variable amounts of irrigation water (deficit irrigation) and nutrient levels. AquaCrop is a menu-driven program where input consists of weather data, crop management and soil characteristics that define the environment in which the crop develops, the sowing or planting day, the simulation period and conditions at the start of the simulation period are input.

2.5.2 Crop Simulation Models

The environment and the physiological processes of a crop are embedded in the soil-plant-water and the climate interactions. Variations in the performance of plant growth development (yield and dry matter) are observed in the local environmental conditions depending on the level of crop management. Complex cropping system processes of the relationships are examined by appropriate crop simulation models that simplify real variables into primary decision making solutions for crop management. The models however do not simulate all the processes (*Arianna et al., 2015*). Crop simulation models are useful in understanding underlying physiological mechanisms by simulating crop growth, productivity and yield.

Crop simulation models are either predictive (simulate crop yield) or explanatory (focused on specific systems described in detail). Predictive models are built on empirical functions (statistical relationships) and provide predictions under specific environmental conditions (*Jin et al., 2014*). Explanatory models are mechanistic (process-oriented) and require more input data than empirical functions (*Basso et al., 2015*). Intermediate complexity models (hybrid) apply a mix of empirical and mechanistic approaches (*Arianna et al., 2015*) depending on the process to analyze.

Commonly used crop simulations include; (1) Agricultural Production Systems Simulator (APSIM), predict crop production in relation to biophysical process (*Mohanty et al., 2015*) under Climate–Plant–Soil–Management factors and address resource management issues, (2) Decision Support for Agro-technology Transfer (DSSAT), simulates growth, development and yield through integration of soil, crop phenotype, weather and management options (*Jones et al., 2003*) on a uniform area under prescribed or simulated management, (3) INFOCROP is a generic crop model (*Aggarwal et al., 2006*) and simulates effects of weather, soils, agronomic management (planting, nitrogen, residues and irrigation), (4) Cropping System Simulation (CropSyst), is a process –based multi-year and multi-crop model (*Stockle et al., 2003*) used to analyze the effect of cropping system management on crop productivity and environment, (5) Crop Environment Resource Synthesis (CERES) is a process – based model and analyzes effects of weather, soil, planting method, irrigation, and fertilizer management (*Gurbir et al.,2013*) on the crop yield and development, (6) Soil–Plant–Atmosphere System Simulation (SPASS) is used to simulate dynamic processes in crop production that include biomass growth, water uptake, and nitrogen uptake, (7) World Food Studies (WOFOST) is a mechanistic model of annual field crops that explains crop production processes of photosynthesis and respiration as influenced by environmental conditions. The model calculates attainable yield, biomass and water use for a location with known soil type, crop type, weather data and crop management, (8) CROPWAT was developed by FAO for estimating crop water requirements and irrigation guidelines. Due to limitation of the original algorithm of overestimating crop water needs (Mathew and Stephen, 2002), it has been modified with the Penman – Monteith estimation of evapotranspiration and (9) AquaCrop model is a water productivity model that predicts yield as a function of water supply (FAO, 2017). The model is based on biomass production (B) as a function of the amount of transpiration (T) for constant water use efficiency (WUE) normalized by reference evapotranspiration.

AquaCrop model is based on the daily soil moisture extraction, the model calculates canopy cover expansion, transpiration and evaporation components of ET and, depending on the crop harvest index built up, computes crop yield at harvest date. The model has a soil fertility module to make adjustments for non-optimal fertility conditions common in many agricultural systems (Villalobos and Fereres, 2016). The model is widely utilized throughout the world because of its flexibility of calibration and validation using experimental data in environments of application.

2.5.3 AquaCrop model Conceptual Framework and calculation simulation processes

The challenge to be self sufficient in food and to maintain sustainable productive environment requires a productivity function that optimizes capital resources that control food crop production.

Water resources remain limiting and demand applications of improved irrigation strategies that guarantee sustainable water productivity. AquaCrop model is a water productivity model that predicts crop yield response to limited irrigation water. The model conceptual framework apply the local environment and management changes on crop development to simulate deficit irrigation strategies and crop yields for different water productivity levels.

Current research models the scenario to establish the optimum yield levels of maize grown under normal environmental conditions with regulated amounts of water and nutrient levels. AquaCrop model is used to predict yield gaps of maize yields under different environmental climate scenarios of Uasin Gishu County. To interpret the model soil-plant-atmosphere continuum given in Figure 2.1, a conceptual framework presented in Figure 2.2 simplify the change that occur between the demonstration plots activities and the target goal of maize yield gap predictions.

(i) Calculation and Simulation processes of AquaCrop model

AquaCrop model achieves its simulation process of dry grain yield through a step-wise interaction scheme of simulating crop development, crop transpiration, biomass production and finally the yield formation (FAO, 2016). The model requires input of the initial soil moisture and salt content conditions specified at the beginning of growing cycle and other parameters are fine-tuned during simulation process.

(ii) Simulation of crop development

The model simulates crop development by considering green canopy cover expansion above the ground and development of the crop roots below the ground surface. The model considers green canopy cover to vary from 0 % (when the soil is bare during date of sowing) to 100 % (at full canopy cover) in the absence of any stress. Through simulation of the soil water balance in the root zone, AquaCrop determines the level of water stress and informs on the status of development of the crop and subsequently canopy cover development. The model uses leaf expansion to mark the upper water stress threshold given by the soil moisture content near field capacity and canopy senescence to mark the lower water stress threshold closer to moisture content at crop wilting point respectively (FAO, 2016). As moisture gets depleted by the crop in the soil below leaf expansion threshold, the green canopy cover development is slowed down and at canopy senescence threshold the canopy cover dies off. The effects of water level thresholds similarly affect root zone expansion and is consequently reflected by the effect on the green canopy cover development. In addition to the statistical analysis of crop development, effect of soil fertility and salinity are also considered during evaluation of the observed field data and the simulation results. The observed green canopy cover trend is compared with the simulated data from the model.

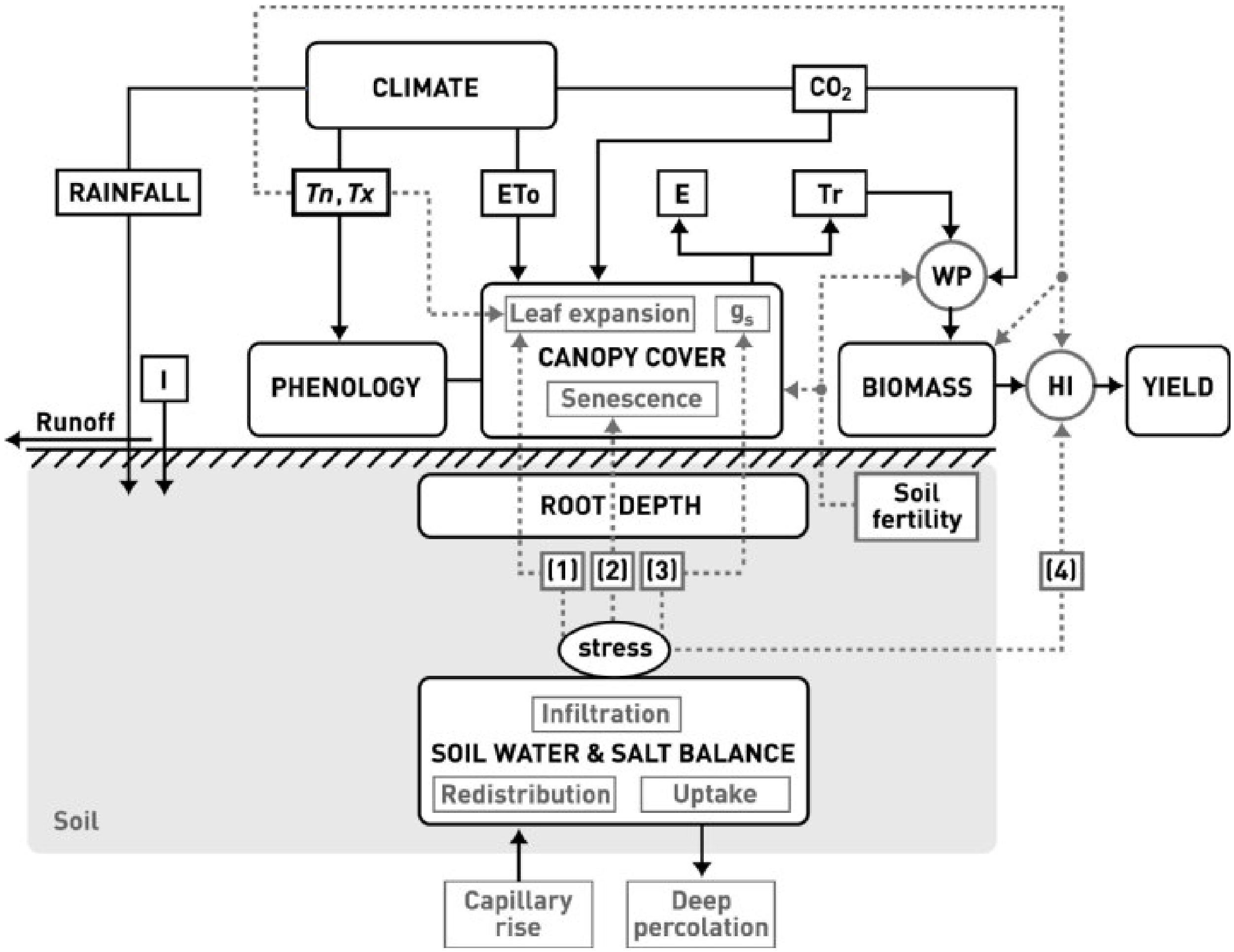

Figure 2.1: AquaCrop Model (soil-plant-atmosphere continuum) courtesy (FAO, 2017)

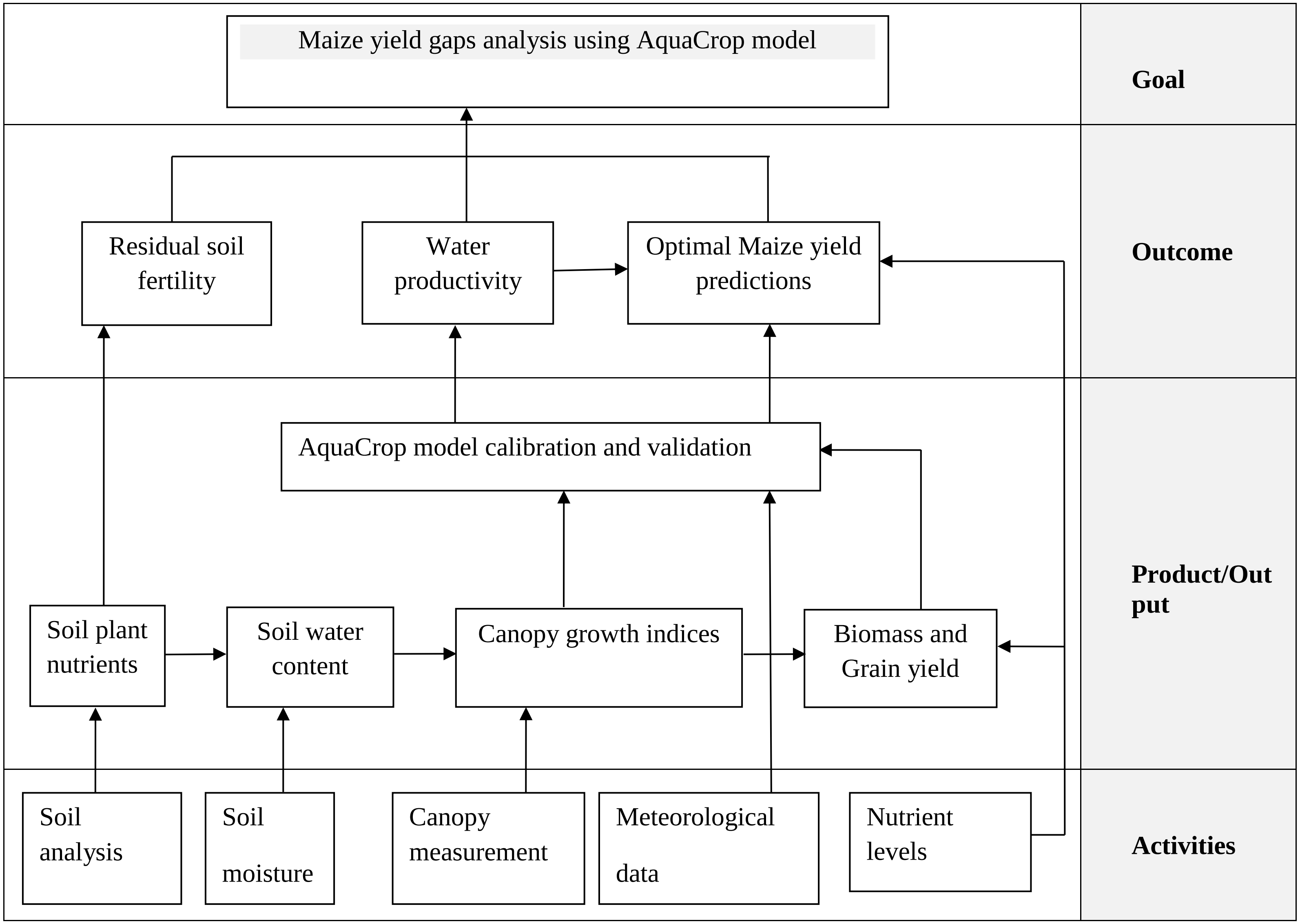

Figure 2.2: AquaCrop model yield gap prediction conceptual model

(iii) Simulation of Transpiration

Transpiration process carry moisture from plant roots to the leaves where evaporation takes place. Green canopy cover provides the surface for transpiration to take place and therefore controls the amount of moisture released into the atmosphere. Transpiration is calculated from reference evapotranspiration (ET_o) based on the prevailing weather conditions and the crop characteristic coefficient of proportionality (K_{CTr}) balances the function given in equation 2.4 (FAO, 2016).

$$Tr = K_{CTr} \times ET_o \tag{2.4}$$

The value of the coefficient (K_{CTr}) controls the development of the green canopy cover depending on the stage of crop development. Fluctuation of the moisture depletion in the root zone causes the stomata cells to respond accordingly. Low moisture in the soil root zone triggers the stomata to close and transpiration will be reduced and consequently crop development is affected. AquaCrop model uses stomata closure as another threshold considered in the transpiration function and introduce an additional constant of proportionality (K_s) given in equation 2.5 (FAO, 2016). The coefficient influences the amount of transpiration depending on the level of stomata closure and directly affects canopy cover. The observed soil water content retained in the root zone is compared with the simulated data.

$$Tr = K_s \times KCTr \times ET_o \tag{2.5}$$

(iv) Simulation of Biomass production

Biomass production occurs when the crop manufactures its food using carbon dioxide (CO_2) and water (H_2O) by photosynthesis taking place on the crop green canopy/biomass area. Carbon dioxide from the atmosphere enters the crop through the stomata and moisture is absorbed from the crop roots through the plant stem to the leaves for food production and lost into the atmosphere as transpiration water through the stomata opening. The amount of Evaporation (E) lost into the atmosphere from the soil and crop leaf surfaces does not contribute to biomass production and is not considered by the model for simulation. Other events not simulated include pests and diseases and damage by hailstones. Unit amounts of moisture transpired into the atmosphere contribute to building up the crop Biomass (B). Total amount of Biomass produced is derived from a proportionality function of the sum of elemental transpiration that occurred during the period of crop development. The slope of the function is referred to as Biomass Water Productivity (WP) defined as the amount of biomass produced in an area of unit m^2 per unit millimeter (mm) depth of water transpired and given in equation 2.6 (FAO, 2016).

$$B = WP \times (\sum Tr) \tag{2.6}$$

Biomass water productivity is valid only for specific climatic conditions and CO_2 concentrations. The constant is corrected in order to be applicable to diverse locations by normalizing Transpiration (Tr) using ET_o as a climate index and referred to as normalized WP^* given in equation 2.7 (FAO, 2016). Dried above-ground biomass is compared with the simulated data.

$$B = WP^* \times \sum \left(\frac{Tr}{ETo}\right) \tag{2.7}$$

(v) Simulation of Crop Yield

AquaCrop model uses Biomass (B) data to simulate crop yield (Y) as a fraction of the total biomass produced. The fraction multiplier given in equation 2.8 is referred to as Harvest Index (HI) and builds up during the physiological development of the crop to a maximum value denoted as Reference Harvest Index (HI_o) at maturity and dependent on the type of crop. Fruit and grain producing crops are referred to as determinant (FAO, 2016) and their Harvest Index (HI) fraction start accounting from the date of flowering when green canopy cover is at its maximum.

$$Y = HI \times B \tag{2.8}$$

The model considers the Harvest Index (HI) as a function of the specific crop characteristic reference Harvest Index (HI_o) and the multiplier is used to adjust its value during simulation to account for water and/or temperature stresses.

CHAPTER THREE

RESEARCH DESIGN AND METHODOLOGY

3.1 Introduction

The research was carried out to assess the water productivity of maize in a suitable production area where the crop is not affected by any environmental conditions except water requirements and nutrient fertilizers. Initial soil analysis was carried out at the site to specify prevailing nutrient amounts before sowing of maize was done. Timely agronomic practices, weed control, top dressing using Calcium Ammonium Nitrate (C:A:N), pests and disease control were managed appropriately to minimize the effect on the maize crop potential in the demonstration site.

3.2 The Study Area

The research was located at Saroiyot farm about 2km South-East of Kapsoya Meteorological Station and about 5km from Eldoret Town along the Eldoret-Plateau Road (Fig.3.1). Grid referencing of the experimental plots lie at an average elevation of 2,117m above mean sea level and the mini-meteorological station located at a latitude of $0^{o}30'52''$ North of the equator, and a longitude of $35^{0}18'2''$ East. The area is characterized by bimodal rainfall season experienced between the months of April to June (peak season) and September to November (low season). Dry conditions are experienced from end of November to end of March (Fig.3.2). Kapsoya meteorological weather station is located near the farm and provided data required for the research design that included; daily values of air temperature (minimum and maximum), relative humidity, precipitation, solar radiation, and wind speed recorded at a height of 2m above the ground.

Other climatic data required for the research design and as input of AquaCrop model was the calculated daily reference Evapotranspiration (ET_o) for the location. The model has an inbuilt ET_o calculator and compute using Penman-Monteith approach (Allen, et al 1998). The calculator generated ET_o values for 34 years (1981 – 2014) using Kapsoya meteorological station climate data required for the research design. Dominant soil at the site is clay loam, well drained with deep water table at depths greater than 10m.

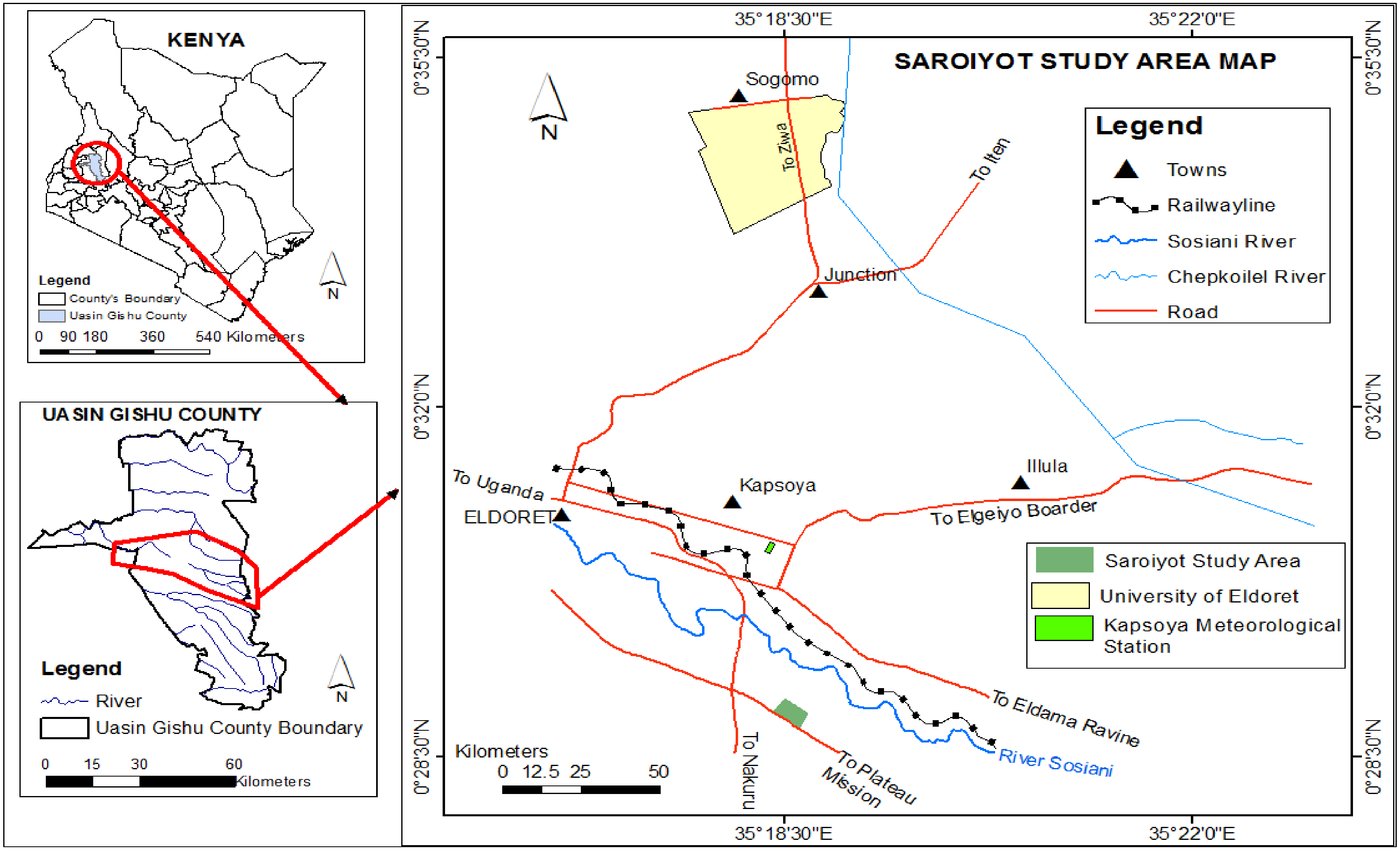

Figure 3.1: **Location Map of the Project site along Plateau road (Source: Author)**

Estimated soil moisture content values for clay loam at field capacity (θ_{fc}) and at permanent wilting point (θ_{pwp}) is equal to 35.2vol% and 18vol% respectively and therefore the available moisture content ($\theta_{fc} - \theta_{pwp}$) is 172mm per metre of the soil. Cuenca, (1989) recorded similar values of 36vol% and 18vol% for clay loam soil at field capacity (θ_{fc}) and at permanent wilting point (θ_{pwp}) respectively.

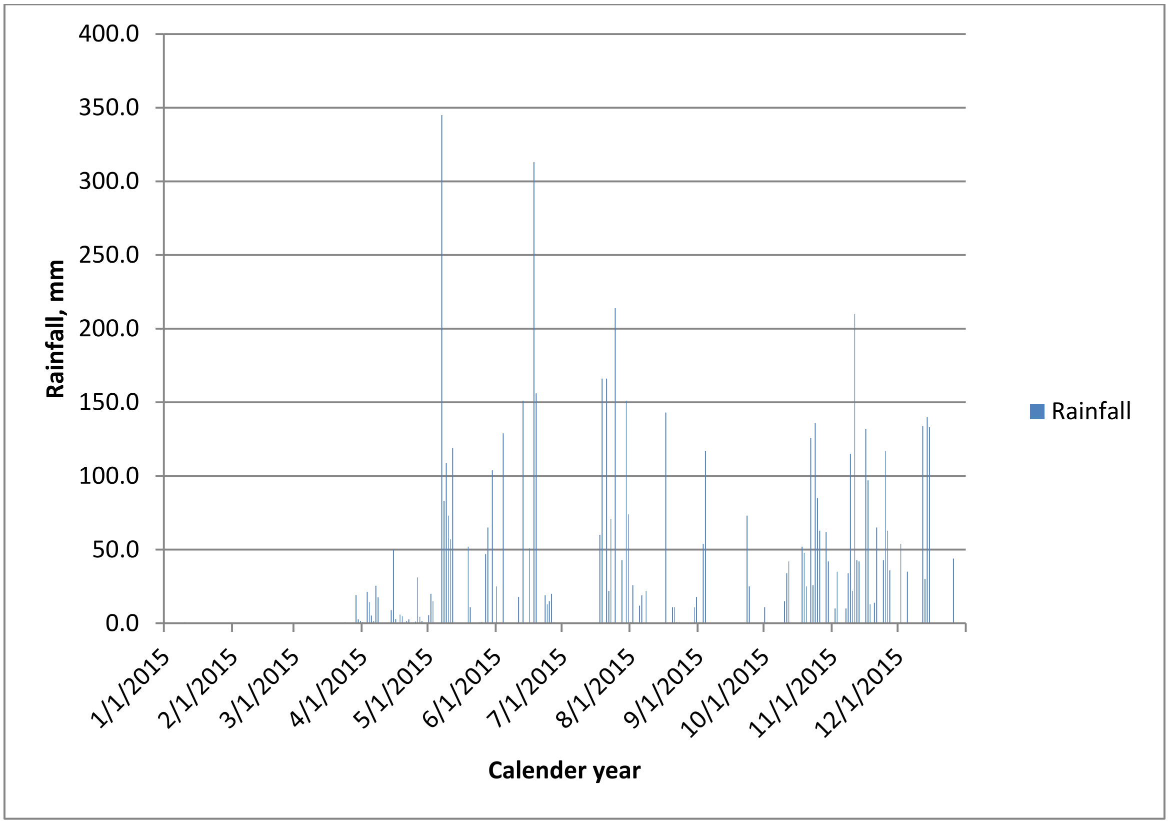

Figure 3.2: Saroiyot research site rainfall data for 2015

3.3 Research Design and Methodology

The site conditions were first investigated before carrying out the research layout. All background information needed to facilitate successful installation of the demonstration plots was carried out and source of both equipments and specialized personnel needed during the research process. Setting up of the site mini meteorological station was done by staff from Kapsoya meteorological station.

3.3.1 Site Description

The farm has continuously been utilized for the last two decades to grow maize through mechanical tillage using disc plough and conventional planters for seed sowing and fertilizer application. Source of water at the farm is a shallow well manually dug to a depth of about 15m and water was lifted using a submersible electric pump to a plastic tank of 5000 litres placed at an elevated platform constructed using factory treated timber poles to a height of 3m. Water was conveyed to the demonstration plots using one inch uPVC plastic pipes (class C) by gravity feeding and controlled at each of the three replica plots using gate valves.

Water application to the maize crop in the plots was achieved through a 16mm diameter drip irrigation laterals with drippers discharging at 1.5 x 10^{-3} m^3/hr (1.5litres per hour) and spaced at 300mm. A mini meteorological station was set up near the experimental plots with a standard rain gauge (manual) and a Stevenson screen holding maximum and minimum thermometers, dry and wet bulb thermometers and relative humidity measurements (Plate 3.1). Dew point and vapour pressure computational formula (program) was obtained from Kenya meteorological department at Eldoret (Kapsoya station). The site climatic data were recorded for the whole year to cover the duration of the plot observations and the maize crop growing period.

Plate 3.1: Set up of the Stevenson screen and the rain gauge at Saroiyot farm.

3.3.2 Experimental Design and Treatments

The research design considered three replica experimental plots, each measuring 675cm wide by 825cm long separated by 10m open space, marked out in a 2 acre piece of land at Saroiyot farm. Replica plot dimensions were derived from the standard maize planting spacing of 25cm between the plants along the row and an inter-row spacing of 75cm. A rain-fed controlled plot of similar dimensions was marked out and separated by a 10m space from the three replica plots. Soil moisture sampling analysis was measured within the replica plots and deficit irrigation scheduling plan was adopted for the research plots water application.

Field data measurement was carried out for root zone soil moisture, maize crop green canopy cover, above ground biomass and dry grain yield were recorded for each of the 75 plots. The plots were considered to be representative of a larger area with the same conditions of treatment and the quantitative research assumed the results of the experimental studies represent a sampling process where a sub-set of cases are selected in order to draw conclusions about the entire set and should be true for the entire population. This approach was taken due to restricted growth of maize under the rainfall shelter (Plate 3.2) that facilitated rainfall cut off and monitoring of deficit irrigation. Also there was adequate ventilation of the shelter to minimize variations in temperature and humidity. Similarly prohibitive expenses, time and accessibility required to obtain information from the whole population necessitated use of sampling plot design.

Each replica block was divided into 25 plots where differential application of deficit irrigation and nutrient fertilizer were managed and maize crop canopy, biomass and yield data were measured. The plots were obtained from the matrix of five (5) levels of moisture application regimes of 50%, 65%, 80%, 90% and 100% of maize crop consumptive use of water and matched with five (5) levels of nutrient fertilizer application amounts of 20%, 40%, 60%, 80% and 100% of the standard recommended planting and top dressing input per plant. Lateral movement of moisture across the plots was eliminated using vertical lining of polythene at the edge of each plot (Plate 3.2).

Alphabetical letters W and F were adopted as symbols to represent Water and Fertilizer variables respectively and their application levels were indicated as subscript indices and presented as a matrix in Tables 3.1. Three (3) replica plots were constituted from Table 3.1 using randomized complete block design matrix and the resultant plot labels are tabulated in Tables 3.2 (a), (b) and (c).

Rain-fed plots presented in Table 3.3 have similar sizes with replica plots and fully dependent on rainfall and applied with the same levels of nutrient fertilizer amounts of 20%, 40%, 60%, 80% and 100%. All plots were conventionally set up to face geographical North direction to minimize wind effect blowing towards the west and reduce the shedding from sun radiations.

Plate 3.2: Steel frame wheeled rainfall shelter (Source: Author)

Sowing of maize in the research plots was carried out on 15th April 2015 using Kenya Seed Ltd certified maize hybrid H629 cultivar seeds sourced from authorized distributor. Recommended sowing spacing of 25cm within the row and 75cm between the rows was adopted and one seed per planting hole to give a total population density of 53333 plants per hectare. The planting date was within the recommended planting season of maize in the location of the research site. The crop was planted using Di-Ammonium Phosphate fertilizer (D:A:P) with Nitrogen, Phosphorus and Potassium formulation of 18:46:0 at the recommended rate of 75kg per acre from soil analysis by CropNuts Laboratory Services – Nairobi (Appendix I). Emergence of all the seeds took an average of 7days from the date of sowing (DOS) and the population was maintained throughout the growing period.

Table 3.1: Plot matrix combinations of applied levels of water and fertilizer

INPUT PARAMETERS		**Deficit irrigation water applied (W) at 50%, 65%, 80%, 90% and 100%**				
		$\mathbf{W_{50}}$	$\mathbf{W_{65}}$	$\mathbf{W_{80}}$	$\mathbf{W_{90}}$	$\mathbf{W_{100}}$
Fertilizer applied (F) at 20%, 40%, 60%, 80% and 100%	$\mathbf{F_{20}}$	$F_{20}W_{50}$	$F_{20}W_{65}$	$F_{20}W_{80}$	$F_{20}W_{90}$	$F_{20}W_{100}$
	$\mathbf{F_{40}}$	$F_{40}W_{50}$	$F_{40}W_{65}$	$F_{40}W_{80}$	$F_{40}W_{90}$	$F_{40}W_{100}$
	$\mathbf{F_{60}}$	$F_{60}W_{50}$	$F_{60}W_{65}$	$F_{60}W_{80}$	$F_{60}W_{90}$	$F_{60}W_{100}$
	$\mathbf{F_{80}}$	$F_{80}W_{50}$	$F_{80}W_{65}$	$F_{80}W_{80}$	$F_{80}W_{90}$	$F_{80}W_{100}$
	$\mathbf{F_{100}}$	$F_{100}W_{50}$	$F_{100}W_{65}$	$F_{100}W_{80}$	$F_{100}W_{90}$	$F_{100}W_{100}$

Table 3.2 (a): Replica No. 1 Plot layout matrix

INPUT	**Irrigation water applied (W) at 50%, 65%, 80%, 90% and 100%**				
Fertilizer applied (F) at 20%, 40%, 60%, 80% and 100%	$F_{100}W_{65}$	$F_{60}W_{90}$	$F_{100}W_{80}$	$F_{20}W_{65}$	$F_{20}W_{100}$
	$F_{100}W_{50}$	$F_{60}W_{100}$	$F_{40}W_{50}$	$F_{20}W_{80}$	$F_{80}W_{80}$
	$F_{40}W_{100}$	$F_{80}W_{65}$	$F_{40}W_{65}$	$F_{60}W_{65}$	$F_{40}W_{80}$
	$F_{40}W_{90}$	$F_{100}W_{100}$	$F_{80}W_{90}$	$F_{80}W_{50}$	$F_{80}W_{100}$
	$F_{20}W_{90}$	$F_{20}W_{50}$	$F_{60}W_{80}$	$F_{60}W_{50}$	$F_{100}W_{90}$

Table 3.2 (b): Replica No. 2 Plot layout matrix

INPUT	Irrigation water applied (W) at 50%, 65%, 80%, 90% and 100%				
Fertilizer applied (F) at 20%, 40%, 60%, 80% and 100%	$F_{100}W_{90}$	$F_{20}W_{90}$	$F_{20}W_{50}$	$F_{80}W_{100}$	$F_{40}W_{90}$
	$F_{20}W_{65}$	$F_{60}W_{50}$	$F_{40}W_{50}$	$F_{20}W_{80}$	$F_{40}W_{80}$
	$F_{100}W_{80}$	$F_{80}W_{90}$	$F_{100}W_{50}$	$F_{60}W_{100}$	$F_{80}W_{50}$
	$F_{100}W_{65}$	$F_{20}W_{100}$	$F_{40}W_{100}$	$F_{60}W_{65}$	$F_{100}W_{100}$
	$F_{60}W_{90}$	$F_{80}W_{80}$	$F_{40}W_{65}$	$F_{60}W_{80}$	$F_{80}W_{65}$

Table 3.2 (c): Replica No. 3 Plot layout matrix

INPUT	Irrigation water applied (W) at 50%, 65%, 80%, 90% and 100%				
Fertilizer applied (F) at 20%, 40%, 60%, 80% and 100%	$F_{60}W_{50}$	$F_{40}W_{90}$	$F_{60}W_{65}$	$F_{40}W_{50}$	$F_{40}W_{100}$
	$F_{60}W_{100}$	$F_{80}W_{50}$	$F_{100}W_{50}$	$F_{80}W_{80}$	$F_{20}W_{80}$
	$F_{40}W_{65}$	$F_{80}W_{65}$	$F_{80}W_{100}$	$F_{100}W_{80}$	$F_{100}W_{65}$
	$F_{60}W_{80}$	$F_{40}W_{80}$	$F_{80}W_{90}$	$F_{20}W_{100}$	$F_{60}W_{90}$
	$F_{20}W_{90}$	$F_{20}W_{50}$	$F_{100}W_{90}$	$F_{20}W_{65}$	$F_{100}W_{100}$

Table 3.3: Rain-fed Plot layout matrix

Fertilizer applied (F)	Rain-fed plot layout matrix				
20%	F_{20}	F_{20}	F_{20}	F_{20}	F_{20}
40%	F_{40}	F_{40}	F_{40}	F_{40}	F_{40}
60%	F_{60}	F_{60}	F_{60}	F_{60}	F_{60}
80%	F_{80}	F_{80}	F_{80}	F_{80}	F_{80}
100%	F_{100}	F_{100}	F_{100}	F_{100}	F_{100}

Scheduled activities were planned for the unit experimental block plot data measurements during the maize crop growing season. The activities were categorized into; amount of fertilizer applied during sowing and top dressing, water application for deficit irrigation, dripper discharge diameter of wetting, amount of soil moisture content, daily climate data, crop growth monitoring data, green canopy cover measurements, biomass, maize grain yield and residual soil nutrients analysis after crop harvest.

The three replica plots were fully sheltered from rainfall using fabricated wheeled mobile rainfall shelters constructed using steel frames designed to expand to the height of a mature maize crop. The shelter was gladded with 1000 gauge ultra-violet (UV) treated polythene sheet recommended for greenhouse crop production and fitted with small 150mm diameter rubber wheels (Plate 3.2) adopted from the ICRISAT model (Appendix VIII). The rainfall shelter was always wheeled open early in the morning by 6.00 a.m. to expose the maize crop to natural light conditions and avoid shedding throughout all the daylong, and when to cut off rainfall at all times during growing period. The shelter was wheeled back to shed the crop in the evening hours by 7.00 p.m.

Designed drip irrigation system layout was installed and irrigation of the demonstration plots was carried out according to the designed differential treatments (Plate 3.3) based on the consumptive use of water and the irrigation interval of maize crop. Soil moisture regime was regularly measured by sampling at the root zone depth of about 0.3m to monitor the levels of deficit irrigation applied and ensure approximate to the design levels.

Nutrient enrichment of the crop was achieved by top dressing with calcium ammonium nitrate (C:A:N) fertilizer in two split doses applied on the soil surface within the canopy area covered by irrigation water. The first application was done when the maize crop was at knee high (35 days after sowing) and the second dose was applied at near full canopy at the middle of the vegetative stage (60 days after sowing) both doses give a total of the recommended rate of 75kg of fertilizer per acre. The split method of nutrient fertilizer application allows the crop to spread utilization of the nutrients into the stage when the crop is vigorously growing and in demand of available nutrients in the soil. The design application levels of the respective plots were adopted in determining nutrient fertilizer rates of plots. Agronomic practices of weeding, control of pests and diseases and general monitoring were strictly observed throughout the growing period.

Plate 3.3: Deficit irrigation (Drip irrigation) field application system layout (Source: Author, 2015)

3.3.3 Nutrient Fertilizer application levels

Mineral nutrients in plants are part of the important growth response factors that include light, carbon dioxide and water that influence the plant physiological development and yield levels. Soil fabric stores various levels of the nutrients and because of continuous cropping patterns, available amounts may not be sufficient to maintain a healthy crop and therefore application of mineral fertilizer is done to achieve optimal demand level. Soil moisture levels influence the availability and uptake of the nutrients by plant roots and the effect is noticed more distinct in shallow-rooted annual species than deep-rooted perennial species.

Soil sampling and carrying out chemical analysis provided indication of the capacity of soil to supply required nutrients. The nutrients in the soil are required to move to the plant root surface and their mobility is influenced by the soil structure and the root growth. The nutrients elements form the concentration in the soil solution and reach the root surface through movement in the solution, transported by the solution or the roots grow through transport pathways.

Mineral fertilizer was used to provide the necessary controlled application of nutrition for the maize growth according to the results of the initially sampled soil scan and the available nutrient content initially found in the soil assumed to affect all the plots equally and allow the applied content to be the determinant variable. Contribution of residual nutrients in the soil was considered at the end of the growing season.

Fertilizer amounts were calibrated as a fraction of the recommended agronomic application rates of 75 kg per acre for both planting and top dressing fertilizer using digital weighing scale able to read weights up to 2kg. Application of the levels of nutrients applied to individual plots was achieved using resized bottle top cups which could carry the amounts calibrated for the respective plots. During sowing of the maize seeds, predetermined amounts of planting nutrient fertilizer levels were applied to individual plots as presented in Table 3.4.

Table 3.4: Amounts of nutrient fertilizer calibrated application rates per plant

Period of application	**Calendar date of application (days)**	**Amount of fertilizer applied (in grammes) according to the nutrient design level**				
		F=100%	**F=80%**	**F=60%**	**F=40%**	**F=20%**
During sowing (N:P:K)	DOS (15.04.2015)	4.0	3.2	2.4	1.6	0.8
1st Top dressing (C:A:N)	35 DAS (20.05.2015)	2.0	1.6	1.2	0.8	0.4
2nd Top dressing (C:A:N)	60 DAS (15.06.2015)	2.0	1.6	1.2	0.8	0.4

The mineral fertilizer contains Macro- elements comprising 18 % Nitrogen, 46 % Phosphorus and 0 % Potassium and used during sowing to provide necessary nutrition for root and soot development. Top dressing of the maize was done to enhance vegetative growth vigour using Calcium Ammonium Nitrates (C:A:N) and was applied on the surface of the soil around the plant. Macro-elements comprising Nitrogen, Phosphorus and Calcium provided necessary nutrition for vegetative and flower development.

3.3.4. Soil moisture regime and Crop consumptive use of water

Crop water requirement is referred to as the consumptive use of water estimated using the crop evapotranspiration rate (ET_c) and considered equivalent to the level when moisture in the soil is readily available (RAM) to be taken up by the plant. The amount is obtained from the range between the upper limit at field capacity (θ_{fc}) and a fraction of total available moisture that is allowed to be depleted in the soil storage and is estimated at about half way before depletion of moisture attain permanent wilting point (θ_{pwp}). The upper canopy/leaf expansion moisture depletion threshold is marked by the moisture at field capacity when depletion is at 0 %. Soil analysis of the project site was found to be clay loam soil type dominant and its moisture regime at field capacity is at 35.2 vol% and at permanent wilting point is at 18 vol% and these were also reported by Cuenca (Cuenca, 1989). Field measurements of soil moisture amount in the demonstration plots and for plant consumptive use was monitored through sampling and laboratory determination by gravimetric method.

Soil moisture regimes for maize crop water requirement was divided into the four growth stages comprising the initial, development, mid-season (maximum growth) and late season (senescence) stages, each stage is controlled by crop coefficient (K_c) factors that determine the amount of moisture consumed. Crop sensitivity to water is different in the four growth stages where initial and maximum growth stages were found to adversely affect crop growth vigour and the ultimate yield when the crop was subjected to deficit irrigation. The crop growth in the initial stage is undergoing delicate root and shoot development sensitive to diminished water regimes while the crop at maximum growth stage is tussling and maturing and water demand is at the peak for the crop. Regulated amounts of deficit irrigation water were only applied during development and senescence stages. Maize crop coefficient factors (K_c) for the four growth stages were generated using the procedure given in *Steduto et al., 2009* (FAO No. 66) and the results are tabulated in Table 3.5.

Table 3.5: Maize crop growth stages coefficient factors (K_c)

Growth stages	Initial stage	Development Stage						Mid-season (maximum growth)	Late season (Senescence) stage		
Length (days)	30	55						65	30		
Decade (days)	0 - 30	31-40	41-50	51-60	61-70	71-80	81-85	86-150	151-160	161-170	171-180
K_c	0.60	0.68	0.76	0.88	1.0	1.08	1.16	1.2	1.08	0.72	0.35

Deficit irrigation levels applied were a percentage of the actual crop consumptive use of water when soil moisture is readily available for plant use to meet the requirement for transpiration, soil evaporation and losses through drainage.

The amount of soil moisture available may be quantified based on its weight (mass basis), volume (volumetric basis) and the equivalent depth of available soil water. The three terms are interrelated and important physical properties in the soil-plant-water relationships and when analyzing water balance within the crop rooting zone.

The terms are mathematically defined as follows;

$$\text{Mass water content } (\theta_m) = \frac{\text{mass of soil water (Mw)}}{\text{mass of dry soil (Ms)}} \times 100\ (\%) \qquad (3.1)$$

$$\text{Volumetric water content } (\theta_v) = \frac{\text{volume of soil water (Vw)}}{\text{Bulk volume of soil (Vt)}} \times 100\ (\%) \qquad (3.2)$$

The volume of soil water (V_w) available is a product of the wetted surface area and depth of water, while the bulk volume of soil (V_t) is also a product of the wetted surface area and depth of soil under consideration. The wetted surface area under consideration cancel out in volumetric water content (θ_v) and the equation reduces to an equivalent depth (mm or m) of the soil water per unit depth (m) of the soil and the relationship is redefined as:

$$\text{Equivalent depth of soil water } (d_{ew}) = \frac{\text{depth of soil water (dw)}}{\text{depth of bulk volume of soil (Dt)}} \quad \text{m/m} \quad (3.3)$$

The equivalent depth of soil water in mm (water) per unit depth (m) of bulk soil depth is equal to 1000 times volumetric water content (θ_v) in m (water) per unit metre of soil depth.

The value of the equivalent depth of soil moisture (mm or m) per unit depth (m) of the plant root zone is determined by the product of the soil bulk density (ρ_b) and mass water content (θ_m) by considering the density of water (ρ_w) equal to 1 g/cm^3 and given by dividing equations 3.1 and 3.2 to give equation 3.4:

$$\text{Volumetric water content } (\theta_v) = \text{Soil bulk density } (\rho_b) \times \text{Mass water content } (\theta_m) \quad (3.4)$$

The presentation of soil moisture content using mass basis is applied because of convenience in the laboratory measurement of weights of wet soils and dried samples in the oven. Calculated equivalent depth of the soil water is then used in scheduling deficit irrigation design and monitoring the amount of soil moisture retained in the soil plant root zone during depletion process.

Soil texture and structure determine the amount of water that a soil can hold. When soil is saturated with irrigation water, gravitational forces cause rapid downward drainage of loosely held water and decreases the soil moisture content to a level when the forces holding soil moisture balances the force of gravity. The retained moisture is favourable for plants abstraction by the roots suction strength and utilized through imbibing by the roots for use in the manufacture of plant food through the process of Transpiration (T) and another portion is lost into the environment by Evaporation (E). The two processes occur simultaneously and represent the amount of water that is required by plants for their physiological growth and referred to as Evapotranspiration (ET) or the consumptive use of water by plants. The resulting level of amount of water in the soil after gravitational drainage mark the upper limit of soil moisture held in the soil porosity and referred to as moisture at field capacity (θ_{fc}). Initial depletion of moisture by the crop in the demonstration plots began from the field capacity level to different critical levels depending on deficit irrigation design before next scheduling of irrigation take place. The amount of water applied into the plant roots is dictated by the storage capacity of the soil and the rate of water intake (infiltration) during irrigation. The amount was quantified using the water budget technique as applied by AquaCrop model in balancing its water interaction between the soil-plant-water-and the atmosphere.

When plants take up water from the soil, its volumetric amount reduces progressively while soil matric forces holding the moisture increase in response of the depletion indicating an increase in the strength required by plants to abstract the soil moisture. As the moisture content in the soil is diminished and depending on the type of soil and crop tolerance to moisture stress, the lowest limit when a crop no longer respond to moisture uptake is referred to as the moisture at permanent wilting point (θpwp). At permanent wilting point the soil is dry and the available moisture content is so tightly held by matric forces that plant roots are no longer able to extract the water and plants die.

Calculation of root zone soil water content, θ_{rz} (mm of water) in the demonstration plots was derived from the product of measured equivalent depth, d_w of soil water (mm/m) using Equation 3.2 and the crop rooting zone depth, D_{rz} (m) as presented in Equation 3.5.

$$\theta_{rz} = 1000 \text{ x } \theta_v \text{ (mm/m) x } D_{rz} \text{ (m)} \qquad (3.5)$$

When moisture content in the soil is at field capacity (θ_{fc}), the value used for θ_v is θ_{fc}. Moisture content of soil sampled in the demonstration plots were determined using the gravimetric mass basis method and converted into the volumetric basis for simulation application in AquaCrop model.

3.3.5 Irrigation scheduling and Deficit irrigation of Maize crop

Average levels of maize crop water consumption for the entire growing season stages from date of sowing (DOS) to senescence period was derived from the climate file developed using historical daily environmental weather parameters of temperature, humidity, wind speed, sunshine and rainfall obtained from Kapsoya meteorological station readings located about 5km from the demonstration site. Reference crop evapotranspiration values were calculated using ET_o calculator based on Penman-Monteith equation for ET_o (*Allen et al., 1998*) incorporated in AquaCrop model.

Average decade (10-day) values of crop consumptive use of water by maize were generated using Equation 3.6 (*Steduto et al., 2012*) and the growing season irrigation data.

$$ET_c = K_c * ET_o \tag{3.6}$$

The amount of water abstracted by maize (ET_c) from the soil must be replenished and equal to the net depth (I_{net}) of irrigation application. Scheduling of when to irrigate was achieved by comparing the daily consumption and the amount of moisture readily available in the soil (RAM). The amount is a fraction of total available moisture that is allowed to be depleted in the soil storage given in Equation 3.7

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$$RAW = p * TAM \tag{3.7}$$

The fraction denoted by letter "p" in Equation 3.7 is about 60% for maize crop (Geerts & Raes, 2009). Under full irrigation strategy every irrigation schedule refills the soil moisture to its field capacity and compensated for losses by using application efficiency (ξ) of 80% recommended for drip irrigation system to allow gross irrigation application amounts denoted by I_{gross}.

Deficit irrigation strategy refills according to the fraction of readily available moisture (RAM) being considered. The research monitored soil moisture by depletion rates by applying three alternative options that included; the average decade crop Evapotranspiration (ET_c), soil sampling moisture content measurement by gravimetric method and the irrigation interval (I_I) strategies given by Equation 3.8. Predetermined duration of the irrigation intervals were obtained according to deficit irrigation percentage moisture levels denoted by, α of 100, 90, 80, 65 and 50 considered during the design. Moisture application level of α =100% implies the irrigation interval function is considering full irrigation strategy.

$$\text{Irrigation Interval, } I_I \text{ (days)} = \frac{\text{Net Irrigation applied (Inet)}}{\alpha * \text{ETc}} \qquad (3.8)$$

Different research plot configurations resulted in different intervals of irrigation and hence different irrigation duration (I_t) that lead to different stress levels induced to the maize crop by deficit irrigation.

The only source of water used for the requirements of growing of maize in the research plots was supplied from a controlled drip irrigation system using shallow well water pumped into an overhead tank placed at a raised platform 3m high. Rain water was cut-off from reaching the maize crop in the research plots by using a constructed mobile rainout shelter and to guarantee only irrigation water is the source of water into the plant roots in the soil. Known amounts of water were applied at predetermined interval periods and according to the deficit irrigation levels of the research design. Monitoring of the amount of moisture stored in soil was done after every irrigation schedule and subsequently in between the interval periods.

Applicable values of moisture balance in the soil storage and the irrigation intervals for maize in the research plots are based on AquaCrop model generated design. Soil moisture sampling for gravimetric measurement was carried out regularly to a certain reliability of deficit irrigation applied to the respective plots. Soil moisture data obtained for the entire crop growing season are tabulated in Appendix III.

3.3.6 AquaCrop model generation of Irrigation scheduling

Generated irrigation scheduling plan for the five deficit irrigation application water levels in the research is presented in Table 3.7 according to the soil moisture depletion thresholds given in Table 3.6.

The model simulation results of net application depth (mm) based on the above deficit irrigation plan and the numbers of irrigation events are presented in Table 3.7. The proportion (%) of total amount of irrigation does not compare with the deficit irrigation design because only during the development and late season stages of the crop growth cycle was the strategy applied. Both the initial and mid-season stages received normal amounts of irrigation water guided by the upper limit threshold of leaf expansion growth of half-storage depletion of readily available water.

Table 3.6: Soil moisture depletion thresholds as a fraction of readily available water (RAW)

Crop Growing Stage	**Length (days)**	**Deficit irrigation application plan (% RAW)**				
		W_{100}	**W_{90}**	**W_{80}**	**W_{65}**	**W_{50}**
Initial	30	50	50	50	50	50
Development	55	50	55.5	62.5	76.9	100
Mid-Season	65	50	50	50	50	50
Late Season	30	50	55.5	62.5	76.9	100

Table 3.7 (a): Generated drip irrigation schedules of net application

Day of g rowth period	Date	Irrigation simulation of net application depth (mm)				
		W_{100}	**W_{90}**	**W_{80}**	**W_{65}**	**W_{50}**
1	15 April		14.5	14.5	14.5	14.5
2	16 April	22.5				
10	24 April					
11	25 April					
13	27 April					
16	30 April		23.0	23.0	23.0	23.0
18	2 May	25.0				
29	13 May					
42	26 May					
44	28 May					
46	30 May					
47	31 May	47.7				
48	1 June		53.9			
52	5 June				71.3	
60	13 June					
64	17 June					
66	19 June			85.2		
72	25 June					
73	26 June	56.1				
77	30 June		63.8			
81	4 July					109.5
83	6 July					
86	9 July					
88	11 July				56.4	
91	14 July	55.8				
95	18 July		56.9			
96	19 July					
101	24July			56.8		
102	25 July					57.7
104	27 July					
105	28 July					
106	29 July				56.7	
108	31 July	55.9				
111	3 August					
112	4 August		56.4			
117	9 August					
118	10 August			57.5		
119	11 August					56.6

Table 3.7 (b): Generated drip irrigation schedules of net application

122	14 August					
123	15 August				58.0	
124	16 August	54.7				
127	19 August					
128	20 August		56.0			
133	25 August			55.8		
134	26 August					55.2
136	28 August					
137	29 August				53.7	
138	30 August	53.9				
139	31 August					
141	2 September					
142	3 September		54.3			
147	8 September			53.0		
149	10 September					55.1
153	14 September	54.4				
156	17 September					
160	21 September		21.7			
161	22 September				41.1	
165	26 September					
166	27 September					
169	30 September	Irrigation cut-off				
180	11 October	Maturity (Harvest)				
Total amount of irrigation		426.0	400.6	394.8	388.5	371.6
% of deficit irrigation		100	94.0	92.6	91.1	87.2
No. of irrigation events		9	9	7	8	7

3.4. Data Collection

3.4.1 Introduction

The research study of the demonstration plots aimed at obtaining data required for running AquaCrop model for simulating water productivity of maize crop. The relevant information investigated at the site included: soil characteristics, weather data, crop data, applied moisture and fertilizer to the crop, crop canopy cover, crop yield, above ground dry matter and the residual soil nutrients after crop harvest. Collection of the required data was carried out using standard calibrated equipments from certified public institutions having regularly calibrated equipments and where needed, professional experts with the relevant expertise and experience were consulted.

3.4.2 Soil type and its physical properties

The soil profile provides the physical properties of the site and its capacity to store both moisture and nutrients needed by the plants for their growth. Representative soil sampling pits in the research site were excavated on each of the replica plots and analysis was carried out to establish the number of horizons and dominant soil type in its profile, variations of its bulk density with depth and its capacity to hold soil water available for plant consumptive use. Investigations on the soil properties measurement were done using equipments from the Ministry of Public Works Regional Laboratory in Eldoret. Soil bulk density (ρ_b) was measured at different depths of the profile using sand replacement method (Plate 3.4) and the site soil moisture content at field capacity (θ_{fc}) was estimated by carrying out gravimetric measurements of the soil moisture content (mass basis) of the soil which had undergone over 24 hours drainage after being saturated (Table 3.8).

Infiltration tests were also carried out on four different sites which are representative of the demonstration plots and the results were similar with an average infiltration rate of about 5.0 mm per hour. The results indicated the texture of top soil is Clay mixed with organic matter and humus commonly known as the red volcanic clays therefore categorized as clay loam in the design and scheduling of the irrigation system and during calibration of the AquaCrop model.

Table 3.8 (a): Soil physical properties at Saroiyot project site

Soil Profile Depth (mm)	Plot Replica No. R-1			Plot Replica No. R-2			Plot Replica No. R-3		
	Moisture Content (%)	Dry Density (kg/m^3)	Bulk Density (kg/m^3)	Moisture Content (%)	Dry Density (kg/m^3)	Bulk Density (kg/m^3)	Moisture Content (%)	Dry Density (kg/m^3)	Bulk Density (kg/m^3)
150	35.6	1092	1480.7	35.7	1113	1510.3	34.4	994	1336
150	32.2	1172	1549.4	32.1	1226	1619.5	33.6	1233	1647.3
150	31.0	1198	1569.4	30.7	1150	1503.0	34.1	1300	1743.3
150	31.0	1234	1616.5	28.0	1343	1719.0	36.4	1315	193.7
150	30.6	1262	1648.2	33.6	1390	1857.0	20.1	1469	1764.3
150	22.3	1399	1711.0	26.6	1333	1687.6	22.1	1296	1582.4

Table 3.8 (b): Top soil physical properties at Saroiyot project site

Soil Type	Bulk density (kg/m^3)	Infiltration Rate (mm/Hr)	Moisture Content at Field capacity, θ_{fc} (%)	Moisture Content at Permanent wilting point, θ_{pwp} (%)
Clay Loam	1442.3	5	35.2	18

Plate 3.4: Excavated Soil sampling pit at the demonstration site (Author, 2015)

3.4.3 Field Canopy Cover Measurements

Canopy cover (CC) expansion was measured at midday and in the absence of the interfering clouds by considering the projected area of the soil surface covered by the green canopy of maize as a fraction of the unit ground surface area considered. The portion of crop green canopy cover projected on the soil surface by the crop leaves and the stalk at noon was sketched out on brown paper (Plate 3.5) and area analyzed using geometrical square-grid method. A sheet of brown paper with the width equal to the inter-row spacing of maize crop was laid and the edge of the shaded area was drawn on the paper. The shaded fraction of the total plot area occupied by the crop was monitored by repeating the measurements approximately every decade and depending on the available clear sky. Areas calculated were documented as percentage of the unit plot occupied by the maize crop considered.

Maximum green canopy cover (CC_x) achieved for 100% irrigation was used in the calibration of the AquaCrop model. Field canopy cover measurements data are tabulated in Appendix VI and values of maximum canopy cover (CC_x) from the respective treatments are tabulated in Table 3.9. Bare soil during sowing had zero canopy cover but initial canopy cover after emergence was recorded as $CC_o = 0.27\%$ and during maximum vegetative crop development gives maximum development of canopy. Canopy senescence refer to canopy die off and sets in as soil moisture stress level drops below leaf expansion threshold and when the crop reach maturity. Input parameters on canopy cover development required by the model during calibration include; initial canopy cover (CC_o), canopy growth coefficient (CGC), maximum canopy cover (CC_x) and canopy decline coefficient (CDC).

Plate 3.5: Green Canopy cover measurement of the projected shade at noon (Source: Author, 2015)

The model calculation and simulation of canopy cover consider the period of crop development from the day of sowing and values of the coefficients specific to the crop. Depending on the crop population controlled by planting spacing chosen, initial canopy cover (CC_o) was set by the model. Canopy development follows exponential growth controlled by its canopy growth coefficient (CGC) to full cover (Farahani, 2009) and the trend is estimated by the equation 3.9.

$$CC = CC_o \, e^{CGCt} \tag{3.9}$$

During canopy senescence, exponential decay is controlled by canopy decay coefficient (CDC) estimated by the equation 3.10.

$$CC = CC_x - (CC_x - CC_o)\, e^{-CGCt} \quad (3.10)$$

Table 3.9: Values of maximum Canopy cover (CC_x) data of the three replica plots

Moisture application level (F_{100})	Maximum Canopy cover (CCx,%)	Days after sowing (DAS)
W_{50}	73.8	106
W_{65}	85.0	106
W_{80}	82.5	106
W_{90}	69.6	106
W_{100}	80.9	106

3.4.4 Residual Soil Nutrients measurements

Soil mineral elements are found in the soil in various amounts depending on the natural source and/or fertilizer application increase and remain in the soil if the planted crop does not exhaust in abstraction during its nutritional requirements. The amount of residual soil nutrients contribute in supporting any vegetative growth and also transported by drainage water during infiltration and/or surface runoff into the natural waterways. The level of residual soil nutrients in the research plots was evaluated by carrying out soil sampling at the level of roots in each of the individual plots after maize crop harvest and scanning the amounts of the main nutrients (N,P,K,Ca,Mg,Mn,pH) believed to contribute more in crop production and affect environmental conservation. The results of the soil analysis carried out at Kenya Tea Research Foundation - Kericho (Appendix III) shows that sufficient amounts of nutrients are left in the soil after crop maturity and harvesting. Increased levels of unutilized nutrients contribute to increased chemicals in the soil that lead to adverse conditions such as acidification and may be translocated into large water masses and cause eutrophication and vegetative growth such as the water hyacinth.

3.4.5 Field Maize crop biomass and Grain yield measurement

The end of senescence stage occurred after 180 days after sowing (DAS) when the maize cob, the leaves and the stalk had dried and irrigation was no longer necessary but ready for harvest.

Non-destructive method was adopted in determining biomass data from the demonstration plots and was measured by weighing the above ground harvested dried maize grains and the stalk dry matter obtained by cutting and weighing sun dried Stover (stalk) and the weight of dried cob. Harvesting of the maize grains was done by cutting the maize cob (ear) for each plot to separate from the Stover (stalk) and shelled to separate the Kernels (grains) from the close-up cob. The grains were sun dried to an average moisture content of 13.5% (dry basis) recommended for commercial maize food processing and confirmed using public works oven. The stalk above the ground were cut into pieces of about 30 cm long and dried inside the greenhouse to guarantee continuous drying and monitoring to minimize losses by pests and rodents. The amount of dry matter for the respective demonstration plots were weighed using an electric scale after confirming that further drying caused no further change.

Biomass production is considered to include: the roots, above ground maize crop stem, leaves, flowers and the grain yield. AquaCrop model core concept of simulation is Biomass Water Productivity (WP) that relates the cumulative amount of water used by the crop during its transpiration and the total amount of biomass produced. The conservative crop parameter has the units of biomass (kg) per unit volume (m^3) of water transpired (*Steduto et al, 2007*). AquaCrop model translates crop water productivity into a normalized biomass water productivity (WP*) parameter given as the slope of biomass production versus cumulated normalized transpiration given in Equation 3.11.

$$WP^* = \frac{\text{Biomass}}{\sum\left(\frac{\text{Tr}}{\text{ETo}}\right)} \qquad (3.11)$$

Both the normalized biomass water productivity and transpiration coefficients were used in calibrating the model when comparing simulated values of biomass and yield with the measured field data.

A similar concept not used by the model is the water use efficiency (WUE) that considers water used by the crop for evapotranspiration (ET) in relation to the amount of yield (Y) produced. The parameter is an efficiency indicator that quantifies the output yield as a result of the investment made on the input water applied. The units of WUE are given as the amount of Yield (kg) per unit volume (m^3) of evapotranspiration water. The amount of water consumed in WUE (=WP_{ETc}) considers both transpiration and the soil surface evaporation unlike in the WP that considers only transpiration.

Soil moisture stress caused by the chemical effect in the nutrient fertilizer affect biomass production by influencing canopy cover development where transpiration takes place and the crop water productivity. The research results on grain yield and biomass production was shown to be affected by different levels of nutrient fertilizer applied.

The research emphasis was to establish maize crop yield response to deficit irrigation water under varied levels of nutrient fertilizer applied during seed sowing and top dressing the crop at the growth development stage when demand of plant nutrients is high. Harvested product was the maize grains that constituted the crop yield and AquaCrop model simulates its value as a function of amount of Biomass produced.

3.5 Data Analysis

Monitoring, collection and analysis of raw data from the experimental plots began soon after the date of sowing of the maize crop. The impetus of the research design was the weather data that was analyzed and uploaded into the AquaCrop model input file formats. Processed weather data was used to calculate Reference Evapotranspiration (ET_o) required by the model to develop the local area climate file needed during simulation processes. Initial soil sampling and analysis was carried out before sowing in order to obtain recommendations of the right amount of fertilizer nutrients to apply (Table 3.4). Nutrient fertilizer levels were applied during sowing and when top dressing in split amounts of two equal portions and the levels of deficit irrigation moisture were applied during the development growth stage and last season (Senescence) stage. Canopy cover (CC) measurement data were analyzed for every decade and used to derive coefficients needed during simulation by the model. Above ground biomass data, grain yields, residual nutrients obtained from soil analysis and yield gap analysis were carried out at the end of the growing period.

The design levels of applied moisture and nutrient fertilizer were used to analyze the trends of dependable variables for interpretation of their correlations and solutions of the identified research problems. Deductions and scrutiny of collected raw field data were achieved using a combination Microsoft Excel and the Statistical Package for Social Scientists (SPSS) software to elaborate on the accuracy levels of the results simulated by AquaCrop model. Both descriptive and inferential statistics were used to explore the data sample and measures of the quantitative analysis and generated graphical representation of the results. Explanations were given of how moisture regime and the nutrient fertilizer levels applied affected the crop biomass and yield and through comparisons enabled summaries across the plots data that enabled the results of obtaining the optimum values that gave the optimum yield as simulated by the model.

3.5.1 Statistical Analysis of Grain Yield of Maize

Demonstration plots data on grain yield of maize from the three replica plots were analysed to establish the response to various levels of both deficit irrigation and applied nutrient fertilizer during sowing and when top dressing. The data were evaluated for normalcy by considering their frequency distribution using a histogram. Estimate of central tendency was established using the mean and the spread of grain yield values around central tendency (dispersion) was achieved using the range and standard deviation. The shape of the resulting distribution of grain yield data was analysed by considering the values of kurtosis statistics and skewness values.

Results of grain yield of maize of the three replica plots were checked for their significance and possible agents of variations identified using Analysis of Variance (ANOVA).

Descriptive statistics were used to check the distribution of deficit irrigation design levels of 50%, 65%, 80%, 90% and 100% as an impetus to the study of the relationship of different moisture content levels applied and the average yields in the three replicas respectively.

Individual trends of grain yield in the respective plots were analysed to establish their variations due to the applied deficit irrigation moisture levels. The effect of the moisture content levels were derived by considering the trend of the combined grain yield averages of the respective deficit irrigation levels.

Distribution of the nutrient fertilizer levels selected during the design of 20%, 40%, 60%, 80 and 100% were subjected to the descriptive statistics and applied to study their effect on the grain yield of maize. The influence of the combined fertilizer levels applied during both sowing and when top dressing was presented and their trends analysed. Their effect on the respective averages of grain yield was evaluated and causes of variation were considered.

Confirmatory tests of dependency by dry maize grain yield on the independent moisture and nutrient fertilizer variables were carried out using chi-square statistic (χ^2) at $\alpha = 0.05$.

3.5.2 Optimal level of moisture and nutrient fertilizer combinations for maximum yield

Analysis of variance (ANOVA) was employed to derive the optimal level of moisture and nutrient fertilizer application in the soil that results in maximum grain yield of maize. Data on grain yield were grouped into three categories of low yields (< 700g), average yields (700 < Yields <1400g) and highest yields (>1400g) of approximate equal number of data units. Distribution of data in each group was analysed and values of maximum moisture and fertilizer levels respectively that apply were determined. The overall goal of the research was to simulate optimal yield level of maize under deficit irrigation and different fertilizer nutrient levels using AquaCrop model. The optimal values of moisture and fertilizer obtained by statistical analysis were used during validation of the model simulation.

3.5.3 Correlation of residual nutrient levels to grain yield, moisture and nutrient fertilizer levels

The demonstration plots were set up in a farm ploughed and harrowed annually using conventional disc ploughs and disc harrows respectively and has been growing maize for over two decades. The research investigated the amounts of residual nutrients present in the soil after harvesting the maize crop. Representative samples of soil from each of the 75 plots were analysed for the residual amounts of Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), Manganese (Mn) and the soil pH and the results are tabulated in Appendix IV. The analysis considered amount of quantities and their significance in the soil in the absence of the crop after harvest. Inference statistics were used to classify the results of analysis into three categories of significant, moderate and low effects. Numerical elements of NPK applied during sowing were compared with the initial values present in the soil before date of sowing and the effects of the amounts added during sowing. Calcium (Ca) was added into the soil during top dressing and its effect was investigated in the residual amounts.

The interaction of plant and soil result in abstraction of soil moisture and nutrients required for normal plant growth and grain yield production. Amount of residual nutrients present in the soil may occur from unfavourable conditions of abstraction, translocation away from the plant roots or accumulation from previous years of application.

The analysis further correlated amounts of residual nutrients present in the soil with the harvested grain yield, the levels of deficit irrigation and nutrient fertilizer treatments applied. Pearson's R quantitative evaluation between the variables was applied through SPSS. Graphical scatter plots were used to study the variations of the nutrients in response to changes of soil pH and the amounts of soil colloids (clay and humus) which are repositories of nutrients and moisture in the soil.

3.5.4 Correlation of biomass to grain yield, treatment levels of moisture, nutrient fertilizer and the residual nutrients

The research data on biomass comprised the above ground maize crop stem, leaves, flowers and the grain yield. AquaCrop model considers above ground biomass for cereals. Measurements of biomass amounts in the respective treatments in the demonstration plots were analysed for their correlation with the grain yield, levels of both deficit irrigation and applied nutrient fertilizer and the residual nutrients measured. Descriptive statistics of the data were examined using the statistical package for social scientists (SPSS).

3.6 AquaCrop model and calibration of its simulation input parameters

AquaCrop is a mathematical model developed by FAO to simulate crop response to water using unique crop-specific parameters. The model simplifies expressions of complex system of interaction between the plant and soil under a water scarcity environment and specific climatic conditions by using a relatively small number of commonly available input parameters that are selected and tuned for different crops and soils but maintain accuracy of plant physiological and soil water budget processes (FAO, 2017). The model was developed from running simulations of several crop varieties for several years under different field management scenarios and environments. Field experiment results at Saroiyot farm were used to calibrate and validate the model parameters adjusted during simulations to assess yield response to water for the maize crop.

Calibration of AquaCrop model was done by adjusting its input parameters in order to achieve predications of better fit of simulated data with the experimental data. Values of the observed experimental results were used as inputs in fine tuning process and model simulation to predict the output of yield, biomass, canopy cover and soil water content. Predicted output was compared with the experimental data and their difference minimized by adjusting repeatedly the amount of moisture applied until the results were close. Individual input file parameters of crop, irrigation and field management were calibrated before running the model to simulate the experimental data.

3.6.1 Calibration of AquaCrop model input parameters

The algorithms that drive the model have been developed and specified as input parameters and govern all the physiological requirements of crop production. The parameters are specific to prevailing local conditions and are stored and tuned during calibration in the following model files: climate, crop, soil, field and irrigation management. Running the model involves specifying inputs of prevailing environmental conditions and field data in the files and will simulate the effect on the output generated biomass, crop yield, canopy cover, soil water content and its performance indicator of water productivity (FAO, 2016).

AquaCrop model scheme of operation requires weather, rainfall and carbon dioxide (CO_2) data and the interaction processes are driven by the link to the sun as the source of energy. Daily values of weather data used include: minimum and maximum air temperature, rainfall, wind speed measured at 2 m above ground surface, solar radiation, mean relative humidity (RH) and mean annual CO_2 concentrations. During conceptualization and design of the experimental plots, climatic data for 34 years (1981-2014) from Kapsoya Meteorological station were used to run ET_o Calculator and generate daily values that are exported into the model. Created ET_o data file in the model is combined with the rainfall file, temperature file and mean annual CO_2 concentration file to create Saroiyot Climate file. Climate data collected using a mini-weather station at Saroiyot farm experimental site was used during calibration and validation of the model.

Crop parameters comprise of real time field measurements during the research period from date of sowing the maize crop (DOS) up to the period of grain harvesting. The important calendar dates for the maize crop required by the model include; date of sowing (DOS), date of emergence, date of maximum canopy cover, duration of flowering, start of senescence date to maturity (Table 3.10). Maize crop coefficients and thresholds used by the model are core to the model and were obtained from long term evaluations during development.

Growth of the effective rooting zone length was projected at the rate of 2.5 cm/day (FAO, 2017). Above ground biomass was measured using the non-destructive method at the end of maturity of the maize crop through weighing and both the dry grain yield and maize crop harvest index (HI) were determined.

Table 3.10: Maize crop growing stages schedule calendar

Crop Growth Stages	Date Sowing	Date of Emergence	Date of Maximum Canopy cover	Duration of Flowering (days)	Start of Senescence date	Date to maturity
Schedule dates	15-04-2015	22-04-2015	22-07-2015	30	11-09-2015	11-10-2015

Crop parameters that control canopy cover development, biomass, crop yield and the harvest index were calibrated by fine tuning their most influencing parameters respectively. Canopy cover development was monitored by the rate of expansion controlled by canopy growth coefficient (CGC) and its rate of dying off at the end of the growing season controlled by the canopy decline coefficient (CDC). The two coefficients were fine-tuned until the simulated canopy cover (CC) was closely comparable with the field observed values.

The following crop specific coefficients were generated during model calibration: crop coefficient for transpiration at full canopy cover, soil water depletion thresholds for inhibition of leaf growth and stomata conductance, and acceleration of canopy senescence (*Heng et al 2009, Hsiao et al 2009*). Water productivity and transpiration crop coefficients were used to calibrate biomass and crop yield by comparing the simulated water use efficiency (WUE) with the observed data from the field experiments. Harvest Index (HI) was adjusted repeatedly until simulated yields compare closely with the observed yields.

Field management input parameters considers fertility levels, crop residue and soil surface practices, including mulching practices. Soil fertility levels influence canopy cover and the model categorize into non-limiting, high, moderate and poor.

AquaCrop model has two options on water management, either as a rain-fed (no irrigation) or an irrigated crop production. Irrigation option considers water application to field capacity (full irrigation) or deficit irrigation. Water application method used by the model is selected from one of the following irrigation systems; Sprinkler, Surface (Basin, Furrow and Border) and Drip irrigation. The methods are differentiated by the model by the fraction of the soil surface wetted during irrigation. Irrigation file input parameters are based on the option of simulating to either apply net irrigation requirement or develop an irrigation schedule.

3.6.2 Validation of AquaCrop model

Observation and measurements of field data were used to validate the results of the model simulations. Measurements of canopy cover, biomass, and soil water content were uploaded into the model in order to simulate the results of maize water productivity.

3.6.3 AquaCrop model calibration and validation matrix of the independent variables

Calibration and validation of the model was carried out using the observed field data measurements of maize grain yield, canopy cover and soil water content of the reference plot ($F_{100}W_{100}$) and the plots of variable nutrient fertilizer under no moisture stress condition (W_{100}) given by $F_{80}W_{100}$, $F_{60}W_{100}$, $F_{40}W_{100}$ and $F_{20}W_{100}$. Summary of the procedure is tabulated in the layout matrix given in Table 3.11

Table 3.11: Calibration matrix of AquaCrop model

	Calibration	Validation			
Reference (controlled) plot	$F_{100}W_{100}$	$F_{100}W_{90}$	$F_{100}W_{80}$	$F_{100}W_{65}$	$F_{100}W_{50}$
Variable nutrient fertilizer plots	$F_{80}W_{100}$ $F_{60}W_{100}$ $F_{40}W_{100}$ $F_{20}W_{100}$	$F_{80}W_{90}$ $F_{60}W_{90}$ $F_{40}W_{90}$ $F_{20}W_{90}$	$F_{80}W_{80}$ $F_{60}W_{80}$ $F_{40}W_{80}$ $F_{20}W_{80}$	$F_{80}W_{65}$ $F_{60}W_{65}$ $F_{40}W_{65}$ $F_{20}W_{65}$	$F_{80}W_{50}$ $F_{60}W_{50}$ $F_{40}W_{50}$ $F_{20}W_{50}$

3.6.4 AquaCrop model calibration of the soil fertility module

Prediction of maize grain yield due to variable soil fertility is achieved by the model by comparing a reference non- fertility stressed field with a stressed condition according to the prevailing fertility level. Calibration of the soil fertility module involves variation of specific crop parameters as a proportion of the reference plot data presented in Plate 3.6.

Soil fertility stress from 5% to 95% was considered during tuning the model for the stressed condition crop parameters. Adjusted values of maximum canopy cover (CC_x), days after sowing (DAS), canopy growth coefficient (CGC), canopy decline coefficient

(CDC) and biomass water productivity (WP*) are used for tuning the calibrated AquaCrop model inorder to predict new levels of maize grain yields.

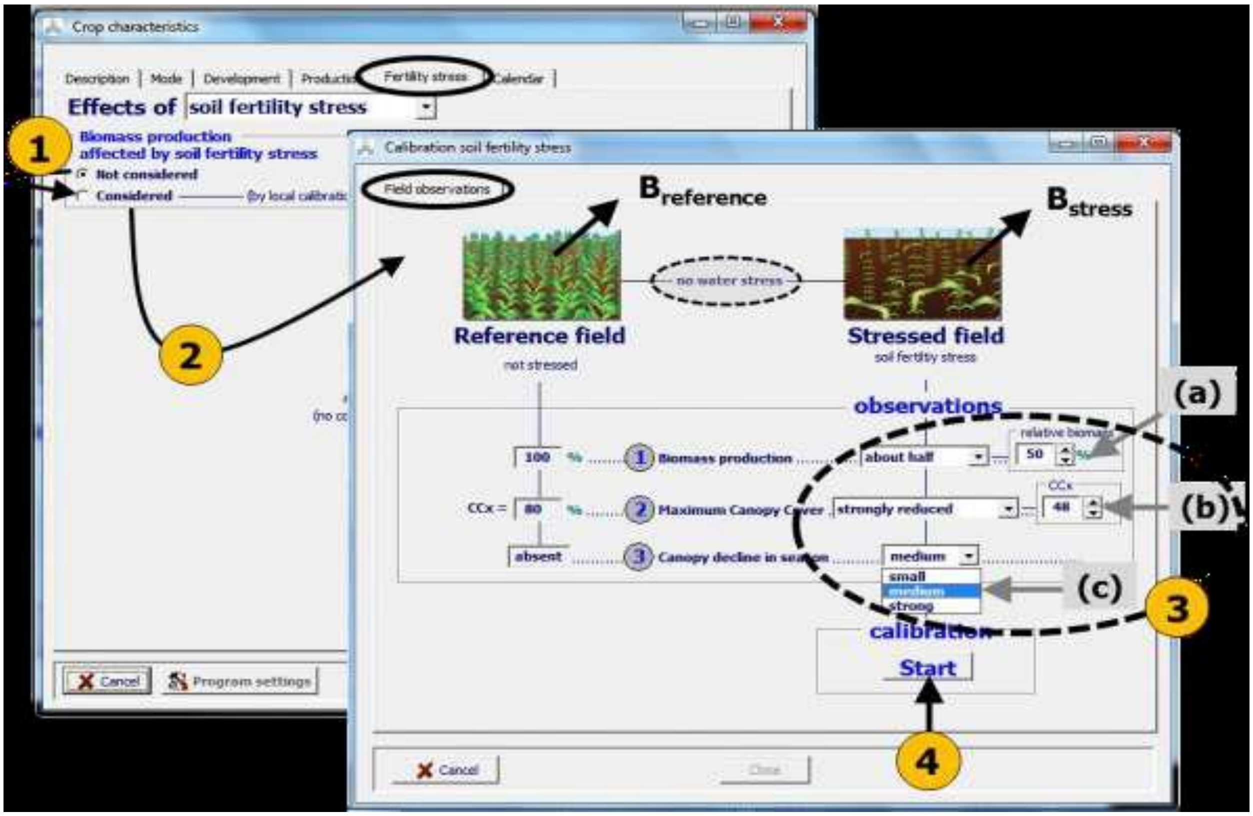

Plate 3.6: AquaCrop model soil fertility stress calibration module (FAO, 2017)

CHAPTER FOUR

RESULTS

4.1 Introduction

Data was collected from demonstration plots set up at Saroiyot farm (75 plots) and divided into 3 replicas and each replica had 25 plots which had variations, in percentage of moisture and fertilizer nutrients applied (Moisture: 50, 65, 80, 90, 100 and Nutrients: 20, 40, 60, 80, 100). Each of the 25 plots had unique combination of moisture and nutrient randomly allocated where observations of the results were independently carried out.

4.2 Response of maize yield to various levels of moisture and nutrient fertilizer applications

Field data matrix of dry maize grains and biomass are presented for the 75 demonstration plots and the results are tabulated in Table 4.2 (a) to (f).

The outputs from the analysis were obtained by subjecting them to statistical explanations and inference.

4.2.1 Average grain yield of maize from the demonstration plots

At maturity harvested dry grain yield data of maize from the entire plots of the three replicas were examined and subjected to the descriptive statistics presented in Table 4.1.

Table 4.1: Descriptive Statistics of grain yield of maize (grammes) per plot

N	Minimum Statistics	Maximum Statistics	Mean Statistics	Standard Deviation statistics	Skewnesss		Kurtosis	
					Statistics	Standard Error	Statistics	Standard Error
75	305	2033	1198.17	368.043	- 0.007	0.277	- 0.057	0.548

The findings of individual plots indicated that the farm had an average yield of 1198.17g with the minimum yield being 305g and a maximum yield of 2033g. The data had a Skewness value of -0.007. This value was not more than twice the standard error hence it was considered to be symmetrical and given in Figure 4.1. The data had a Kurtosis statistic of -0.057 which is between the acceptable range of -3 and 3 to indicate that data were normally distributed. The data were further displayed using the Normality Tests (Q – Q Plot) given in Appendix VII.

Table 4.2 (a): Harvested grain yield (Y) data measurements of the three replica plots

Deficit irrigation water application levels	Harvested grain yield measurements for the respective nutrient fertilizer application levels and replica plots (kg/m^2)														
	F=20%			F=40%			F=60%			F=80%			F=100%		
	R-1	R-2	R-3	R-1	R-2	R-3	R-1	R-2	R-3	R-1	R-2	R-3	R-1	R-2	R-3
W=50%	1.081	0.905	0.643	0.670	0.653	0.637	1.170	0.667	0.739	0.687	0.740	0.478	0.951	0.562	0.612
W=65%	0.963	0.767	0.352	0.867	0.791	0.726	0.799	0.203	0.645	0.672	0.992	0.711	0.983	0.786	0.921
W=80%	0.803	0.782	0.478	1.100	1.087	0.500	1.087	0.855	0.641	0.889	0.891	0.593	0.993	1.001	0.728
W=90%	1.253	0.768	0.578	1.026	0.927	0.816	0.853	1.055	0.396	0.869	0.685	0.422	1.299	1.355	0.642
W=100%	1.318	0.455	0.235	1.062	0.430	0.779	0.837	0.583	0.800	1.123	1.157	0.743	0.929	0.758	0.955
Rain-fed	0.981			0.747			1.143			0.775			0.975		

Table 4.2 (b): Harvested average grain yield (Y) data measurements of the three replica plots

Deficit irrigation water application levels	Average grain yield measurements of the three plots for the respective treatments (ton/ha)					Average grain yield under deficit irrigation (ton/ha)
	F=20%	F=40%	F=60%	F=80%	F=100%	
W=50%	8.76	6.53	8.59	6.35	7.08	7.46
W=65%	6.94	7.95	5.49	7.92	8.97	7.45
W=80%	6.88	8.96	8.61	7.91	9.07	8.29
W=90%	8.66	9.23	7.68	6.59	10.99	8.63
W=100%	6.69	7.57	7.40	10.08	8.81	8.11
Rain-fed	9.81	7.47	11.43	7.75	9.75	9.24

Table 4.2 (c): Above ground biomass (B) data measurements of the three replica plots

Deficit irrigation water application levels	Harvested above ground biomass measurements for the respective nutrient fertilizer application levels and replica plots (kg/m^2)														
	F=20%			**F=40%**			**F=60%**			**F=80%**			**F=100%**		
	R-1	**R-2**	**R-3**	**R-1**	**R-2**	**R-3**	**R-1**	**R-2**	**R-3**	**R-1**	**R-2**	**R-3**	**R-1**	**R-2**	**R-3**
W=50%	2.37	2.00	1.55	1.61	1.54	1.48	2.70	1.57	1.70	1.66	1.78	1.27	2.13	1.37	1.53
W=65%	2.14	1.89	0.94	1.68	1.77	1.89	1.98	0.64	1.49	1.72	2.31	1.75	2.18	1.75	2.25
W=80%	1.81	1.69	1.40	2.47	2.61	1.34	2.56	1.88	1.62	2.06	2.12	1.47	2.27	2.36	1.94
W=90%	2.76	1.87	1.60	2.32	2.33	1.86	1.81	2.27	1.09	2.01	1.65	1.14	3.20	2.91	1.53
W=100%	3.02	1.04	0.69	2.48	1.13	1.86	1.96	1.37	1.90	2.68	2.70	1.81	2.22	1.81	2.17
Rain-fed	2.05			1.78			2.56			1.71			2.20		

Table 4.2 (d): Above ground average biomass (B) data measurements of the three replica plots

Deficit irrigation water application levels	Average above ground biomass measurements for the respective nutrient fertilizer application levels and replica plots (ton/ha)					Average above ground biomass (ton/ha)
	F=20%	**F=40%**	**F=60%**	**F=80%**	**F=100%**	
W=50%	19.7	15.4	19.9	15.7	16.8	17.5
W=65%	16.6	17.8	13.7	19.3	20.6	17.6
W=80%	16.3	21.4	20.2	18.8	21.9	19.7
W=90%	20.8	21.7	17.2	16.0	25.5	20.2
W=100%	15.8	18.2	17.4	24.0	20.7	19.2
Rain-fed	20.5	17.8	25.6	17.1	22.0	20.6

Table 4.2 (e): Calculated Harvest Index (HI) of the three replica plots

Water applied (W)	Calculated Harvesting Index (HI), Grain yield and Biomass data (kg/m^2) for the respective nutrient fertilizer application levels and replica plots															
	F	F=20%			F=40%			F=60%			F=80%			F=100%		
	R	R-1	R-2	R-3	R-1	R-2	R-3	R-1	R-2	R-3	R-1	R-2	R-3	R-1	R-2	R-3
50%	Y	1.081	0.905	0.643	0.670	0.653	0.637	1.170	0.667	0.739	0.687	0.740	0.478	0.951	0.562	0.612
	B	2.37	2.00	1.55	1.61	1.54	1.48	2.70	1.57	1.70	1.66	1.78	1.27	2.13	1.37	1.53
	HI	0.456	0.453	0.415	0.416	0.424	0.430	0.433	0.425	0.435	0.414	0.416	0.376	0.446	0.410	0.400
65%	Y	0.963	0.767	0.352	0.867	0.791	0.726	0.799	0.203	0.645	0.672	0.992	0.711	0.983	0.786	0.921
	B	2.14	1.89	0.94	1.68	1.77	1.89	1.98	0.64	1.49	1.72	2.31	1.75	2.18	1.75	2.25
	HI	0.450	0.406	0.374	0.516	0.447	0.384	0.404	0.317	0.433	0.391	0.429	0.406	0.451	0.449	0.409
80%	Y	0.803	0.782	0.478	1.100	1.087	0.500	1.087	0.855	0.641	0.889	0.891	0.593	0.993	1.001	0.728
	B	1.81	1.69	1.40	2.47	2.61	1.34	2.56	1.88	1.62	2.06	2.12	1.47	2.27	2.36	1.94
	HI	0.444	0.463	0.341	0.445	0.416	0.373	0.425	0.455	0.396	0.432	0.420	0.403	0.437	0.424	0.375
90%	Y	1.253	0.768	0.578	1.026	0.927	0.816	0.853	1.055	0.396	0.869	0.685	0.422	1.299	1.355	0.642
	B	2.76	1.87	1.60	2.32	2.33	1.86	1.81	2.27	1.09	2.01	1.65	1.14	3.20	2.91	1.53
	HI	0.454	0.411	0.361	0.442	0.398	0.439	0.471	0.465	0.363	0.432	0.415	0.370	0.406	0.466	0.420
100%	Y	1.318	0.455	0.235	1.062	0.430	0.779	0.837	0.583	0.800	1.123	1.157	0.743	0.929	0.758	0.955
	B	3.02	1.04	0.69	2.48	1.13	1.86	1.96	1.37	1.90	2.68	2.70	1.81	2.22	1.81	2.17
	HI	0.436	0.438	0.341	0.428	0.381	0.419	0.427	0.426	0.421	0.419	0.429	0.410	0.418	0.419	0.440
Rain-fed	Y		0.981			0.747			1.143			0.775			0.975	
	B		2.05			1.78			2.56			1.71			2.20	
	HI		0.479			0.420			0.446			0.453			0.443	

Table 4.2 (f): Average calculated Harvest Index (HI) for the respective nutrient fertilizer and moisture levels

Deficit irrigation application levels	**Average calculated Harvesting Index (%), Grain yield and Biomass data (ton/ha)**						**Calculated Harvest Index (%) using average grain yield and biomass in ton/ha**
	Fertilizer (F)	F=20 %	F=40%	F=60%	F=80%	F=100%	
W=50%	Y	8.76	6.53	8.59	6.35	7.08	7.46
	B	19.7	15.4	19.9	15.7	16.8	17.5
	HI	44.5	42.4	43.2	40.4	42.1	42.6
W=65%	Y	6.94	7.95	5.49	7.92	8.97	7.45
	B	16.6	17.8	13.7	19.3	20.6	17.6
	HI	41.8	44.7	40.1	41.0	43.5	42.3
W=80%	Y	6.88	8.96	8.61	7.91	9.07	8.29
	B	16.3	21.4	20.2	18.8	21.9	19.7
	HI	42.2	41.9	42.6	42.1	41.4	42.1
W=90%	Y	8.66	9.23	7.68	6.59	10.99	8.63
	B	20.8	21.7	17.2	16.0	25.5	20.2
	HI	41.6	42.5	44.7	041.2	43.1	42.7
W=100%	Y	6.69	7.57	7.40	10.08	8.81	8.11
	B	15.8	18.2	17.4	24.0	20.7	19.2
	HI	42.3	41.6	42.5	42.0	42.6	42.2
Rain-fed	Y	9.81	7.47	11.43	7.75	9.75	9.24
	B	20.5	17.8	25.6	17.1	22.0	20.6
	HI	47.9	42.0	44.6	45.3	44.3	44.9

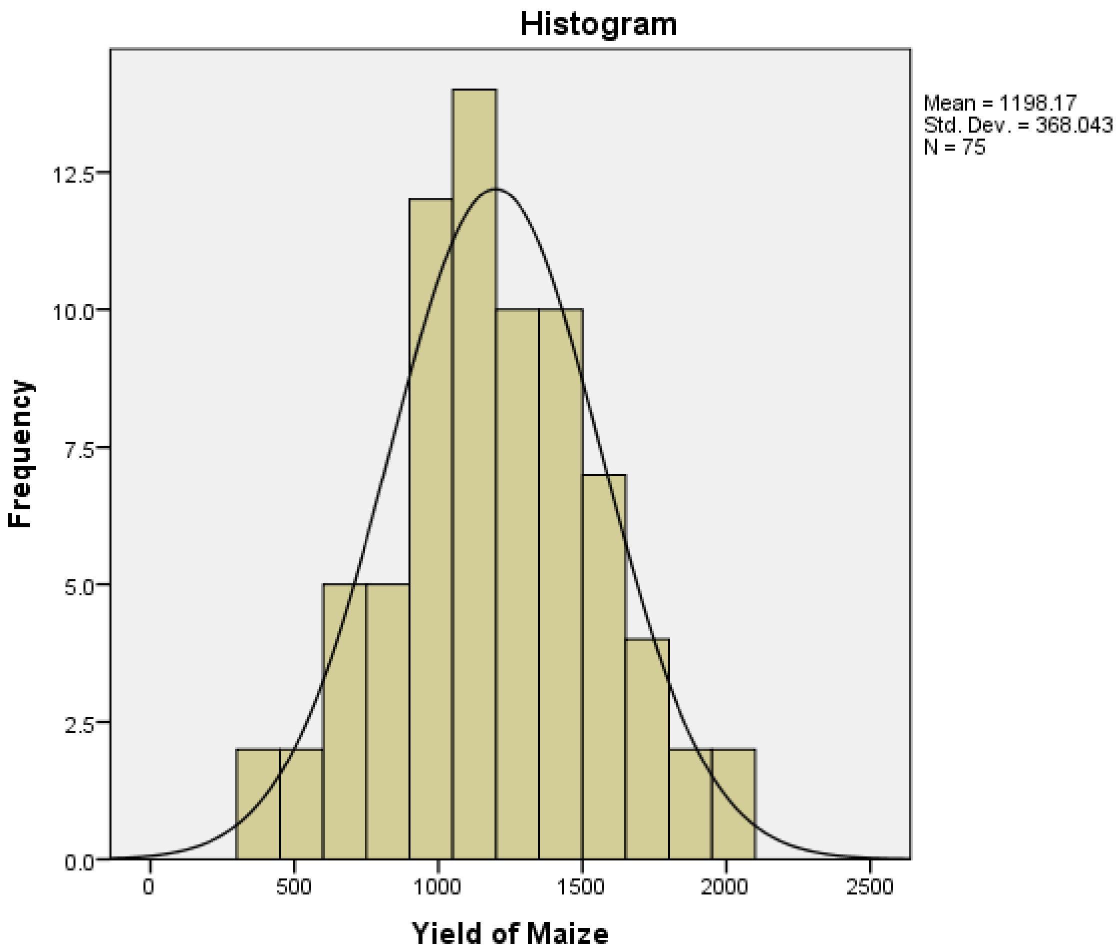

Figure 4.1: Symmetric representation of maize grain yield data of the study

4.2.2 Average grain yield of maize from the replica plots

The average yields from the 3 replicas were computed and the results presented in Table 4.3. The variations between the three replicas were also checked to determine if the variations were significant in an effort to determine the factors that could be affecting the variations.

Table 4.3: Average grain yield (g) of maize of the three replica plots

Replica	N	Mean Statistics	Standard Deviation Statistics	Standard Error	95% Confidence Interval for Mean		Minimum Statistics	Maximum Statistics
					Lower Bound	Upper Bound		
1	25	1457.08	274.686	54.937	1343.7	1570.46	1005	1977
2	25	1191.32	371.71	74.342	1037.89	1344.75	305	2033
3	25	946.12	260.733	52.147	838.49	1053.75	353	1433
Total	75	1198.17	368.043	42.498	1113.49	1282.85	305	2033

The study findings indicated that Replica No.1 had the most yields with a mean of 1457.08g followed by Replica No.2 with 1191.32g and Replica No.3 had the lowest yields with a mean of 946.17g presented in Figure 4.2. This clearly illustrated that the three replica plots had varying levels of residual nutrients available and local variation of the soil humus content due to continuous use of the farm for maize production and possible spread of farm yard manure from crop residues and livestock in the farm before sowing of the maize.

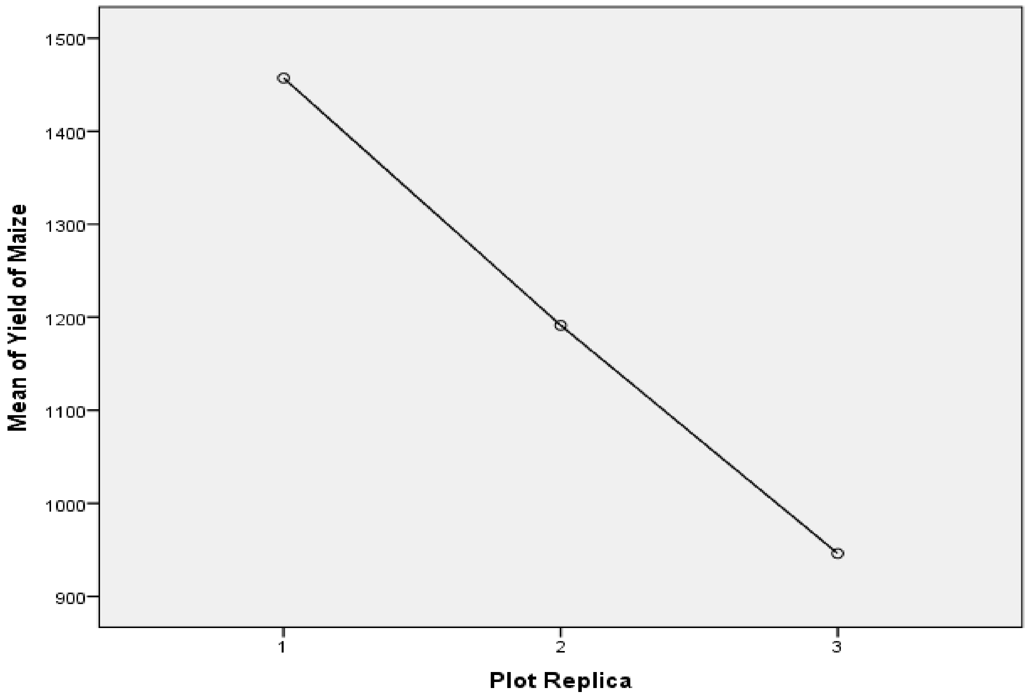

Figure 4.2: Variations in the maize grain yield from the three replicas

The variations of the yields in the replicas were checked using ANOVA to determine their levels of significance and the results are presented in Table 4.4.

Table 4.4: Variation significance of maize grain yield in the three replicas

Yield of Maize subjected to ANOVA					
	Sum of Squares	**df**	**Mean Square**	**F**	**Significance (p)**
Between Groups	3265263	2	1632631	17.393	0.000
Within Groups	6758446	72	93867.3		
Total	10023709	74			

The results indicated that there were significant variations (p= 0.000) in the 3 replica plots in terms of the grain yield of maize achieved under the various treatments of deficit irrigation and fertilizer nutrient applications. These variations meant that there were other factors in the soil varied between the 3 replicas and the study considered the influence of the residual nutrients after crop harvest and the soil pH as possible causative agents as indicated in Table 4.3.

4.2.3 Dependency test of maize grain yield on moisture and nutrient fertilizer levels

The demonstration plot treatment using moisture and nutrient fertilizer application as independent variables were tested separately for their dependency with the observed maize grain yield. Chi-square statistic (χ^2) at confidence level of 95% ($\alpha = 0.05$) was applied to test a null hypothesis that the variables are independent of maize grain yield given in Table 4.5.

The level of significance, $p = 0.0016$ is less than $\alpha = 0.05$ and therefore the null hypothesis is rejected and indicate there is an association between moisture application levels and the maize grain yield. Similar analysis for the nutrient fertilizer levels gave significance, $p = 0.0$ and again show that there is an association.

Table 4.5: Chi-square (χ^2) test of independence of moisture with the maize grain yield in the three replicas

Moisture Treatment	Maize grain yields (ton/ha)						df	$\Sigma(O-E)^2/E$
	Observed (O)			Expected (E)				
	R-1	R-2	R-3	R-1	R-2	R-3		
100	9.29	7.58	9.55	9.29	7.58	9.55		0
90	12.99	13.55	6.42	8.361	6.822	8.595		9.7485
80	9.93	10.01	7.28	7.432	6.064	7.64	8	3.42434
65	9.83	7.86	9.21	6.0385	4.927	6.2075		5.5789
50	9.51	5.62	6.12	4.645	3.79	4.775		6.35789
χ^2								25.1096
Critical - χ^2 =15.507					p			0.0016

4.2.4 Quantity of Dry Matter Yield

The quantity of dry matter biomass was subjected to descriptive statistics and gave an average of 1630.4g for the 75 plots which was above the dry grain yield which had been established to be 1198.17g.

The dry matter data had a skewness value of -0.255. This value was not more than twice the standard error hence it was considered to be symmetrical. The data had a kurtosis statistic of –0.317 which is between the acceptable range of -3 and 3 to indicate that it was normally distributed as given in Figure 4.3 and further the Q – Q Plot / Normality Tests.

Consequently comparison investigation of descriptive statistics of both dry maize yield and biomass was carried out and tabulated in Table 4.6.

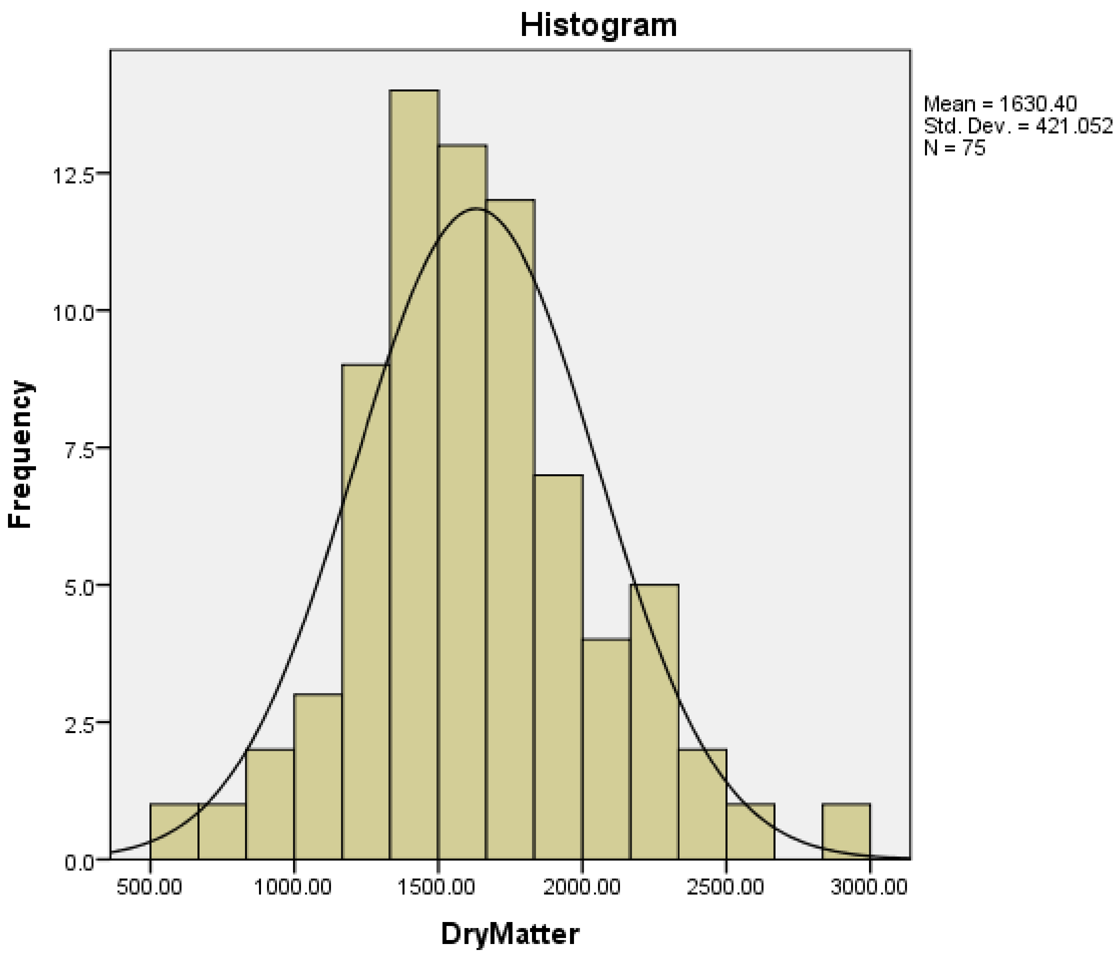

Figure 4.3: Symmetric representation of maize dry matter (Biomass) data of the study

Table 4.6: Descriptive Statistics of both Dry Maize yield and the Biomass

Production	N	Minimum Statistic	Maximum Statistic	Mean Statistic	Standard. Deviation Statistic	Skewness		Kurtosis	
						Statistic	Standard. Error	Statistic	Standard. Error
Dry Yield	75	305	2033	1198.17	368.043	-0.007	0.277	-0.057	0.548
Biomass	75	658	2844	1630.4	421.0521	0.255	0.277	0.317	0.548
Valid N (listwise)	75								

Further to descriptive statistics, ANOVA model was employed to investigate if changes in the biomass production resulted to changes in dry grain yield presented in Table 4.7.

Table 4.7: Percentage differences in dry gain Yield and Biomass in the replica plots

Plot Replica	Production	Mean	Percentage Change	Standard. Error	95% Confidence Interval	
					Lower Bound	Upper Bound
1	Yield	1457.08	22.90%	61.276	1334.929	1579.231
	Dry Matter	1889.88		75.239	1739.893	2039.867
2	Yield	1191.32	25.10%	61.276	1069.169	1313.471
	Dry Matter	1590.6		75.239	1440.613	1740.587
3	Yield	946.12	32.90%	61.276	823.969	1068.271
	Dry Matter	1410.72		75.239	1260.733	1560.707

The results indicated that lower yields results to higher percentage changes in dry matter while higher yields result to lower percentage changes in dry matter.

The relationship between dry grain yield and biomass was further investigated by calculation using the Spearman's correlations shown in Table 4.8

Table 4.8: Relationship between dry grain Yield and Biomass

Symmetric Measure	Value	Asymptotic Standard Error[a]	Approximation T[b]	Approximation Significance
Interval by Pearson's R	0.938	0.016	23.06	0.000[c]
Ordinal by Spearman Correlation	0.918	0.029	19.827	0.000[c]
N of valid cases	75			

The results in Table 4.7 represents a strong significant relationship ($p = 0.000$) between the yield and the dry matter. The results therefore imply that changes in one affect the other. An increase in yield leads to decreased dry matter and vice versa.

The nature of this relationship necessitates the investigation of the relationship between maize yield and dry matter with both moisture and fertilizer applications.

4.2.5 Effect of applied moisture levels on maize yield

The study investigated the relationship between the moisture content applied according to the deficit irrigation strategy levels and the dry maize grain yields in the three replica plots. Descriptive statistics of the grain yield results for each moisture content level were represented for the three replica plots and given in Table 4.9.

Table 4.9: Average dry maize grain yield (g) based on moisture content levels (%)

Moisture Content (W)	N	Mean (g)	Standard. Deviation	Standard. Error	95% Confidence Interval for Mean Lower Bound	Upper Bound	Minimum	Maximum
50	15	1119.4	291.82	75.348	957.8	1281	717	1755
65	15	1117.73	331.259	85.531	934.29	1301.18	305	1488
80	15	1242.93	312.296	80.634	1069.99	1415.88	717	1650
90	15	1294.4	445.989	115.154	1047.42	1541.38	594	2033
100	15	1216.4	445.7	115.079	969.58	1463.22	353	1977
Total	75	1198.17	368.043	42.498	1113.49	1282.85	305	2033

The study findings indicated a varying degree of dry grain mean yields depending on the moisture content level applied. The results of the mean value obtained for each deficit irrigation moisture content level in Table 4.9 are given as W_{50} (1119.40), W_{65} (1117.73), W_{80} (1242.93), W_{90} (1294.40), and at W_{100} (1198.17).

Table 4.10: Distribution of deficit irrigation moisture content data in the three replica plots

	N	Minimum	Maximum	Mean	Standard Deviation	Skewness Statistic	Skewness Standard Error	Kurtosis Statistic	Kurtosis Standard Error
Moisture Content	75	50	100	77	17.896	– 0.255	0.277	– 1.281	0.548

The data had a skewness value of – 0.255. This value was not more than twice the standard error hence it was considered to be symmetrical. The data had a Kurtosis statistic of –1.281 which is between the acceptable range of –3 and 3 to indicate that it was normally distributed for Q – Q Plot / Normality Tests.

The results of mean values of dry grain yield of maize according to the moisture content levels applied are illustrated graphically and presented in the Figure 4.4.

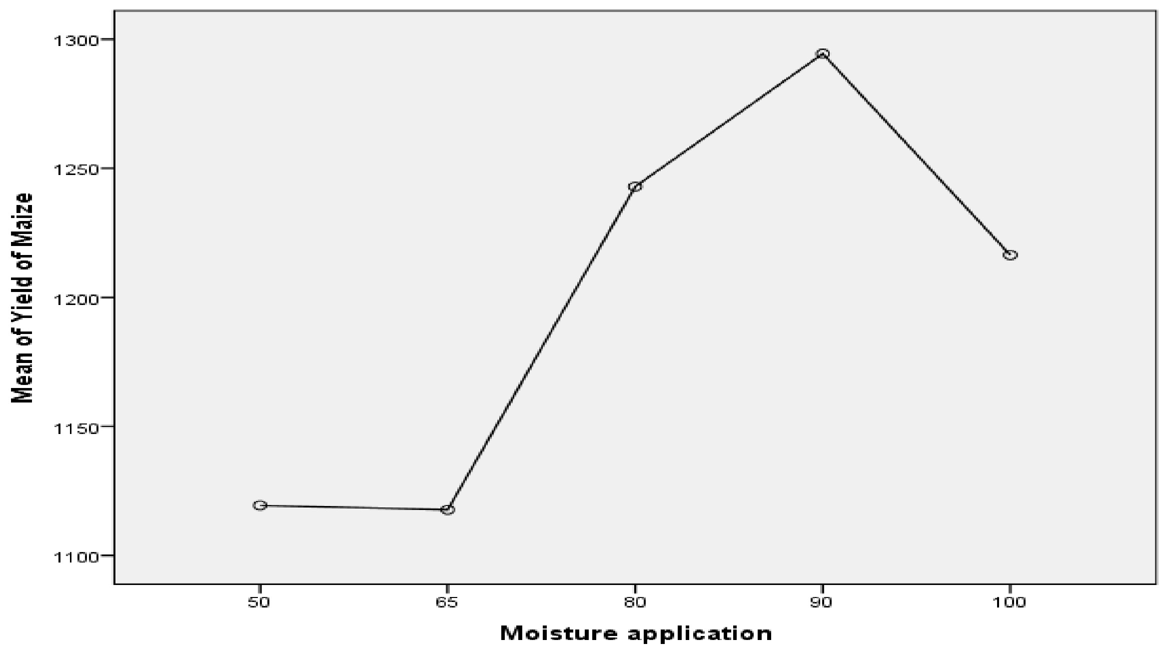

Figure 4.4: Average maize dry grain yield (g) trend according to the moisture content levels applied (%)

The results indicated an almost similar grain yield level at moisture content levels between 50% and 65%. The moisture content levels are within the range of about half the storage capacity of readily available moisture (RAW) amount applied during irrigation of maize and the crop is at the point when moisture stress begin to affect the grain yields as moisture get more depleted towards maximum allowable depletion limit (Upper threshold of canopy and leaf expansion). Any moisture depletion below the threshold value result in stresses setting in and reduce crop yield production.

Available moisture at 50% deficit irrigation was not enough for full crop water demands hence fully utilized and the crop develops its sturdiness to withstand drought. The crop is more resilient to water stress at 50% than at 65% because diminished available water causes the roots to grow further deep in search of moisture and throughout the growing season crop development adjusts to the limited available deficit amount of moisture in the soil. At 65% deficit irrigation moisture application, the available amount of moisture in the soil is slightly more than half storage of RAW but not at the optimum level for the plant roots to sufficiently imbibe its requirements. The roots will not penetrate much and not as sturdy therefore the plant is not as resilient as at 50% moisture level however grain yields improved because of additional moisture. This is further explained by the calculated water productivity given in Table 4.11. Amount of yield obtained per unit amount of water applied was slightly higher for the 65% than 50% moisture application.

Between deficit moisture content at 80% and 90% the grain yield increases by 51.47g (5.15g per unit change in %) and reach a maximum value of 1294.40g at 90%. The biggest increase of 125.2g occurred between 65% and 80% (8.35g per unit change in %). Moisture content in the soil is sufficient within the demands of the crop water requirement for optimal growth regime. Minimal water stress is experienced by the crop at this level and optimal grain yields are expected to occur within the range of the moisture. Above 90% of RAW applied to the crop let to decline of the maize grain yields. This is attributed to moisture content in the soil near filling the pore spaces and limiting plant roots from adequate exchange of gases and therefore as it approaches full suffocation, the crop capacity to bear grain yields is hampered. At 100% moisture content level in the soil, the soil voids are near field capacity and plant nutrient are easily drained out of the root zone because of sufficient dilution and uptake begin to diminish and the crop reduces its capacity to produce at maximum yields.

Table 4.11: Water Productivity of demonstration plot maize yields

Dry yield and water productivity of the plot treatment design matrix						
Nutrient Fertilizer application level (F %)	Water productivity data	Moisture application level (W %)				
		50	65	80	90	100
100	Dry grain yield (kg/m^2)	0.708	0.897	0.907	1.099	0.881
	Amount of irrigation (mm)	371.6	388.5	394.8	400.6	426.0
	WP_{ET} (kg/m^3-H_2O)	2.31	2.36	2.31	2.26	2.21
80	Dry grain yield (kg/m^2)	0.635	0.792	0.791	0.659	1.008
	Amount of irrigation (mm)	371.9	391.5	393.4	410.4	413.4
	WP_{ET} (kg/m^3-H_2O)	2.02	2.06	2.02	1.98	1.96
60	Dry grain yield (kg/m^2)	0.859	0.549	0.861	0.768	0.740
	Amount of irrigation (mm)	370.2	394.2	395.1	399.0	412.4
	WP_{ET} (kg/m^3-H_2O)	1.92	1.97	1.94	1.88	1.87
40	Dry grain yield (kg/m^2)	0.653	0.795	0.896	0.923	0.757
	Amount of irrigation (mm)	315.5	396.6	397.1	399.9	414.2
	WP_{ET} (kg/m^3-H_2O)	2.03	2.05	2.03	1.97	1.95
20	Dry grain yield (kg/m^2)	0.876	0.694	0.688	0.866	0.669
	Amount of irrigation (mm)	314.3	342.3	375.4	378.4	411.7
	WP_{ET} (kg/m^3-H_2O)	1.91	1.93	1.90	1.85	1.81

Trends of average replica dry grain yields according to the moisture application levels for the applied nutrient fertilizer inputs are presented in Figures 4.5.

Low dry grain yields were attained at W_{50} for all the levels of nutrient fertilizer treatments. Individual treatment yield increases with moisture treatment levels to maximum values at W_{80} for nutrient fertilizer treatment levels of F_{60}, F_{80} and F_{100} and a maximum at W_{90} for F_{20} and F_{90} then drops to a lower value at W_{100}. Respective yield trends support the presentation given in Figure 4.4.

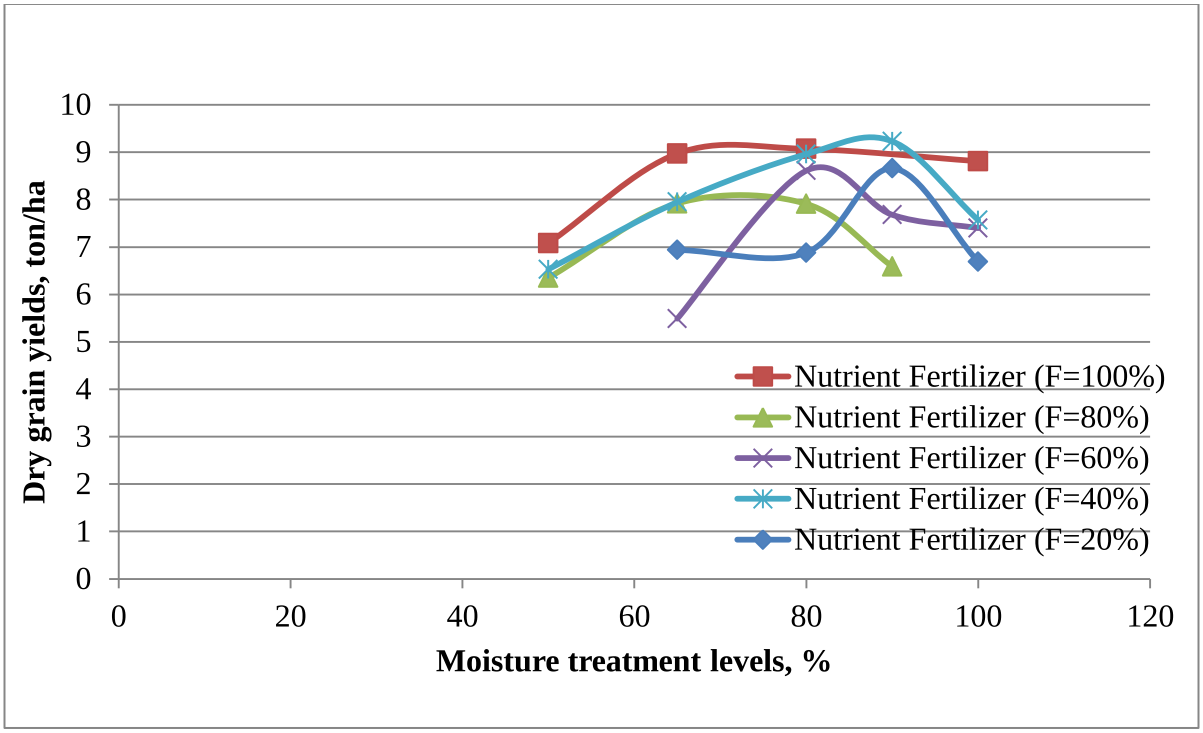

Figure 4.5: Yield trend of dry maize grains with moisture treatment levels for different nutrient fertilizer treatments

Low moisture levels combined with low nutrient levels cause the plant to experience both moisture and fertility stress that trigger crop sturdiness and the roots grow stronger scouting far deeper into the soil profile. This occurred in W_{50} and resulted in comparable yields with W_{65}. Moisture at W_{65} is not sufficient to satisfy the demand for plant water requirement. This causes dilution of the nutrients to concentrations that is injurious to the crop and when coupled with low levels of nutrients lead to low yields. Moisture content at W_{80} is optimum for crop production and cause favourable environment in the soil profile for nutrient dilution and abstraction. Higher moisture levels of W_{90} and W_{100} are in excess of the optimum level and lead to drainage of applied water and taking away nutrient fertilizer into the soil profile denying the crop sufficient amounts. Low fertilizer levels is over diluted and drained away but optimum fertilizer levels lead to increased yield production. High nutrients available lead to concentrations that injure and reduce crop yields.

The trend of biomass production according to the applied moisture application in the graphical representation in Figure 4.6 is similar in pattern with the graph representing the relationship between dry grain yield and moisture content. The yield slightly changes between 50% and 65% moisture content and then increases significantly to 80% and attain its maximum value at 90%. Biomass yields decreases at 100% moisture level after its maximum attributed to near saturation regime that affects the crops ability to uptake water.

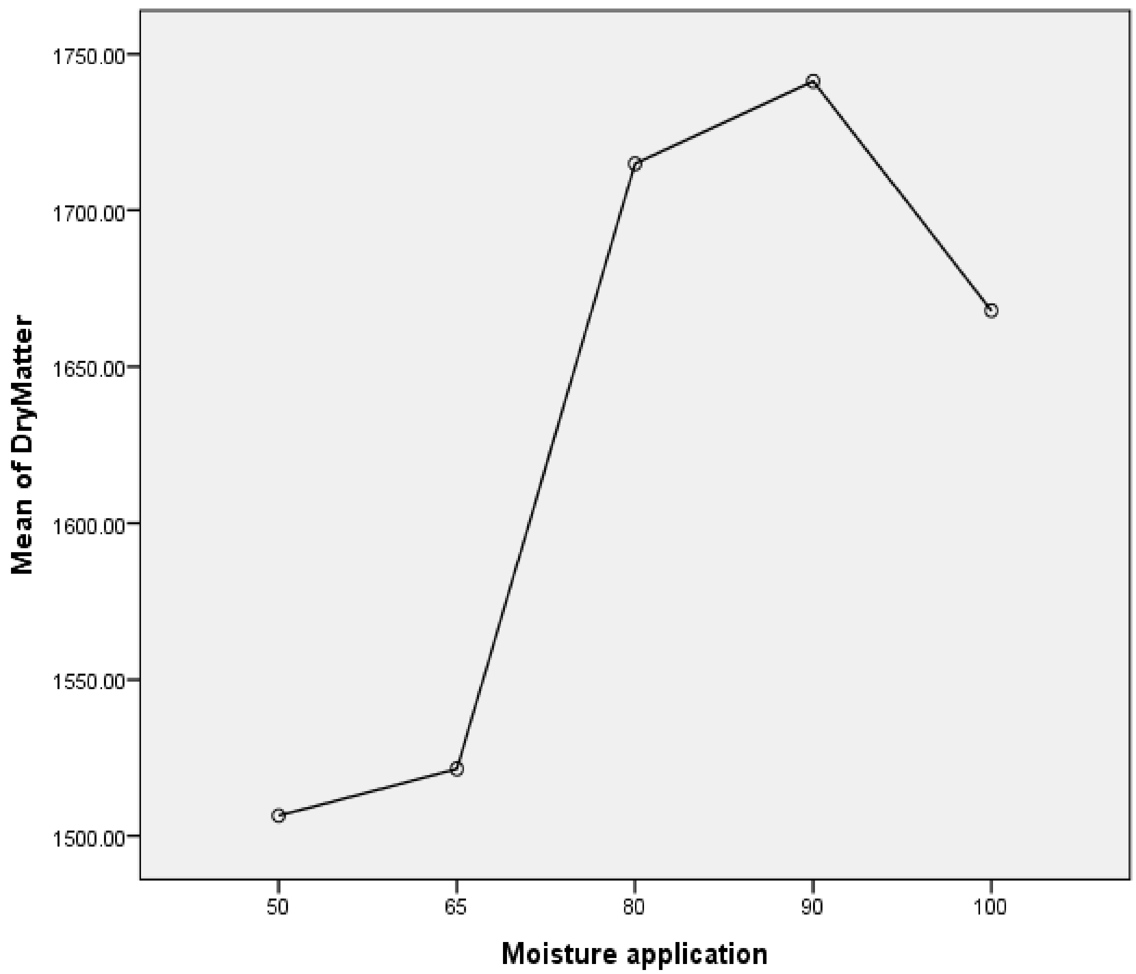

Figure 4.6: Average maize biomass (g) trend according to the moisture content levels applied (%)

4.2.6 Effect of applied nutrient fertilizer levels on dry maize grain yield

Soil nutrients essential for plant growth are grouped depending on the amount of quantities required by the plants into macro-nutrients and micro-nutrients. Macro-nutrients (major elements) are required in large quantities and comprise of Nitrogen (N), Phosphorus (P), Potassium (K), Sulphur (S), Magnesium (Mg) and Calcium (Ca). Micro-nutrients (trace elements) are required by plants in very small quantities but essential and their deficiency cause plant growth not attain maximum yield.

Nutrients required by plants are stored in solution form and held by the soil moisture and the soil colloids comprising of the Clay and Humus proportions. The soil moisture dissolves the nutrients into ionic form readily available for plant roots to absorb from the solution. The extent of the nutrients' availability to plants depend on how well the nutrients and water are retained in the soil pores that is dependent on the water holding capacity of particular soil (Ponge, 2015). Nutrients unavailability to plants occur when the nutrients precipitate on the surface as water evaporates and when it leaches to lower layers of the soil profile and/or when transported during water drainage process. Release of the nutrients to be available to plants is also affected by the soil physical properties that promote water and air movement and the soil pH.

Clays and organic matter hold nutrients and water better than the coarse sandy soils, while low soil pH cause macro-nutrients to be less available to plants but conducive for micro-nutrients which are limited by high soil pH levels. The nutrients available in the soil originate from Nitrogen and the mineral content and/or added as inorganic fertilizer. Application of the fertilizer increases the root growth and ability of crops to forage for water and nutrients. Sufficient nutrition result in an increase of crop yield per unit amount of water applied. High application nutrients to toxic levels result in poor yields compared to when too little amounts are given to the plants.

The study sought to establish the relationship between nutrient fertilizer applied in different quantities to the three replica plots and the effect they had on the yield. The results of the descriptive analysis are presented based on grain yield quantities from each of the fertilizer quantity level and given in Table 4.12.

The study findings indicated that nutrient fertilizer application levels were a fraction of the recommended amount required by each seed during sowing and at top dressing. Different amounts applied resulted in the maize crop producing different grain yields as follows: at F_{20} (1138.07g), at F_{40} (1206.93g), at F_{60} (1133.07g) at F_{80} (1165.13g) and at F_{100} (1189.17g). These variations indicated that nutrient fertilizer play a key role in the growth and ultimate amount of harvested grain yield of maize and the results are illustrated graphically in Figure 4.7.

Table 4.12: Effect of nutrient fertilizer applied on maize grain yield

Nutrient Fertilizer	N	Mean	Standard. Deviation	Standard Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
20	15	1138.07	471.373	121.708	877.03	1399.1	353	1977
40	15	1206.93	313.285	80.89	1033.44	1380.42	645	1650
60	15	1133.07	380.067	98.133	922.59	1343.54	305	1755
80	15	1165.13	317.643	82.015	989.23	1341.04	633	1735
100	15	1347.67	341.589	88.198	1158.5	1536.83	843	2033
Total	75	1198.17	368.043	42.498	1113.49	1282.85	305	2033

Table 4.13: Distribution of nutrient fertilizer application in the three replica plots

	N	Minimum	Maximum	Mean	Standard. Deviation	Skewness		Kurtosis	
						Statistic	Standard Error	Statistic	Standard Error
Nutrient Fertilizer	75	20	100	60	28.475	0.000	0.277	-1.307	0.548

The data had a skewness value of 0.000. This value was not more than twice the standard error hence it was considered to be symmetrical. The data had a kurtosis statistic of -1.307 which is between the acceptable range of -3 and 3 to indicate that it was normally distributed for Q – Q Plot / Normality Tests.

Nutrient fertilizer was applied during maize crop sowing when moisture was at field capacity and sufficient to cause root sprouting and strong healthy crop. The effect of nutrient fertilizer application against the maize grain yield harvested noted that low fertilizer input at 20% resulted in the lowest yield that slightly increased at 40%.

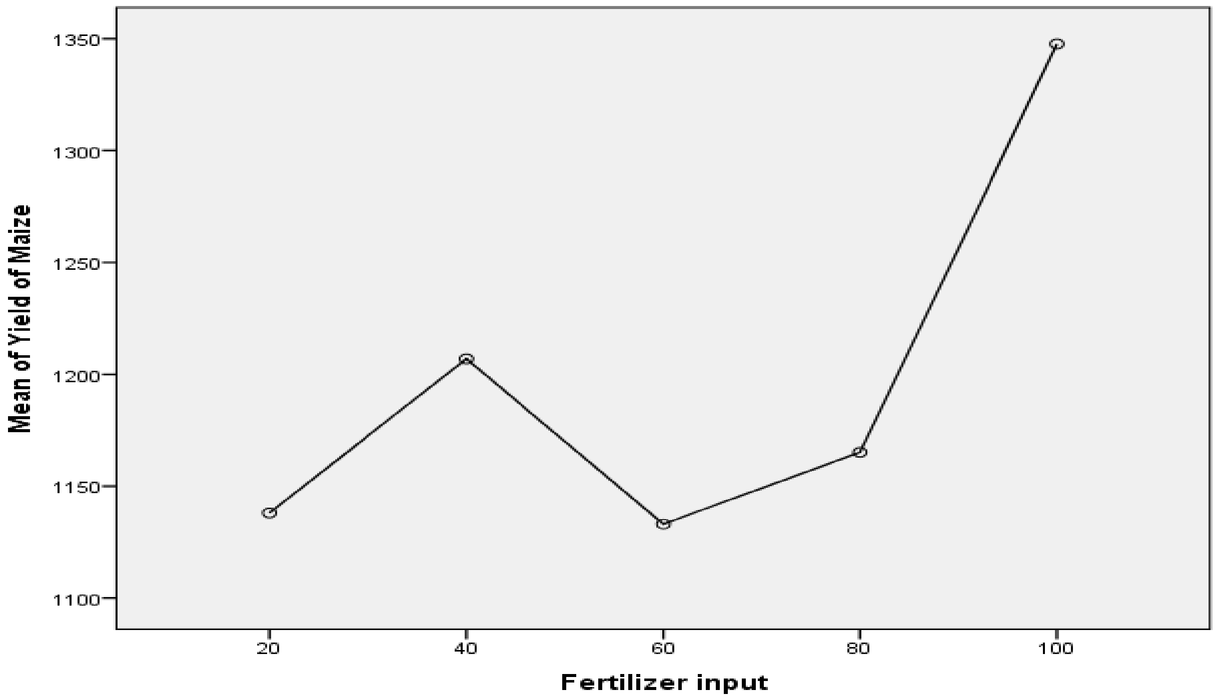

Figure 4.7: Effect of nutrient fertilizer applied on production of maize grain yield

Further increase of fertilizer input to 60% resulted in the grain yield achieved equivalent to the amount achieved at 20%. Nutrient fertilizer application at 20% is too little to sustain a strong and healthy growth of maize and when the available moisture is low, the risk of chemical poisoning is minimal and under high level of moisture the little amount of fertilizer is fully consumed by the crop. Comparatively, nutrient fertilizer at 60% is high enough to sustain growth of the maize crop under favourable moisture content levels in the soil.

Low moisture levels available cause the applied fertilizer to be more concentrated and become poisonous due to chemical stress and the crop growth is hampered. High moisture regime in the soil results in the loss of the fertilizer with drainage water movement beyond a shallow root zone concentrated around the depth of sowing where fertilizer was placed.

Individual trends of dry grain yield as a function of nutrient fertilizer applied for the levels of water applied is given in Figures 4.8.

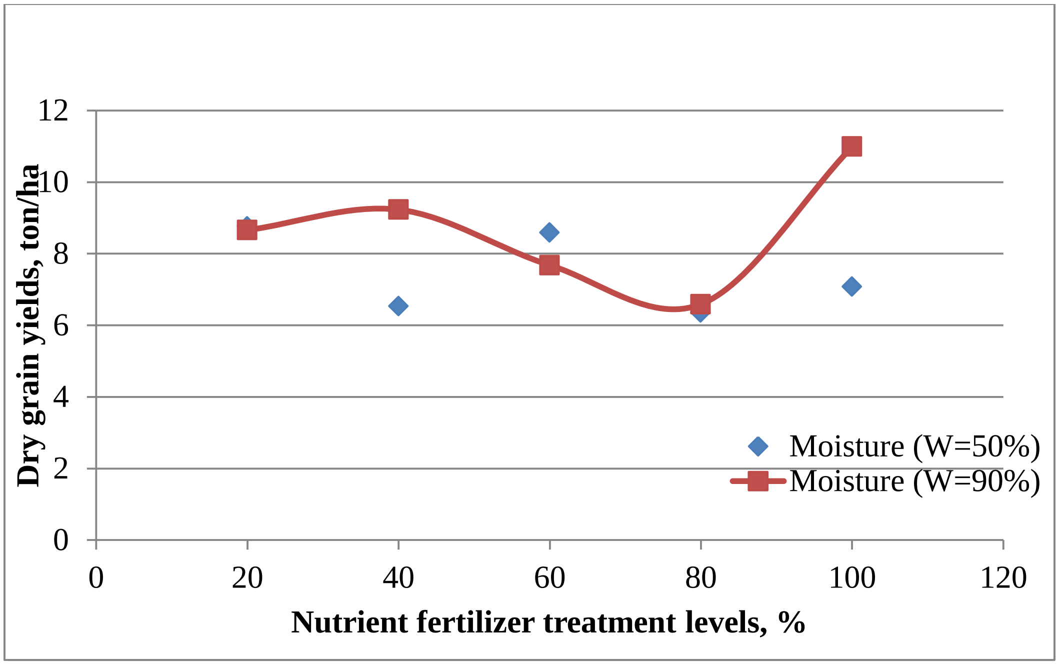

Figure 4.8 (a): Yield trend of dry maize grains with nutrient fertilizer treatment levels for W_{50} and W_{90} moisture treatments

The results indicated a general increase in yields with nutrient fertilizer levels between F_{20} to F_{40} and F_{80} and F_{100} but a dcrease occurred between F_{40} to F_{80} for moisture treatment levels of W_{50}, W_{65}, W_{80} and W_{90}. This representation is similar to the average yield values with nutrient fertilizer in Figure 4.7. The non-stressed W_{100} moisture level plots had a general increase in yields with nutrient fetilizer levels from F_{20} to F_{60} that enhanced to F_{80} followed by a decrease to F_{100}.

The trends presented in Figure 4.8 (a) for moisture treatment levels of W_{50} and W_{90} had a distinct decrease from F_{60} to F_{80} unlike for other treatments of W_{65}, W_{80} and F_{100} in Figure 4.8 (b) which was minimal. This was attributed to low moisture level at W_{50} not sufficient for nutrient dilution but excess moisture available above optimum level in W_{90} that caused over dilution and wash away of nutrients from the roots.

Dry maize grain yields for moisture treatment level at W_{80} was dorminantly higher in all nutrient fertilizer treatment levels.

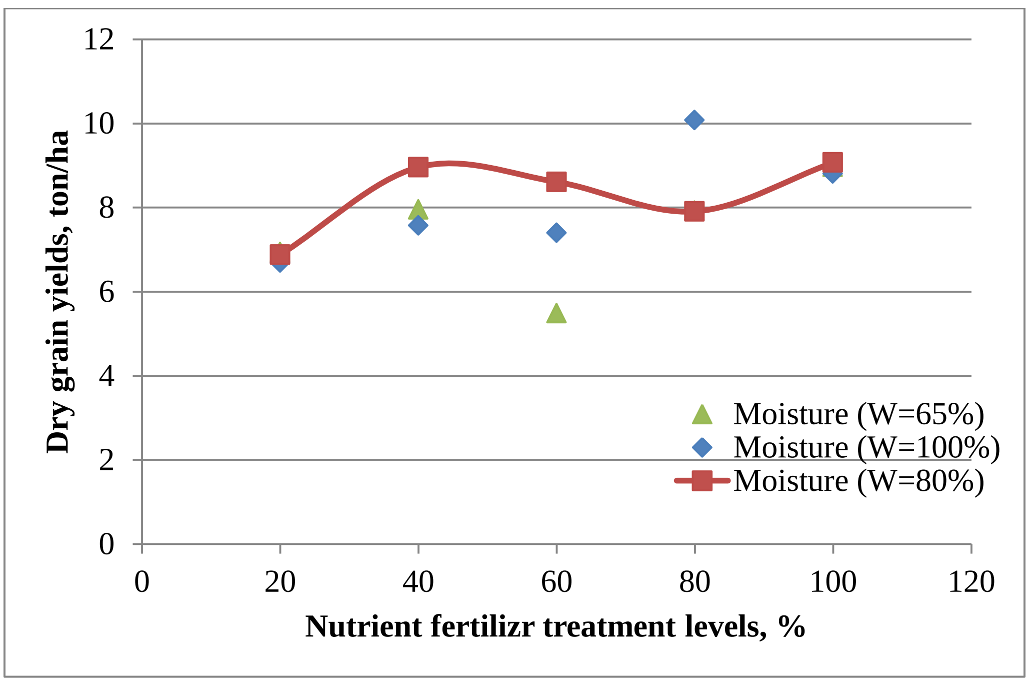

Figure 4.8 (b): Yield trend of dry maize grains with nutrient fertilizer treatment levels for W_{65}, W_{80} and W_{100} moisture treatments

Maize grain yields at F_{40} is more enhanced compared to F_{60} as a result of fertilizer input at 40% of the recommended rate is at a level that is not sufficient to sustain the crop and does not allow chemical poisoning. Under this condition the crop roots will grow both laterally and deeper scavenging for more nutrients under both low and high moisture levels in the soil and the ionized fertilizer is fully imbibed by the maize crop. The crop will develop to be hardier throughout the season and sustain better grain yields than at 60%. Except for 80% and 90% moisture which had a decease up to 80% nutrient levels, grain yield increased after 60% nutrient fertilizer application for W_{65} and W_{100} and attained a maximum production at 100% level.

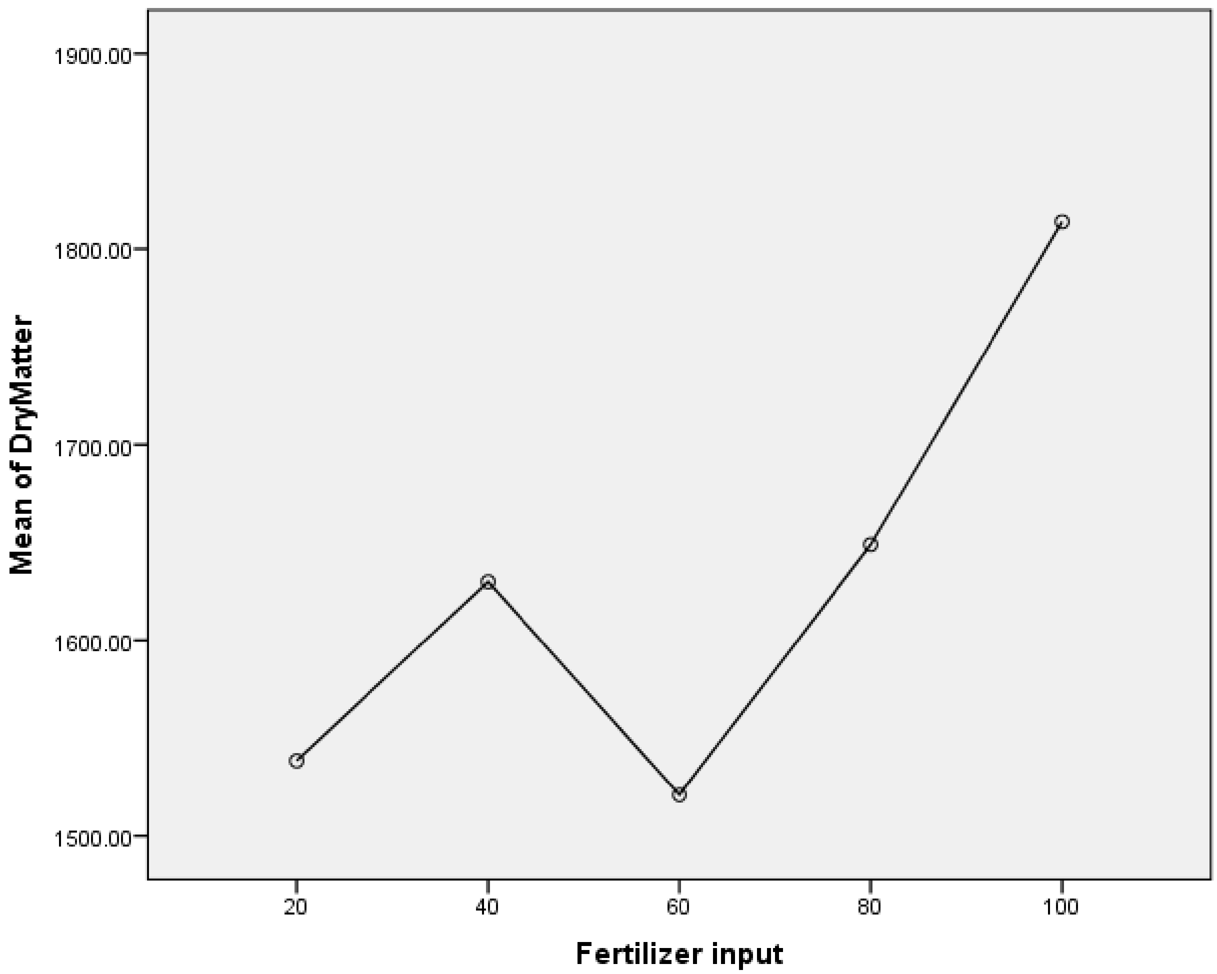

Figure 4.9: Effect of nutrient fertilizer applied on maize dry matter (Biomass)

The study to establish the effect of dry matter on the yield, moisture and nutrient content is presented in Figure 4.9. The trend show the relationship between dry matter and moisture is also similar to that of the relationship between dry grain yield and moisture. Similar decline at 60% is considered the point when the crop is sharing more nutrients between the grain yield and dry matter formation and recorded more biomass production.

4.2.7 Optimal fertilizer and moisture combinations for maximum yield

Considering the research results, the study established the optimal fertilizer and moisture combinations for maximum yields presented in Figure 4.10.

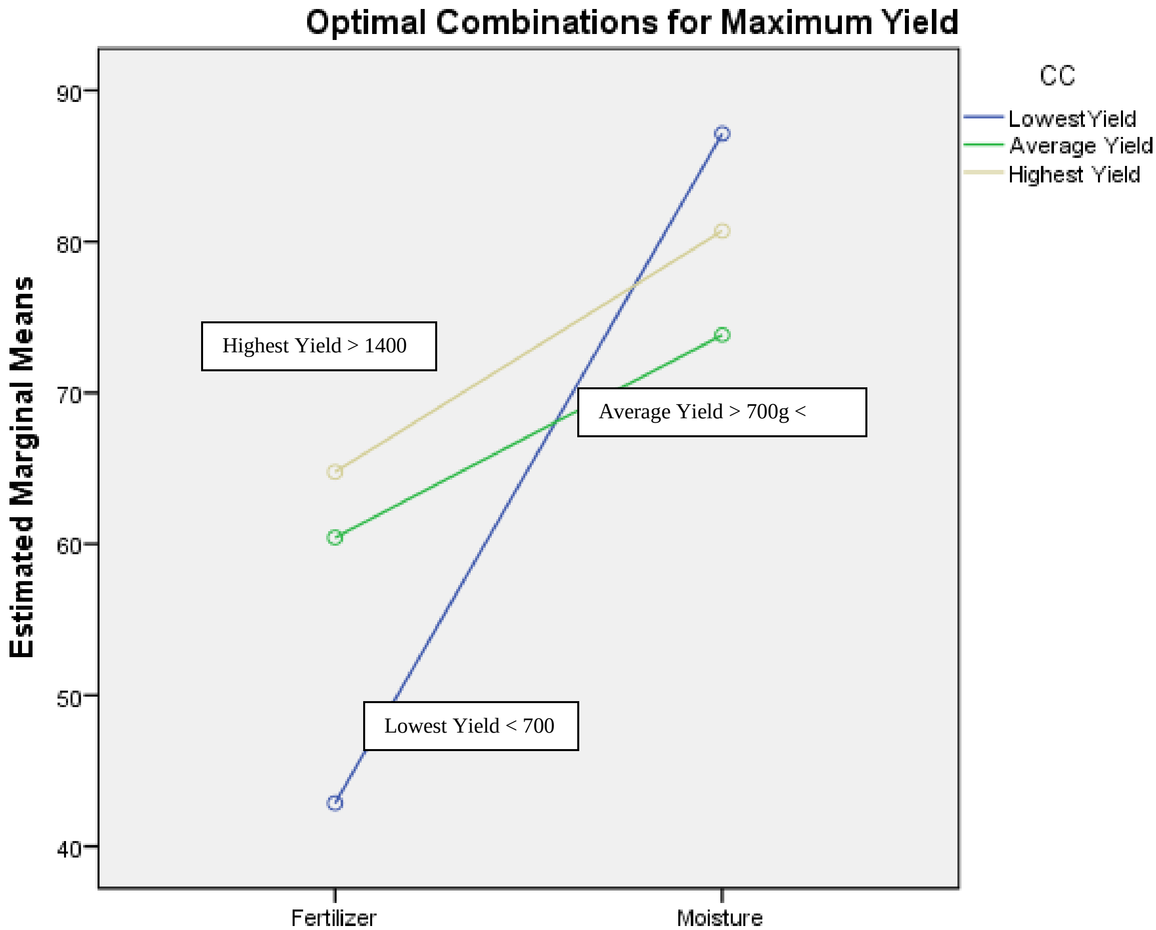

Figure 4.10: Optimal fertilizer and moisture combinations for maximum yield

Application of ANOVA measures were employed by categorizing dry grain yield into groups of Lowest yields (< 700g), Average yields (700g < yields < 1400g) and Highest yields (>1400g) and the results are presented in Figure 4.10.

The study findings noted that optimal combinations that provided the maximum yield were about 65% fertilizer and 80% moisture application levels from the highest yield category. These combinations gave yields of above 1400 grams which was the maximum yield category from the data range given.

Analysis of the observed dry grain yields was considered by comparing their standard deviations (STDEV) to check the influence of variable moisture treatment between W_{50} and W_{100} under deficit irrigation with nutrient fertilizer (F) applications. There was an increase in grain yield variations derived from their standard deviations with the increase in the nutrient fertilizer treatments to a maximum value at F_{80} then decreased to F_{100} as presented in Figure 4.11.

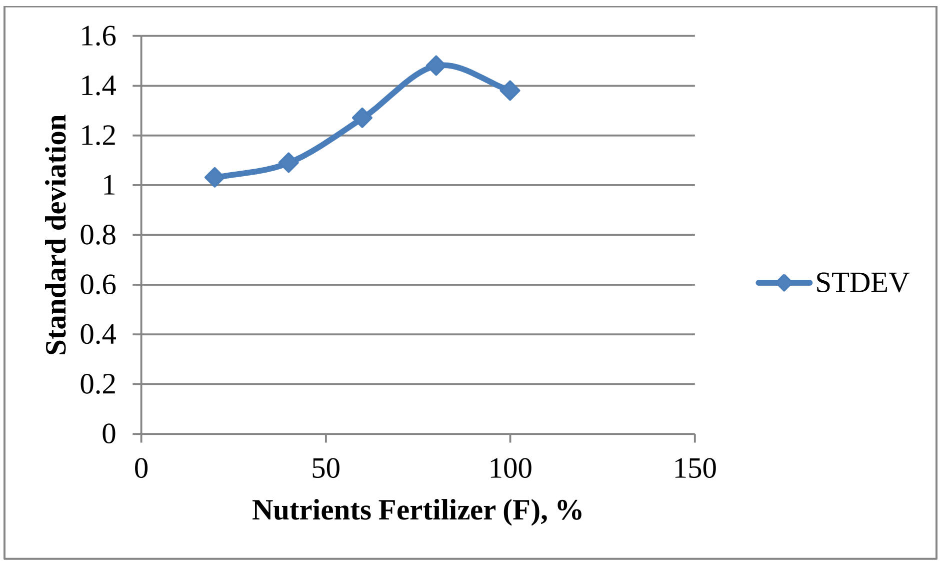

Figure 4.11: Grain yield variations (STDEV) within nutrient fertilizer treatments under deficit irrigation

The trend suggests that variations in moisture applications under deficit irrigation influence the deviations of the grain yields differently from their mean value for different nutrient fertilizer (F) application levels. The relationship suggests maximum deviation in grain yields occur at F_{80} when moisture causes fertilizer use to be maximized for plant growth. Further increase in fertilizer lower the range of grain yield variations achieved under deficit irrigation and leads to decreased productivity. This suggests that there are probably other factors that come into play as fertilizer is increased.

Further considerations of field harvested dry maize grain yields for constant moisture level at W_{100} and when nutrient fertilizer is at F_{100} were investigated for the various levels of treatment of independent parameters. The correlation trends for nutrient fertilizer and moisture variations with the dry maize grain yields are presented in Figure 4.12.

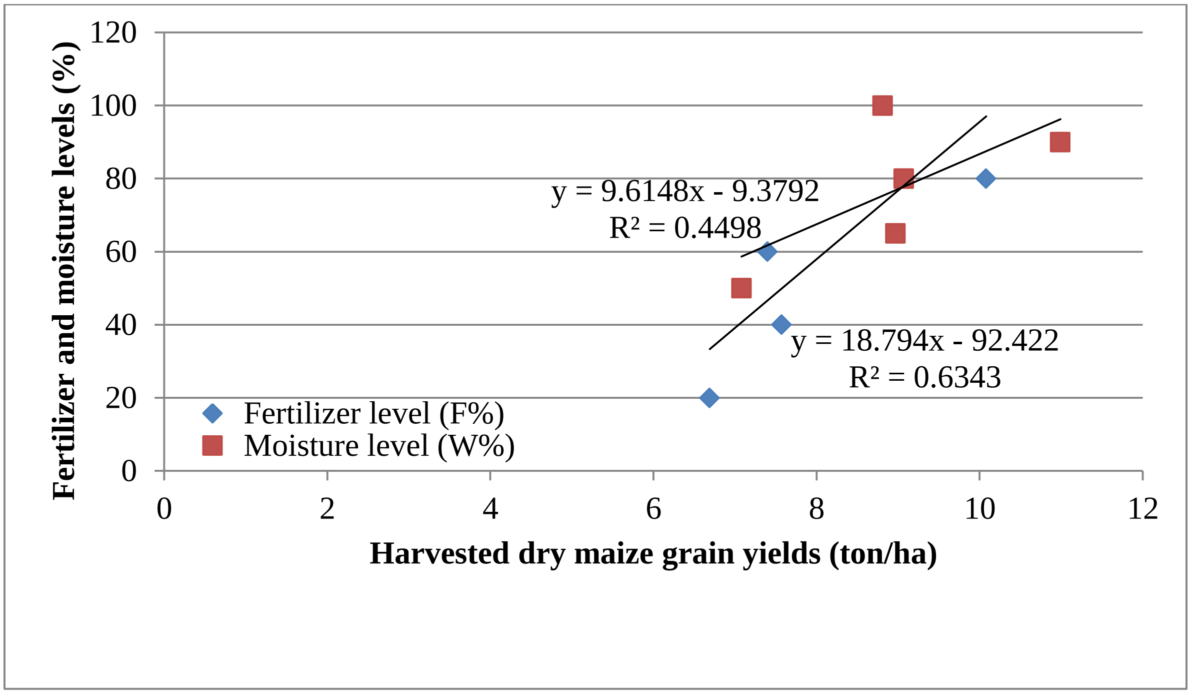

Figure 4.12: Correlation trends for fertilizer and moisture treatments variations with dry grain yields

Correlation findings indicate that variable amounts of dry maize grains are attained at different levels of moisture and nutrient fertilizer applications. Moisture and nutrient fertilizer application levels vary with the maize grain yields with correlation values of R^2=0.45 and 0.63 respectively. The intersection point occur at concurrent moisture and fertilizer level of 75% and attain maize grain yield value of 8.8 ton/ha. These values optimize the amount of grain yield achieved when similar levels of moisture and nutrient fertilizer are applied. Coincidentally the same grain yield value of 8.81 ton/ha was attained at maximum moisture and nutrient fertilizer application level of $F_{100}W_{100}$. This result support the fact that maximum application of inputs lead to uneconomical reduced output which is achieved at economical lower optimal levels.

4.3 Correlation of residual nutrients with maize yield, nutrient fertilizer and deficit irrigation levels

The findings were obtained by applying statistical tools to aid in deriving significant results that represent the correlation of the dependent and independent variables.

4.3.1 Agents of Variations of Maize grain yields

The study investigated the possible cause of variations in the three replica plots in terms of harvested dry grain yields. Possible agents of variations were derived from considering significant effects of individual residual nutrients in the soil. The test checks whether the variances of individual residual nutrient in the 3 replicas and in the total 75 plots are either significant ($p < 0.05$) or not ($p > 0.05$) and the analyzed results are tabulated in Table 4.14.

Table 4.14: Causative agents of variations of yields in the three replica plots (Test of Homogeneity of Variances)

Residual nutrients in soil	Levene Statistic	df1	df2	Significance (p)
Nitrogen (N)	4.094	2	72	0.021
Phosphorus (P)	8.491	2	72	0.000
Potassium (K)	1.006	2	72	0.371
Calcium (Ca)	81.705	2	72	0.000
Magnesium (Mg)	41.026	2	72	0.000
Manganese (Mn)	7.667	2	72	0.001
Soil pH	1.628	2	72	0.203

The results indicated that the three replica plots had varying amounts of Nitrogen ($p = 0.021$), Phosphorus ($p = 0.000$), Calcium ($p = 0.000$), Magnesium ($p = 0.000$) and Manganese ($p = 0.001$). The amount of these nutrients in the soil influences the level yield to be achieved and therefore explains why maize grain yield varied in the replica plots. The amounts of Potassium ($p = 0.371$) and pH ($p = 0.203$) were almost similar and imply that this two did not vary significantly in the three replica plots. Average residual nutrients available in the soil according to the levels of moisture is given in Figure 4.13 and based on nutrient fertilizer applied are presented in Figure 4.14. Detailed laboratory analysis results are attached in Appendix IV.

The study sought to explain in detail how the significant variations ($p < 0.05$) in residual nutrients were affecting the yields by relating the maize grain yields to the nutrient residual amounts in the soil after the crop had been harvested. The results of the residual nutrients mean and their ranking are compared with the level of maize grain yield and their significance derived. Tabulated analyses are presented in Table 4.14.

Table 4.15: Descriptive significance ranking of residual nutrients in the soil against the grain yield

Residual nutrients in soil	Replicas	N	NutrientsMean	Ranking score of residual nutrient in replica	Level of grain yield in the replica	Remarks
Nitrogen (N)	1	25	183.08	1	Highest Yield	Sufficient in Soil after Fertilizer Addition
	2	25	118.88	3	Average Yield	
	3	25	129.56	2	Lowest Yield	
Phosphorus (P)	1	25	16.72	3	Highest Yield	Fully utilized by crop despite 46% addition from Fertilizer (Insufficient in Soil)
	2	25	19.16	2	Average Yield	Utilized by crop to near exhaustion
	3	25	23.12	1	Lowest Yield	Phosphorus locked (Type of Soil)
Calcium (Ca)	1	25	1098.56	1	Highest Yield	Naturally Sufficient in the Replicas Soils
	2	25	907.2	2	Average Yield	Averagely Sufficient in the Replicas Soil
	3	25	600.32	3	Lowest Yield	Low Amounts in the Replicas Soils
Magnesium (Mg)	1	25	448.48	1	Highest Yield	Naturally Sufficient in the Replicas Soils
	2	25	410.32	2	Average Yield	Averagely Sufficient in the Replicas Soil
	3	25	282.96	3	Lowest Yield	Low Amounts in the Replicas Soils
Manganese (Mn)	1	25	158.44	1	Highest Yield	Naturally Sufficient in the Replicas Soils
	2	25	124.84	2	Average Yield	Averagely Sufficient in the Replicas Soil
	3	25	96.08	3	Lowest Yield	Low Amounts in the Replicas Soils

The study results indicated that the amount of residual content of Calcium, Magnesium and Manganese conformed to maize grain yields where high amount of residual nutrient content implied high yields and vice versa. This implied that these minerals residual levels were an indication of the sufficiency of the mineral available in the soil where high residual level meant high sufficiency in the soil and average residual level meant average occurrence and low residual level meant low occurrence in the specific replica under investigation. Magnesium and Manganese are naturally occurring as the mineral content of fine grained soils and was commonly found in the three replica plots but Calcium content was added through top dressing 27%N C:A:N fertilizer to replenish the right natural amount of calcium usually in the soil.

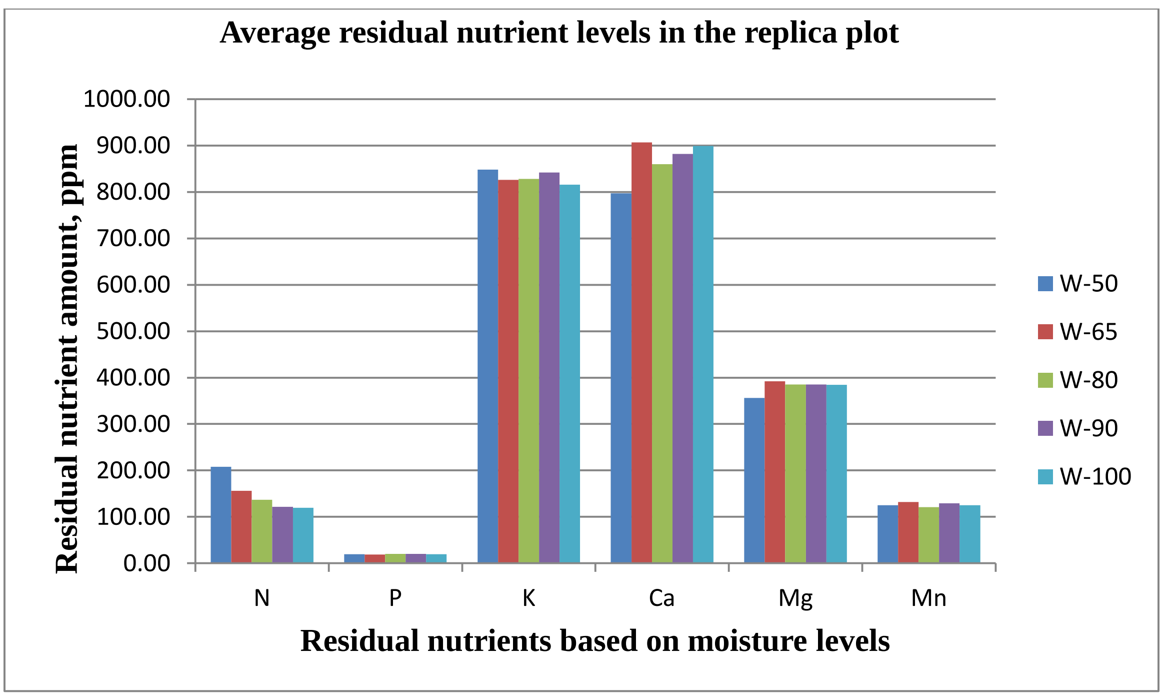

Figure 4.13: Comparisons of average residual nutrients according to the moisture level

Nitrogen and Phosphorus on the other hand were added to the soil through the inorganic N:P:K fertilizer in proportion of 18% Nitrogen and 46% Phosphorus and 0% Potassium. The maize crop required high amounts of Phosphorus hence the replica with the lowest residual amount of Phosphorus had the highest yield implying a high utilization of the Phosphorous while the replica with the highest residual amount had the lowest yield. This implied that replica plots with low yields had Phosphorus locked and never utilized by the crop maybe as a result of the soil structure qualities or formation of compounds with the available cations. Nitrogen was sufficient after addition in the soil with the replica with the highest residual content had the highest yield even though the one with the average yield had the lowest residual. Nitrogen boosts production vegetative growth in plants and may not necessarily translate into the grain yield of maize.

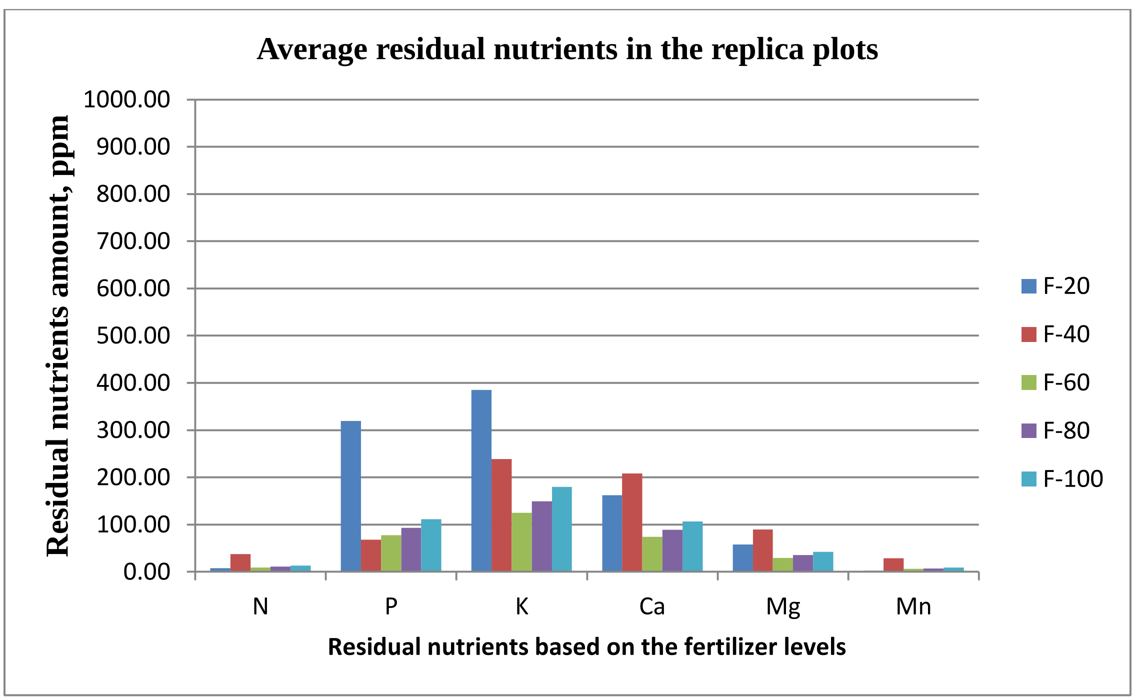

Figure 4.14: Comparisons of average residual nutrients according to the fertilizer level

4.3.2 Correlation between residual nutrients and dry maize grain yield

The study established how generally the dry grain yield of the demonstration plots correlate with the residual nutrients found in the soil after harvesting the maize crop.

Pearson Correlation and the 2-tailed significance of existing correlation were used and the results are shown in Table 4.16. The study results indicated that there was a significant correlation ($p<0.05$) of the grain yield and the residual content of phosphorus, potassium, calcium, magnesium and manganese in the soil but no significant correlation existed between the grain yield and nitrogen ($p = 0.320$) and pH ($p = 0.251$). Detailed results of the correlation are presented in Appendix III. The interpretation meant that the nitrogen added to the soil was converted into compounds that plants consume and could not be detected as elemental nitrogen.

Table 4.16: Correlation between the grain yield of maize and residual nutrients

	Residual Nutrient Nitrogen in soil	Residual Nutrient Phosphorus in soil	Residual Nutrient Potassium in soil	Residual Nutrient Calcium in soil	Residual Nutrient Magnesium in soil	Residual Nutrient Manganes e in soil	Soil pH level at Harvest
Pearson Correlation	0.116	-0.404**	0.283*	0.398**	0.387**	0.407**	-0.134
Significance (2-tailed)	0.32	0	0.014	0	0	0.001	0.251
N	75	75	75	75	75	75	75

<u>Note</u>

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

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

Consequently nitrogen converts to gaseous form and when application is remote from the plant roots then loss is experienced and may not contribute to maize grain yield. On the other hand the pH of the soil did not influence the grain yield because maize tolerates slightly acidic conditions and there were minimal variations in the demonstration plots.

Table 4.17: Relationship between Biomass and Residual Nutrients

Parameter		Residual Nutrient Nitrogen in soil	Residual Nutrient Phosphorus in soil	Residual Nutrient Potassium in soil	Residual Nutrient Calcium in soil	Residual Nutrient Magnesium in soil	Residual Nutrient Manganese in soil	Soil pH level at Harvest
Biomass	Pearson Correlation	0.018	-0.343**	0.174	0.320**	0.296**	0.313**	-0.053
	Sig. (2-tailed)	0.876	0.003	0.135	0.005	0.01	0.006	0.655
	N	75	75	75	75	75	75	75

Notes:

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

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

The study findings given in Table 4.17 indicated that there was a significant relationship ($p < 0.05$) between dry matter (biomass) and residual Phosphorus, Calcium, Magnesium and Manganese residuals in soil. The study also established that there was no significant relationship between residual Nitrogen ($p = 0.876$), Potassium ($p = 0.135$) and Soil pH ($p = 0.655$).

4.3.3 Correlation between residual nutrients with moisture and nutrient fertilizer

The study established the relationship between residual nutrients with the applied moisture content and Fertilizer amounts.

The results were correlated to assess the relationships that result and the nature of these relationships in the study presented in Table 4.18 as a combined correlation table of both fertilizer input and moisture application levels.

Table 4.18: Relationship between residual nutrients with moisture application and nutrient fertilizer input

		Residual Nutrient Nitrogen in soil	Residual Nutrient Phosphorus in soil	Residual Nutrient Potassium in soil	Residual Nutrient Calcium in soil	Residual Nutrient Magnesium in soil	Residual Nutrient Manganese in soil	Soil pH	Fertilizer input	Moisture application
Fertilizer input	Pearson Correlation	0.157	0.036	-0.238*	0.073	0.075	0.198	-0.171	1	0
	Significance (2-tailed)	0.18	0.757	0.04	0.533	0.521	0.089	0.144	0	1
	N	75	75	75	75	75	75	75	75	75
Moisture application	Pearson Correlation	-0.308**	0.039	-0.056	0.097	0.083	-0.014	0.364**	0	1
	Significance (2-tailed)	0.007	0.738	0.632	0.408	0.477	0.907	0.001	1	0
	N	75	75	75	75	75	75	75	75	75

Note

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

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

The study findings indicated that there was a relationship between the fertilizer input and the amount of residual Potassium in the soil ($p = 0.04$) and that there was a relationship between moisture application and residual nitrogen ($p = 0.007$) and soil pH ($p = 0.001$).

Potassium naturally in the soil forms complex compounds in the soil because it is highly reactive with fertilizer inputs. For nitrogen to be assimilated by the plant, moisture must be present else it would break down into nitrogen gas. Moisture facilitates the elements in the soil which vary the pH. There were no other relationships ($p > 0.05$) between fertilizer and moisture on the residuals nutrients that were in the soil.

4.4 Calibration and Validation of AquaCrop model using field data

The process of calibration of AquaCrop model running files and parameters for environment and maize crop was achieved using the results of data recorded from the research site. Local climatic data was recorded in a mini meteorological station and soil characteristics analyzed from observation pits and at the laboratory and the results saved in a text format uploaded into the model.

4.4.1 Calibration of maize crop characteristics

The default maize crop characteristics in the model were calibrated for the local climate and cultivar grown (Hybrid H629) in the research plots for the growing period from 15th April 2015 to 11th October 2015 (180 days from date of sowing). Actual results recorded from Saroiyot demonstration site were used to validate simulation results of the model. Table 4.19 contains calibration results of the maize crop file for both conservative and non-conservative (crop specific parameters) used in the simulation process.

Table 4.19 (a): Calibration of maize crop conservative parameters

S/No.	AquaCrop Parameter	Unit	Value
1	Initial canopy size of an individual seedling	cm^2	5.0
2	Duration of building up Harvest Index (HI)	days	60
3	Effect of canopy shelter in late season coefficient	%	25
4	Mulches coefficient	%	0
5	Crop transpiration coefficient (K_{cTr})	-	1.10
6	Crop transpiration coefficient (K_{cTr}) reduction (Ageing per day)	%	0.20
7	Crop water productivity for C4 crops normalized for climate and CO2 concentrations (WP^*)	g/m^2	30.7
8	Crop water productivity normalized for climate and CO_2 adjustment for yield formation (WP^*)	%	98
9	Effective rooting depth shape factor	-	1.0
10	Canopy expansion sensitivity to water stress	-	moderately sensitive
11	Soil water depletion for canopy expansion fraction (p) (upper limit)	-	0.20
12	Soil water depletion for canopy expansion fraction (p) (lower limit)	-	0.60
13	Stomatal closure sensitivity to water stress	-	moderately sensitive
14	Soil water depletion for stomatal closure fraction (p) (upper limit)	-	0.58
15	Early canopy senescence sensitivity to water stress	-	moderately sensitive
16	Soil water depletion for early canopy senescence fraction (p) (upper limit)	-	0.50
17	Shape factor coefficient for canopy expansion, stomatal closure and early canopy senescence	-	2.0
18	Allowable maximum increase of Harvest Index	%	10
19	Base threshold temperature for crop development	^oC	10
20	Upper threshold temperature for crop development	^oC	30
21	Minimum air temperature range for pollination effect by cold stress	^oC	+10
22	Maximum air temperature range for pollination effect by heat stress	^oC	+30
23	Crop response to soil salinity stress	-	moderately sensitive
24	Saturated electrical conductivity (EC_e) lower thresholds	ds/m	2
25	Saturated electrical conductivity (EC_e) upper thresholds	ds/m	12

Table 4.19 (b): Calibration of maize crop non-conservative parameters (cultivar specific)

S/No.	AquaCrop Parameter		Unit	Value
1	Initial crop canopy cover (CC_o)		%	0.27
2	Plant density population per hectare (spacing 0.75 m x 0.25 m)		No.	53,333
3	Canopy expansion development		-	Moderate
4	Canopy growth coefficient (CGC) per day		%	8.0
5	Maximum canopy cover development		-	Well covered
6	Maximum canopy cover		%	81.0
7	Canopy decline development		-	Very slow
8	Canopy decline coefficient (CDC) per day		%	6.5
9	Duration of canopy decline		day	40
10	Duration from day 1 after sowing to:	emergence	day	7
11		flowering	day	75
12		maximum canopy	day	110
13		start of senescence	day	135
14		maturity	day	180
15	Duration of flowering		day	34
16	Minimum effective rooting depth		m	0.3
17	Maximum effective rooting depth (medium deep rooted crop)		m	1.3
18	Duration from day 1 after sowing to maximum rooting depth		day	57
19	Average root zone expansion per day		cm	2.1
20	Amount of total pore volume under saturation for aeration stress		%	10
21	Reference Harvest Index (HI_o)		%	40
22	Crop water productivity performance under elevated CO_2 concentration sink strength		%	60
23	Reference carbon dioxide concentration [CO_2]		ppm	369.41

4.4.2 Calibration of irrigation scheduling parameters

The irrigation and field parameters are grouped under the management option in AquaCrop model. The model has the options of applying water required for crop production through rain-fed, irrigation or utilizing both options when irrigation is providing supplemental water during the growing season.

The concept of the research was deficit irrigation and therefore rain-fed condition was cut-off using rainfall shelter (Plate 3.2) and soil water content was controlled with the application using only drip irrigation layout on the plots (Plate 3.3). The model utilizes one of the three options when processing amount of the readily available water balance in the soil. The options include; net irrigation water requirement, irrigation schedule provided by the user and generation of irrigation schedule by the model. The research design used the option of generation of irrigation schedule by the model in the application of water through the drip irrigation system for the growing season. The option offers the criteria of timing indicating when to irrigate and the depth of moisture specifying how much to apply. The irrigation water quality was investigated in the laboratory and found pH=5.98 and conductivity=82.4 mg/l, both values specified during the calibration of the irrigation file.

During simulation of irrigation applications a scheduled irrigation towards the end of late season when the crop is undergoing maturity and drying period is cut off because the amount of water is no longer productive. AquaCrop model is not sensitive to the amount of moisture at crop maturity period and leaves unutilized water in the soil profile. The amount of water in deficit irrigation analysis is a wasted resource which should be utilized to improve on the water productivity of the crop. The irrigation schedule is planned to cut off any excess application within the last 10 days to maturity (harvest) and the crop yields are not affected because transpiration no longer causes any change to already attained crop yields. The irrigation cut off (stoppage) did not affect moisture level at W100 which utilized fully their scheduled amounts.

4.4.3 Calibration of the site soil characteristics

Soil water characteristics of the soil in the research site were investigated by excavating soil profile pits. The results indicated the presence of two distinct soil horizons and laboratory analysis of its hydraulic properties grouped the first 0.5m depth to comprise of clay loam and sandy clay loam extend beneath the top soil to about 2.0m below the soil surface. Generated hydraulic properties of the soil by AquaCrop model used in the simulation process are tabulated in Table 4.20.

Soil surface characteristics was considered based on the surface run-off water indicated by a curve number (CN) and soil evaporating surface layer of 0.04m calibrated by readily evaporable water (REW). The model simulation process considered default values of CN and REW of 72 and 11mm respectively.

Table 4.20: Generated soil hydraulic properties calibrated for Saroiyot farm

Description			Soil water content				Penetrability	
Horizon (m)	Soil type	Thickness (m)	TAW (mm/m)	PWP (vol. %)	FC (vol. %)	SAT (vol. %)	K_{sat} (mm/day)	tau
0 – 0.5	Clay Loam	0.5	172	18	35.2	50	125.0	0.47
0.5 – 1.5	Sandy Clay Loam	1.5	168	16	34	49	124.0	0.4

Capillary rise from ground water table was evaluated using the existing shallow well near the research plots where irrigation water was abstracted from. The surface of the ground water table in the well was about 8.0m below the soil surface during the crop growing period. The depth was calibrated for the model characteristics of the ground water table.

4.4.4 AquaCrop model simulation and validation results

The simulation covers the period of maize growing cycle from 15th April 2015 to 11th October 2015. Soil water content available in the profile during sowing was considered as the initial soil moisture condition recorded from the measurements of the excavated pits and the value was found to be at field capacity.

Canopy trends observed during the growing period showed unique partition within the crop growth stages. All the graphs and trends of the various moisture application levels were similar in the initial and development stages up to a transition point at day 85 when nutrition in the soil is depressed and therefore the 2nd top dressing of C: A: N was applied. The transition was marked by a near constant canopy cover over a decade then a new enhanced growth rate is noticed after day 90 to attain the maximum canopy cover (CC_{max}) which was attained at approximately day 106 from day of sowing. Unique constant value displayed by the graphs coincides with the decade when lower (base) leaves dried at the end of the development stage. Occurrence of enhanced growth is attributed to utilization of nutrient fertilizer applied as top dressing that facilitated green canopy growth and led to distinguished trends according to moisture application levels.

The period of unique canopy growth behavior at the end of the crop development growth stage and a transition undergoing into the mid-season stage marked the initiation of maize crop tasseling period that covered the period between day 85 and day 100. During tasseling the maize crop was unfolding younger leaves and tassels at the head that led to the increase in the canopy cover growth measurement. In all the plots and treatment combinations, moisture application level of W_{65} and W_{80} recorded the highest average and comparable values of 83.2% and 82.7% respectively. At the end of tasseling stage the maize crop began grain filling and ripening stage when canopy cover senescence sets in with a slow decline for a period of 45 days throughout the mid-season stage. Canopy cover decline during the late season stage lasted for about 30 days.

AquaCrop model simulation of soil water content measurements at the demonstration plots is based on its mathematical formulation. The model divides the total rooting zone soil profile into compartments of equal depths where soil water content is calculated at the centre of each compartment (FAO, 2017). Mathematical interpolation is used to generate and sum up the whole rooting depth water content based on the calibrated soil properties.

Soil physical properties of Saroiyot site was investigated using excavated pits when the moisture condition at the surface was at field capacity. The results showed that near the surface at depth of 0.15m the moisture content was averaged at 35.2% (volumetric basis). The value gradually reduces throughout the profile to about 23.0% at a depth of about 1.0m. Both the dry and bulk densities of the same site indicated an increase of their values through the soil profile. This result suggests modification of the local condition of soil properties to have experienced compaction as a result of land preparation machinery and therefore may influence the results of the simulations.

4.4.4 (i) Simulation results of AquaCrop model calibration

Assessment of calibrated model under no stress condition ($F_{100}W_{100}$) was done using field data measurements of maize grain yield, canopy cover and soil water content carried out throughout the crop growing season. The results represent the real situation at the site for the period under simulations.

Data used in AquaCrop model calibration are tabulated in Tables 4.19 (a) and (b) and the simulation results of canopy cover correlation trends are presented in Figure 4.15 (a) and (b). The results verify strongly that the model is well tuned and appropriate for accurate simulations of maize crop water productivity analysis at Saroiyot demonstration site.

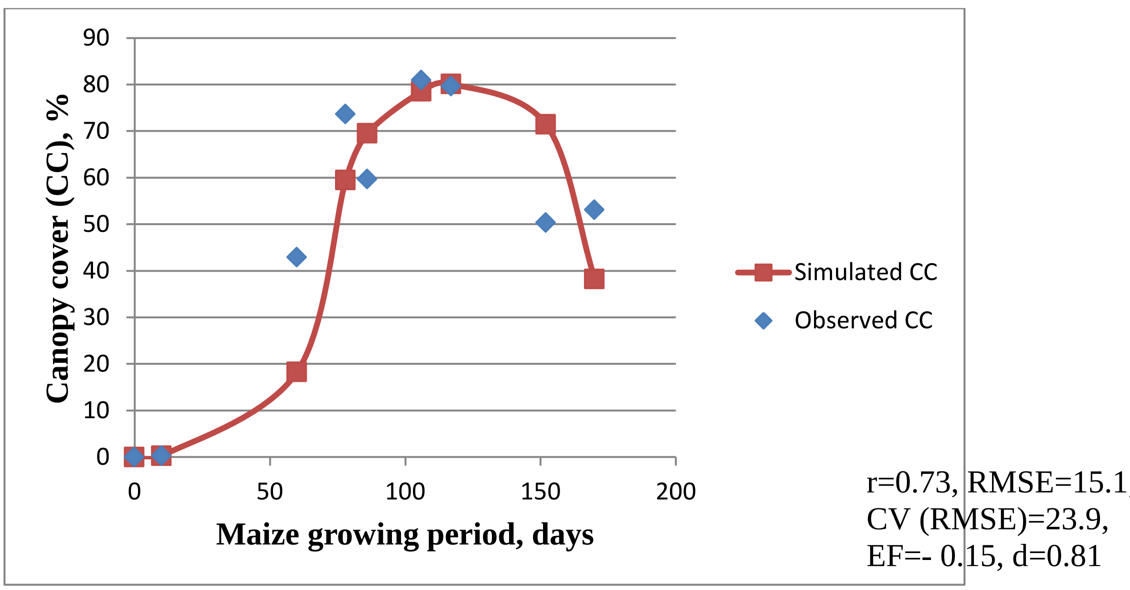

Figure 4.15 (a): Green Canopy cover trends for $W_{100}F_{100}$ treatment

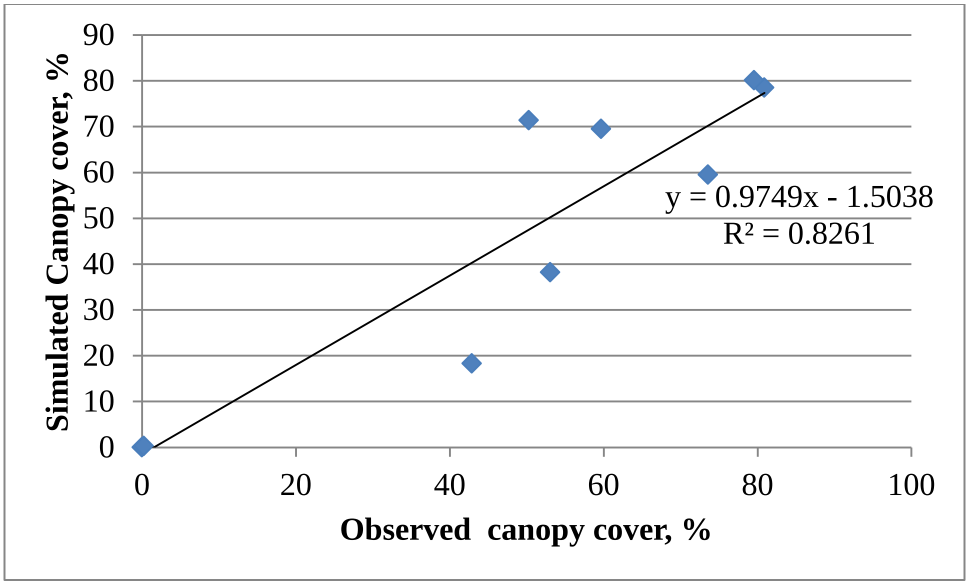

Figure 4.15 (b): Correlation of observed and simulated canopy cover for $W_{100}F_{100}$ treatment

4.4.4 (ii) Validation results of AquaCrop model simulation of calibration

Validation of calibrated AquaCrop model was carried out using designed deficit irrigation application levels of W_{90}, W_{80}, W_{65} and W_{50} for field data measurements of canopy cover, soil water content and maize grain yield. Biomass production was measured only at the end of cropping cycle.

Simulation results of canopy cover are presented in Figure 4.16 (a) and (b) to Figure 4.19 (a) and (b). The model accurately simulates the growth of canopy cover and the crop grain yield production under limited water application at various levels.

Statistical correlation values (R^2) of various treatments of deficit irrigated plots ranged from 0.736 to 0.868 for moisture treatment levels between W_{50} and W_{90}; however a maximum value of 0.8706 was recorded at W_{80}.

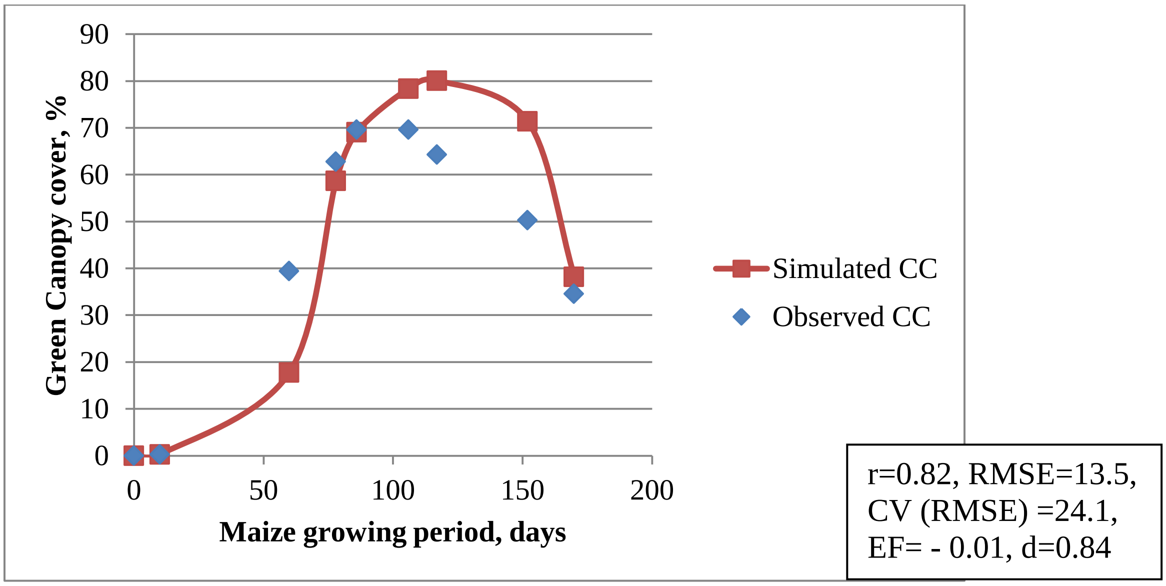

Figure 4.16 (a): Green Canopy cover trends for $W_{90}F_{100}$ treatment

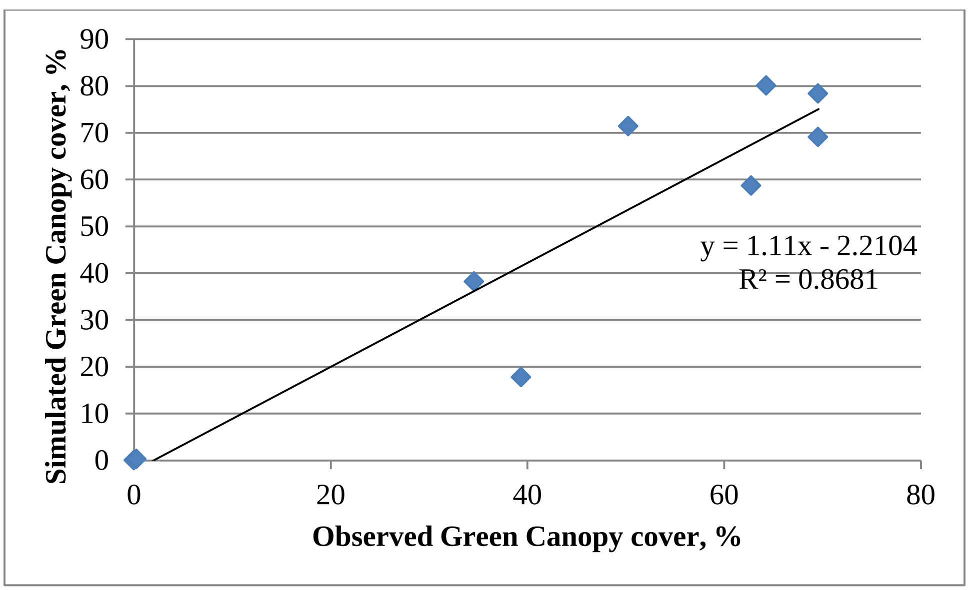

Figure 4.16 (b): Correlation of Green Canopy cover trends for $W_{90}F_{100}$ treatment

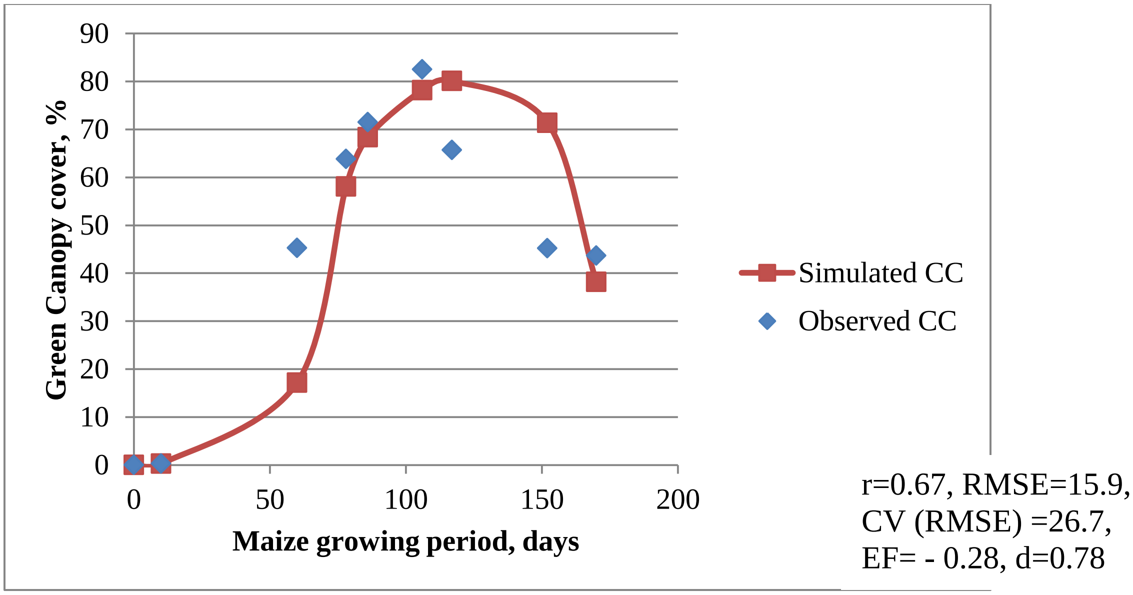

Figure 4.17 (a): Green Canopy cover trends for $W_{80}F_{100}$ treatment

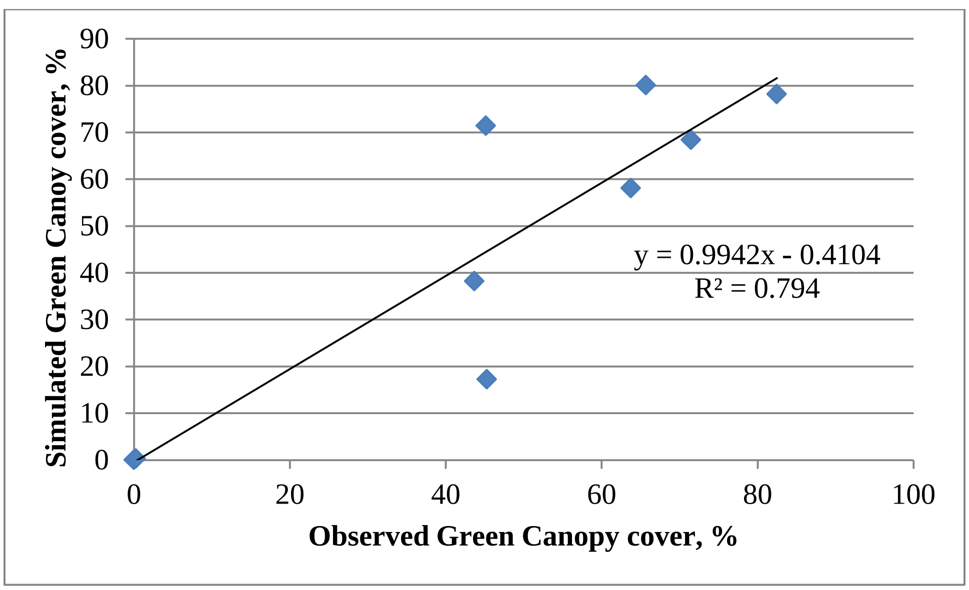

Figure 4.17 (b): Correlation of Green Canopy cover trends for $W_{80}F_{100}$ treatment

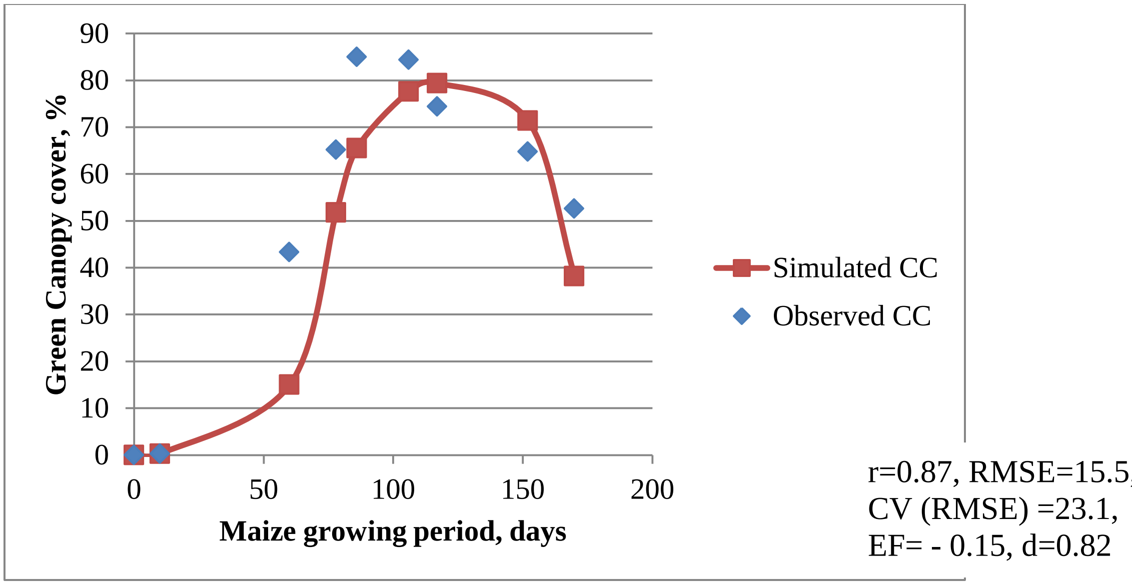

Figure 4.18 (a): Green Canopy cover trends for $W_{65}F_{100}$ treatment

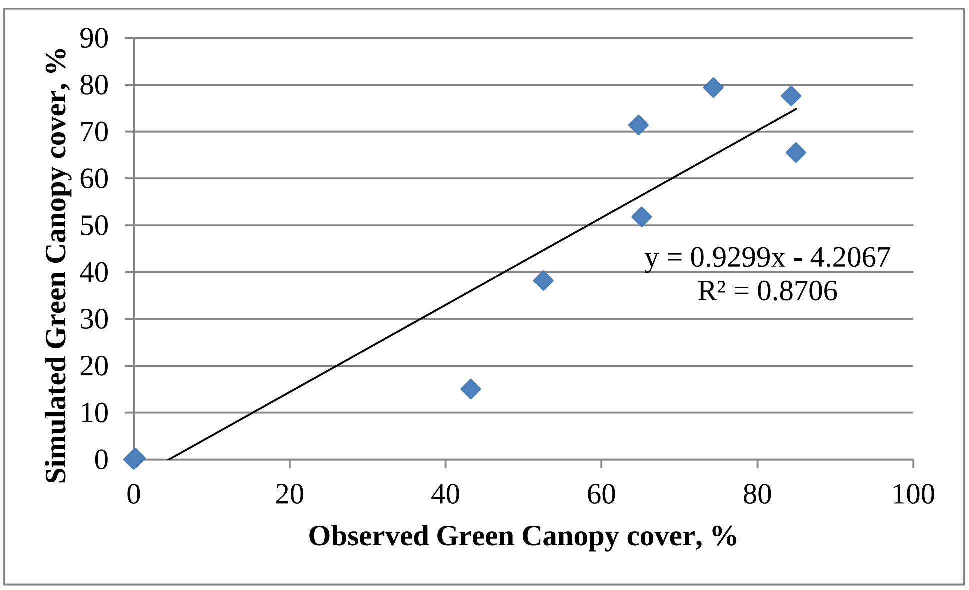

Figure 4.18 (b): Green Canopy cover trends for $W_{65}F_{100}$ treatment

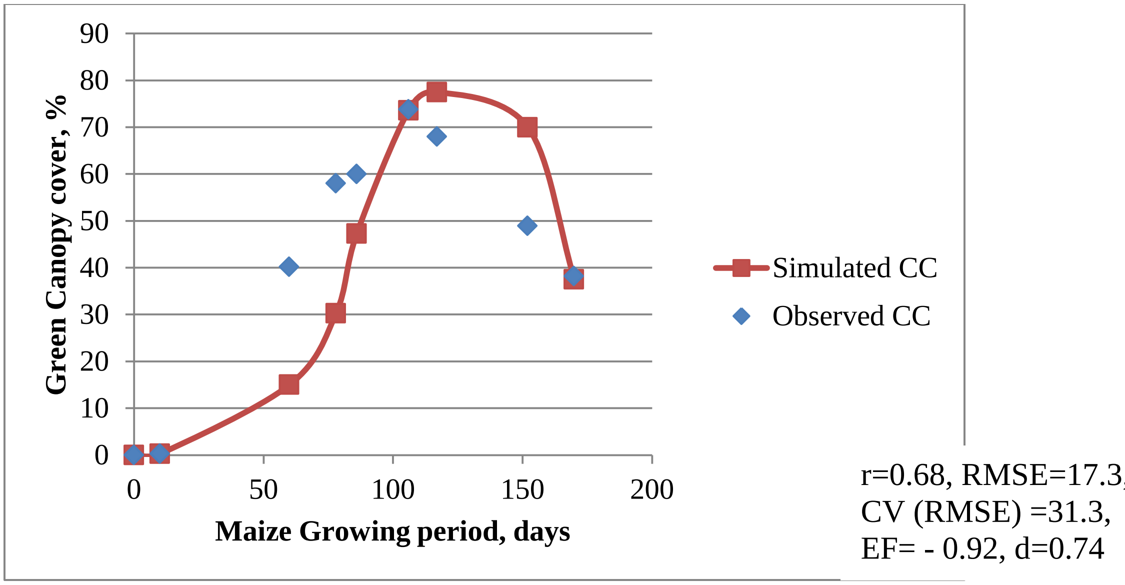

Figure 4.19 (a): Green Canopy cover trends for $W_{50}F_{100}$ treatment

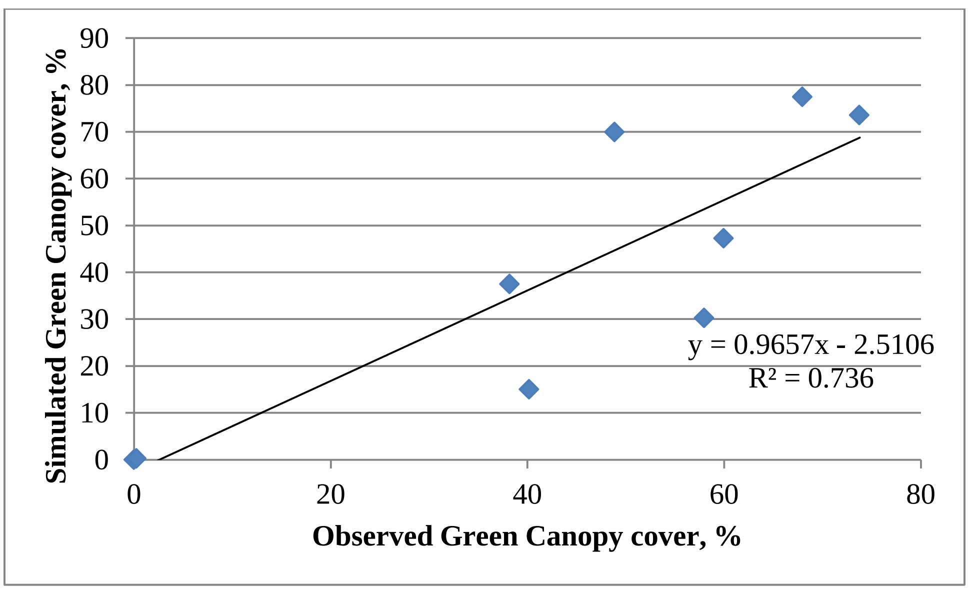

Figure 4.19 (b): Green Canopy cover trends for $W_{50}F_{100}$ treatment

Simulation of dry maize grain yields are presented in Figure 4.20 (a) and (b) for deficit irrigation treatments and support the model calibration for assessing crop water productivity. The enhanced dry yields of 10.99 ton/ha obtained for $W_{90}F_{100}$ is above the simulation value and is considered to be responsible for average correlation value R^2 = 0.5103. Higher yields are attributed to sufficient moisture in the soil throughout the growing cycle coupled with the influence of localized residual nutrients ready to cause efficient fertilizer mobilization into the roots.

AquaCrop model simulation of dry grain yields record increases from a lower yield value associated with lower deficit irrigation moisture treatment of 50% and increase to a maximum dry yield value at 80% moisture level then drop to the calibration yield value at 100% moisture level. The smooth curve is defined by the mathematical model depending on the grain yield level at W_{100} during calibration process.

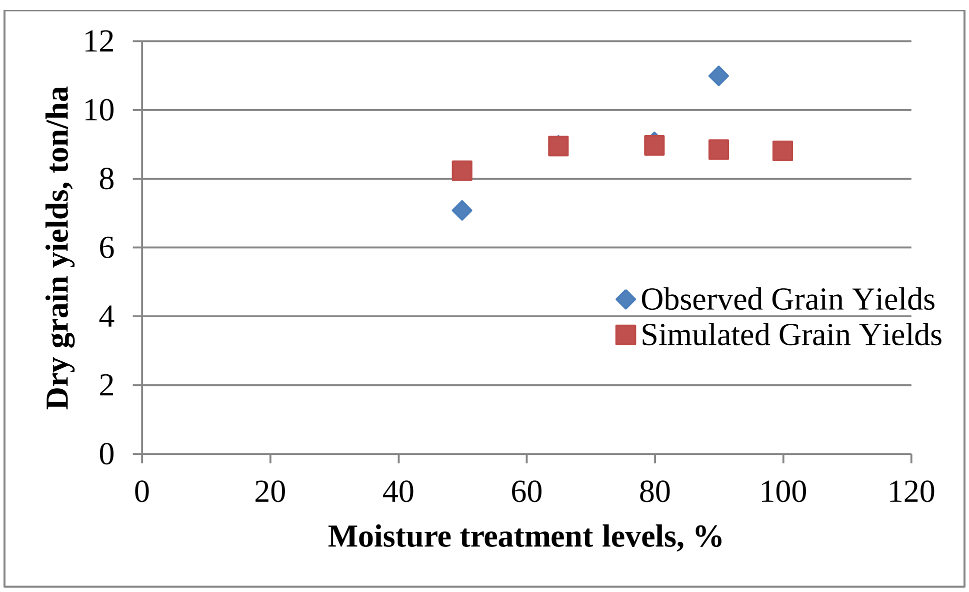

Figure 4.20 (a) Observed and simulated dry grain yields under moisture treatment levels

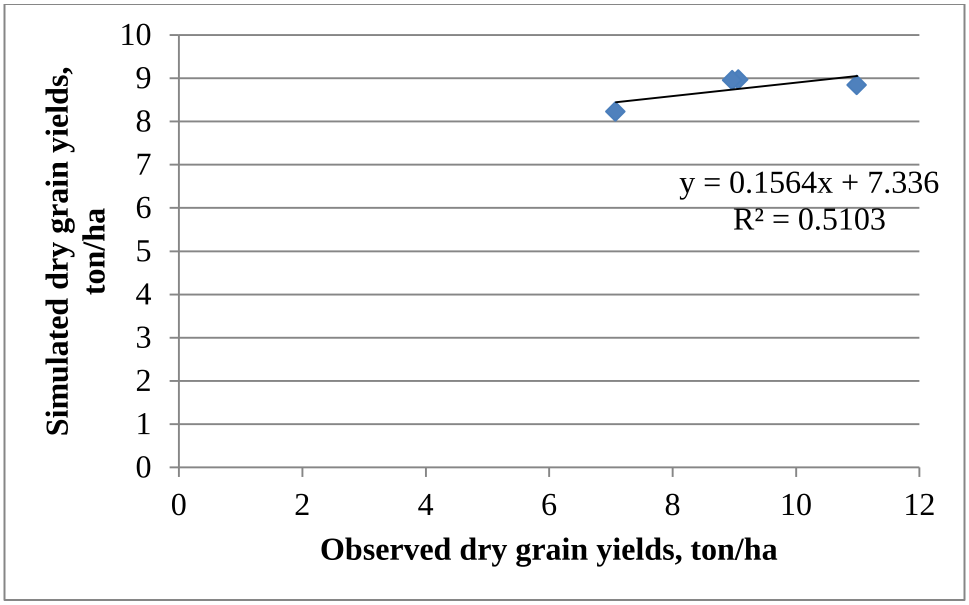

Figure 4.20 (b) Correlation of observed and simulated dry grain yields for W_{90}, W_{80}, W_{65} and W_{50}

Field measurement procedure adopted during soil water content analysis involved every decade sampling the soil at approximate profile depth of about 0.30m for all the 75 plots on the same day. The depth constitutes the top quarter of the rooting zone where maximum rooting growth and moisture depletion occur. Because of deficit irrigation application of water, the plots were at different levels of depleted moisture contents depending on the respective design levels at the time of sampling. Laboratory determination results are presented in unit of millimeters of water (mmH_2O) per unit meter depth of the soil profile. Total rooting zone soil water content for maize crop was then derived by multiplying with the root zone depth. Variations in the soil water storage recorded are attributed to the mathematical procedure by AquaCrop model and gravimetric method used in sampling may influence correlation results presented in Figure 4.21(a) and (b).

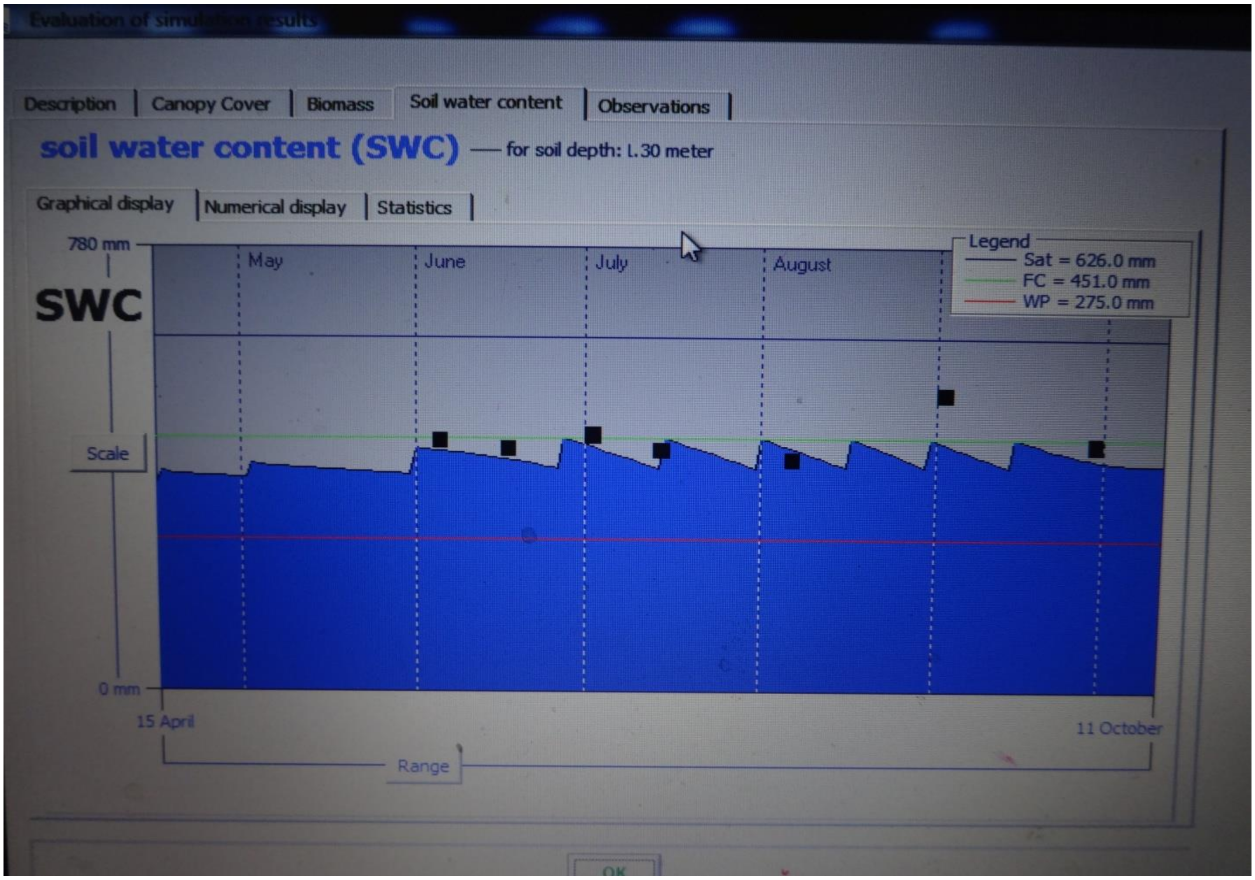

Plate 4.1: AquaCrop model Soil Water Content simulation for $W_{100}F_{100}$ treatment

The results of irrigation water profile and available soil water content (mm of water) presented in Plate 4.1 is defined by the amounts of depletion and replenishment presented as zig-zag trends. To achieve closer correlations of results require higher number of data points by sampling at least three soil moisture measurements within a decade for the whole cropping cycle.

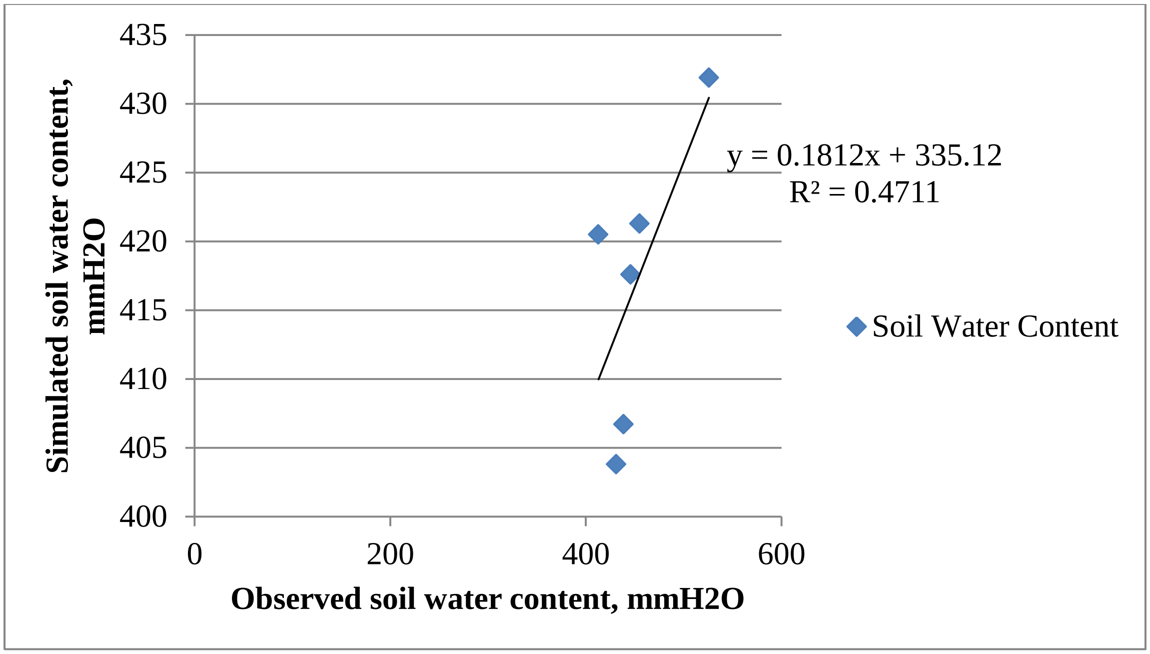

Figure 4.21 (a): Correlation of observed and simulated soil water content for $F_{100}W_{100}$ treatment

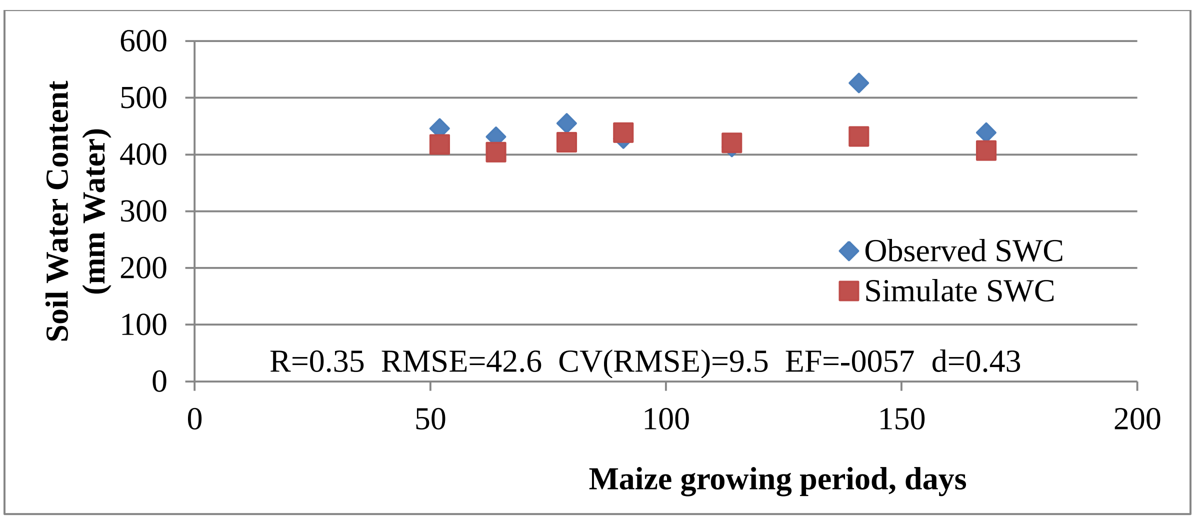

Figure 4.21 (b): AquaCrop model Soil Water Content simulation for $W_{100}F_{100}$ treatment

4.4.5 AquaCrop model calibration and validation for different levels of nutrient fertilizer

Contribution of different nutrient fertilizer levels on maize grain yields were assessed by model calibration under no moisture stress condition (W_{100}) using field record data measurements of maize grain yield, canopy cover and soil water content for $F_{80}W_{100}$, $F_{60}W_{100}$, $F_{40}W_{100}$ and $F_{20}W_{100}$ for the crop growing season. Calibration data used in AquaCrop model calibration are tabulated in Tables 4.21 (a), (b) and (c).

Table 4.21 (a): Calibration of constant maize crop conservative parameters for nutrient fertilizer treatment levels (F_{20}, F_{40}, F_{60} and F_{80})

S/No.	AquaCrop Parameter	Unit	Value
1	Initial canopy size of an individual seedling	cm^2	5.0
2	Effect of canopy shelter in late season coefficient	%	25
3	Mulches coefficient	%	0
4	Crop transpiration coefficient (K_{cTr}) reduction (Ageing per day)	%	0.20
5	Allowable maximum increase of Harvest Index	%	10
6	Base threshold temperature for crop development	^oC	10
7	Upper threshold temperature for crop development	^oC	30
8	Minimum air temperature range for pollination effect by cold stress	^oC	+10
9	Maximum air temperature range for pollination effect by heat stress	^oC	+30
10	Crop response to soil salinity stress	-	moderately sensitive
11	Saturated electrical conductivity (EC_e) lower thresholds	ds/m	2
12	Saturated electrical conductivity (EC_e) upper thresholds	ds/m	12

Table 4.21 (b): Calibration of maize crop conservative parameters specific for nutrient fertilizer treatment levels (F_{20}, F_{40}, F_{60} and F_{80})

S/No.	AquaCrop Parameter	Unit	Values			
			F_{20}	F_{40}	F_{60}	F_{80}
1	Duration of building up Harvest Index (HI)	days	60	65	65	70
2	Crop transpiration coefficient (K_{cTr})	-	1.0	1.05	1.0	1.2
3	Canopy expansion sensitivity to water stress	-	moderately sensitive	moderately sensitive	moderately sensitive	sensitive
5	Soil water depletion for canopy expansion fraction (p) (upper limit)	-	0.20	0.20	0.20	0.15
6	Soil water depletion for canopy expansion fraction (p) (lower limit)	-	0.50	0.50	0.50	0.45
7	Stomatal closure sensitivity to water stress	-	Extremely sensitive	Extremely sensitive	Extremely sensitive	moderately sensitive
8	Soil water depletion for stomatal closure fraction (p) (upper limit)	-	0.25	0.25	0.25	0.50
9	Early canopy senescence sensitivity to water stress	-	Extremely sensitive	Extremely sensitive	Extremely sensitive	moderately sensitive
10	Soil water depletion for early canopy senescence fraction (p) (upper limit)	-	0.35	0.35	0.35	0.51

Table 4.21 (c): Calibration of maize crop non-conservative parameters (cultivar specific) specific to nutrient fertilizer treatment levels

S/No.	AquaCrop Parameter		Unit	Values			
				F_{20}	F_{40}	F_{60}	F_{80}
1	Initial crop canopy cover (CC_o)		%	0.27	0.27	0.27	0.27
2	Plant density population per hectare (spacing 0.75 m x 0.25 m)		No.	53,333	53,333	53,333	53,333
3	Canopy expansion development		-	Moderate	Moderate	Moderate	Moderate
4	Canopy growth coefficient (CGC) per day		%	8.1	8.1	8.2	10.0
5	Maximum canopy cover development		-	Fairly covered	Fairly covered	Well covered	Fairly covered
6	Maximum canopy cover		%	70	79	83	79
7	Canopy decline development		-	Very slow	Very slow	Very slow	Very slow
8	Canopy decline coefficient (CDC) per day		%	6.9	6.1	6.1	7.1
9	Duration of canopy decline		day	40	46	47	40
10	Duration from day 1 after sowing to:	emergence	day	7	7	7	7
11		flowering	day	75	75	75	70
12		maximum canopy	day	107	109	108	89
13		start of senescence	day	140	133	132	140
14		maturity	day	180	180	180	180
15	Duration of flowering		day	37	40	40	40
16	Minimum effective rooting depth		m	0.3	0.3	0.3	0.3
17	Maximum effective rooting depth (medium deep rooted crop)		m	1.3	1.3	1.3	1.3
18	Duration from day 1 after sowing to maximum rooting depth		day	57	57	57	57
19	Average root zone expansion per day		cm	2.1	2.1	2.1	2.1
20	Amount of total pore volume under saturation for aeration stress		%	10	10	10	10
21	Reference Harvest Index (HI_o)		%	40	40	40	40
22	Crop water productivity performance under elevated CO_2 concentration sink strength		%	60	60	60	60
23	Reference carbon dioxide concentration [CO_2]		ppm	369.41	369.41	369.41	369.41

Calibration of nutrient fertilizer levels $F_{80}W_{100}$ results of canopy cover simulation and their correlation trends are presented in Figure 4.22 (a) and (b).

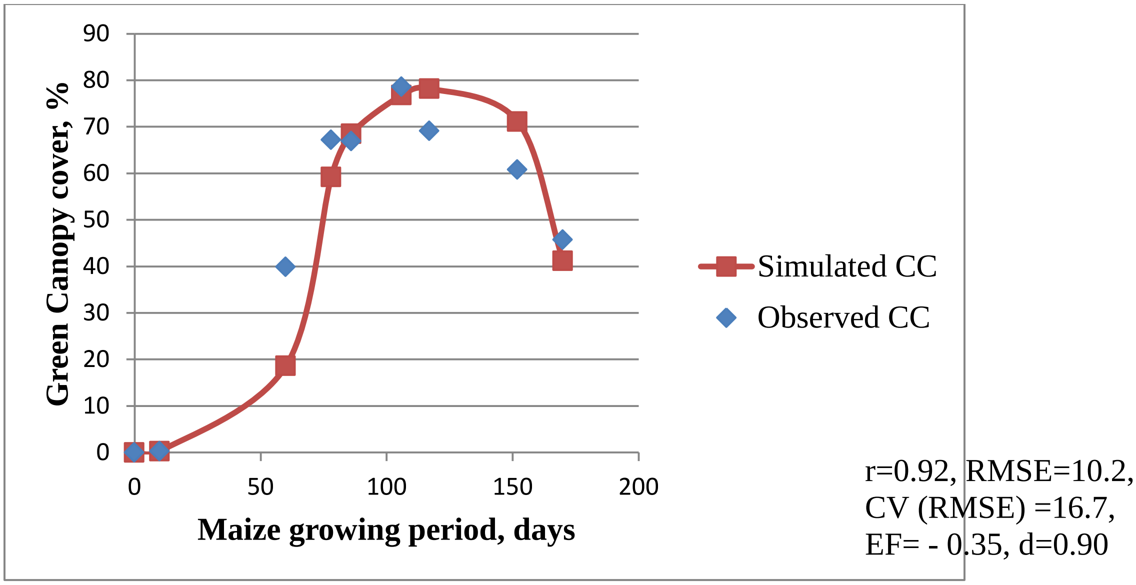

Figure 4.22 (a): Green Canopy cover trends for $F_{80}W_{100}$ treatment

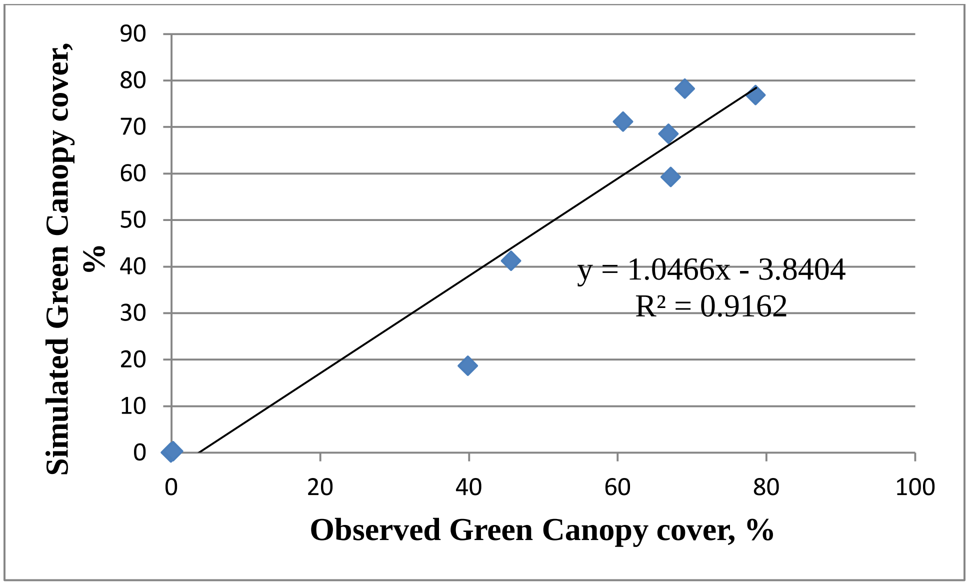

Figure 4.22 (b): Correlation of Green Canopy cover trends for $F_{80}W_{100}$ treatment

Validation simulation results of $F_{80}W_{100}$ using $F_{80}W_{90}$, $F_{80}W_{80}$, $F_{80}W_{65}$ and $F_{80}W_{50}$ Canopy cover correlations and maize grain yields are presented in Figure 4.23 (a) – (d) and Figure 4.24 (a) and (b).

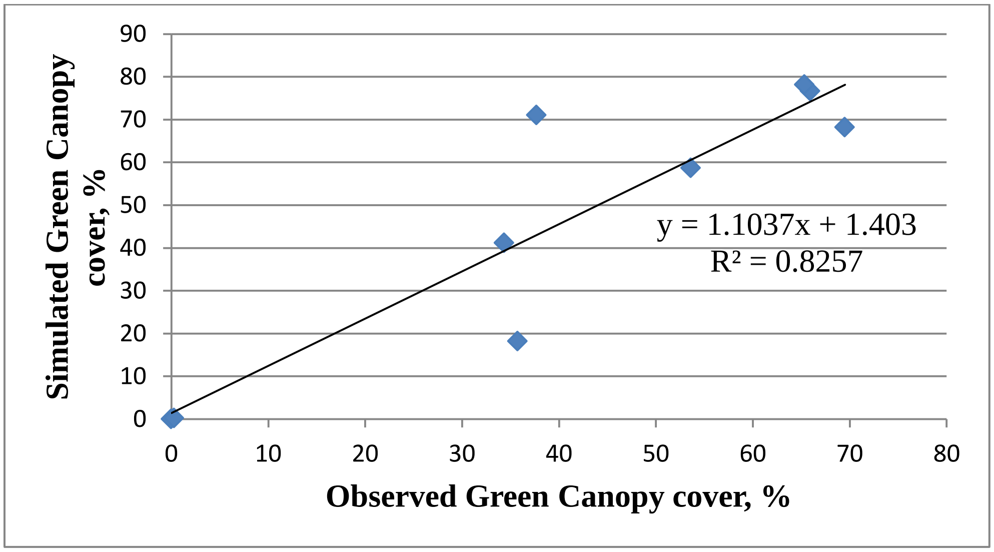

Figure 4.23 (a): Correlation of Green Canopy cover trends for $F_{80}W_{90}$ treatment

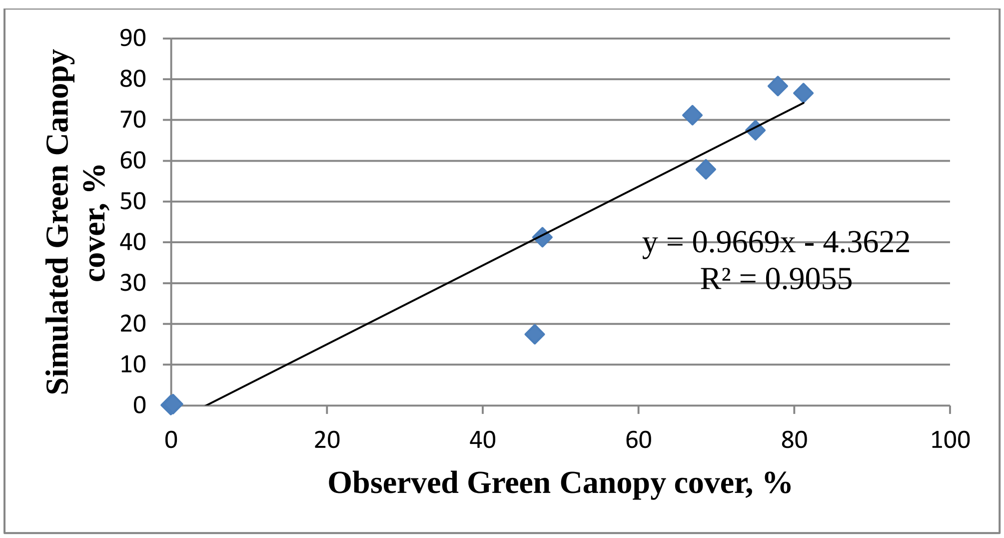

Figure 4.23 (b): Correlation of Green Canopy cover trends for $F_{80}W_{80}$ treatment

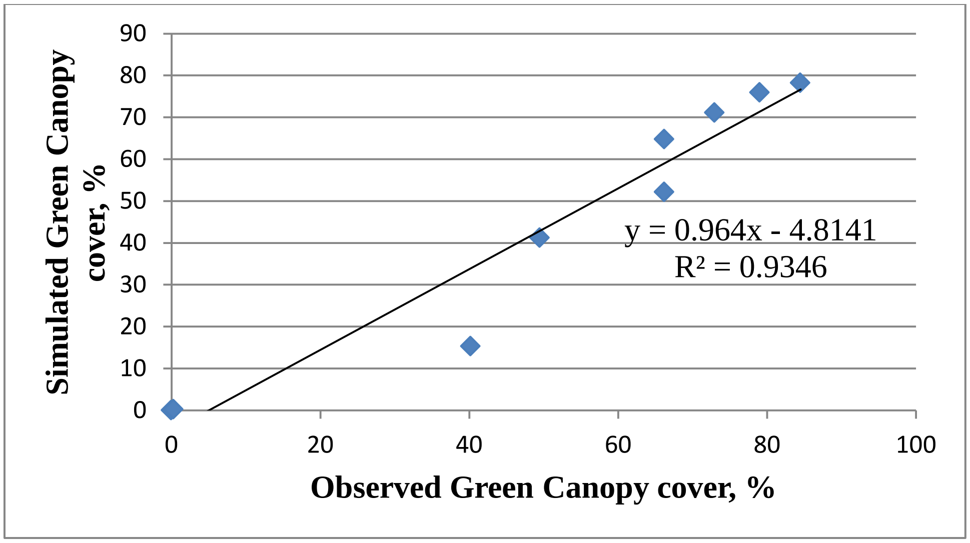

Figure 4.23 (c): Correlation of Green Canopy cover trends for $F_{80}W_{65}$ treatment

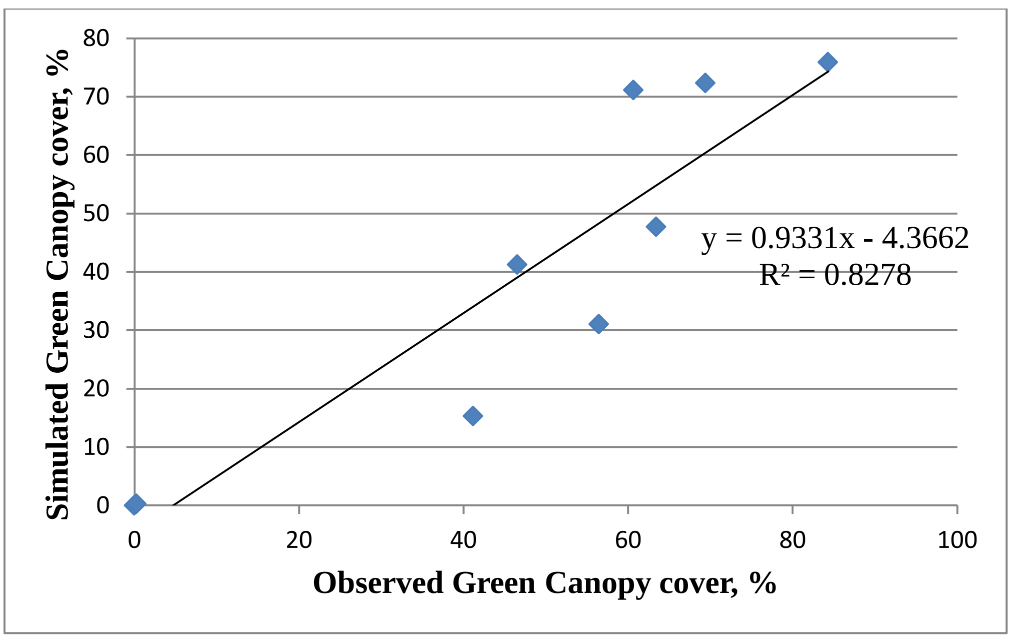

Figure 4.23 (d): Correlation of Green Canopy cover trends for $F_{80}W_{50}$ treatment

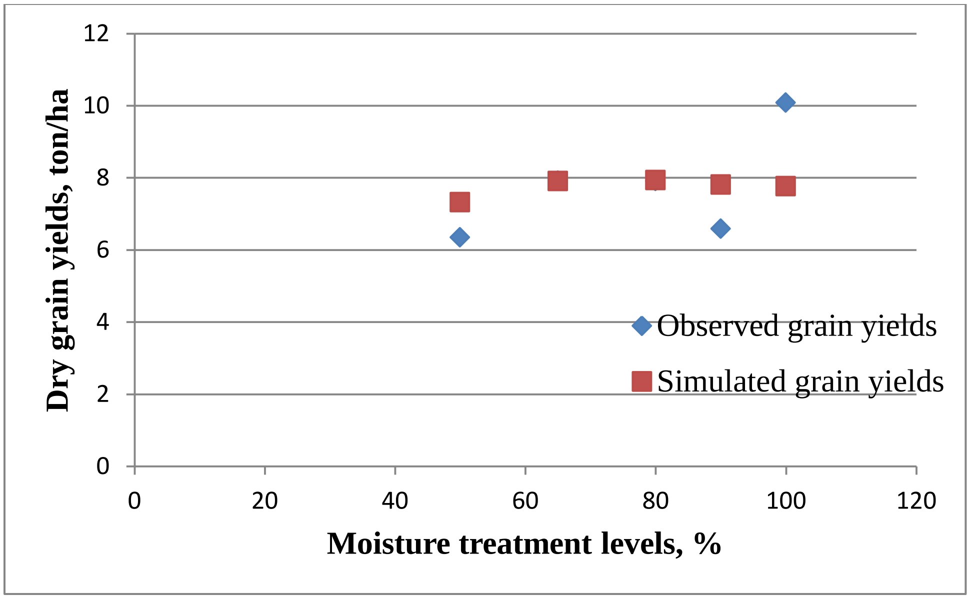

Figure 4.24 (a) Validation results of dry grain yields for treatment levels of $F_{80}W_{90}$, $F_{80}W_{80}$, $F_{80}W_{65}$ and $F_{80}W_{50}$

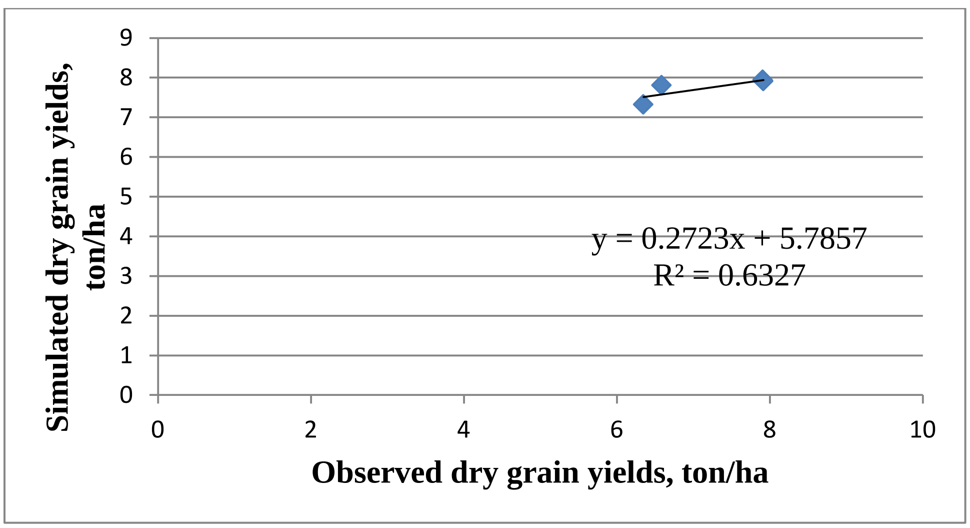

Figure 4.24 (b) Correlation results of observed and simulated dry grain yields for treatment levels of $F_{80}W_{90}$, $F_{80}W_{80}$, $F_{80}W_{65}$ and $F_{80}W_{50}$

Calibration of nutrient fertilizer levels $F_{60}W_{100}$ results of canopy cover simulation and their correlation trends are presented in Figure 4.25 (a) and (b).

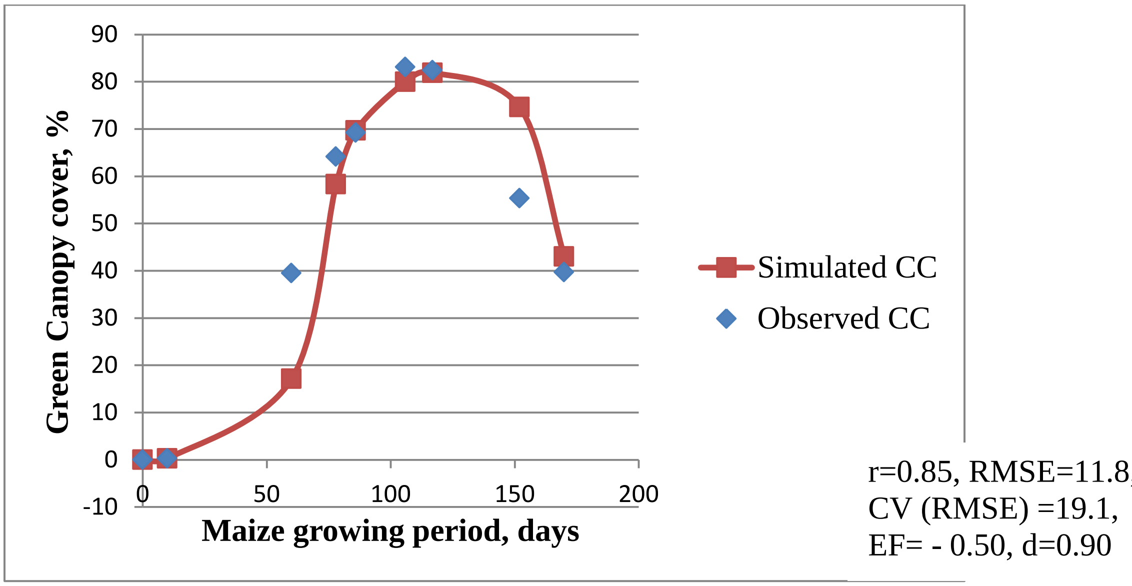

Figure 4.25 (a): Green Canopy cover trends for $F_{60}W_{100}$ treatment

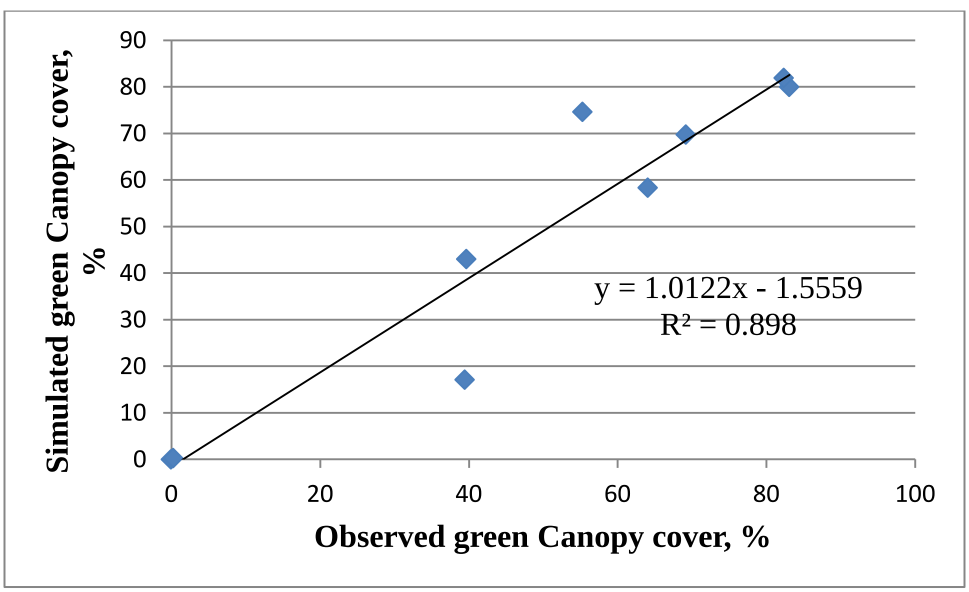

Figure 4.25 (b): Correlation of Green Canopy cover trends for $F_{60}W_{100}$ treatment

Validation simulation results of $F_{60}W_{100}$ using $F_{60}W_{90}$, $F_{60}W_{80}$, $F_{60}W_{65}$ and $F_{60}W_{50}$ Canopy cover correlations and maize grain yields are presented in Figure 4.26 (a) – (d) and Figure 4.27 (a) and (b).

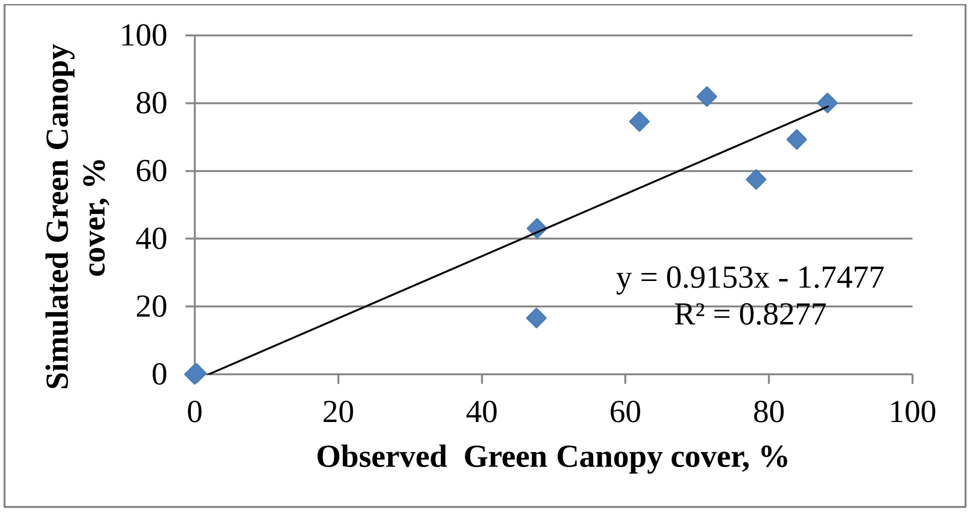

Figure 4.26 (a): Correlation of Green Canopy cover trends for $F_{60}W_{90}$ treatment

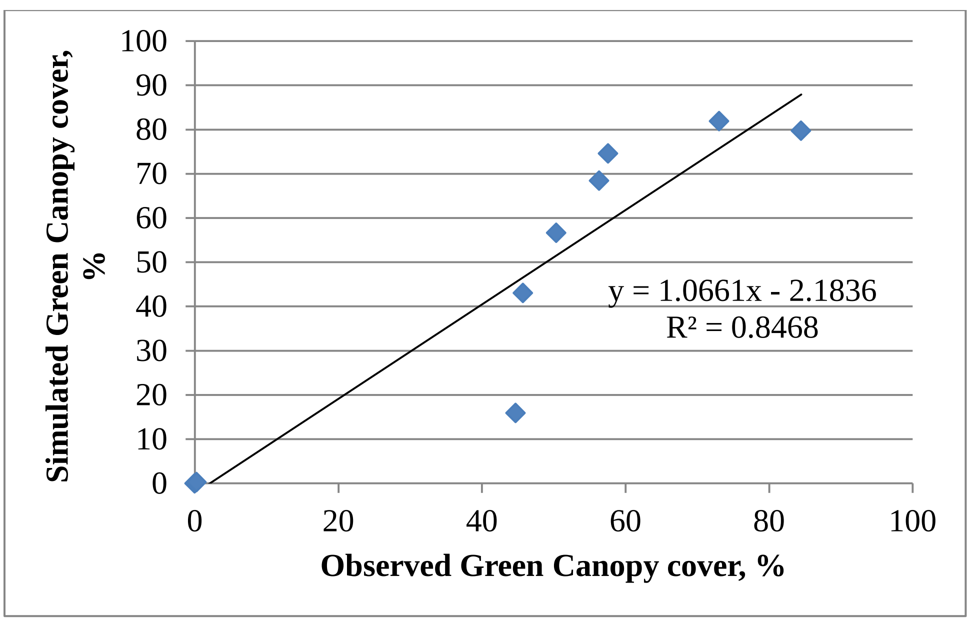

Figure 4.26 (b): Correlation of Green Canopy cover trends for $F_{60}W_{80}$ treatment

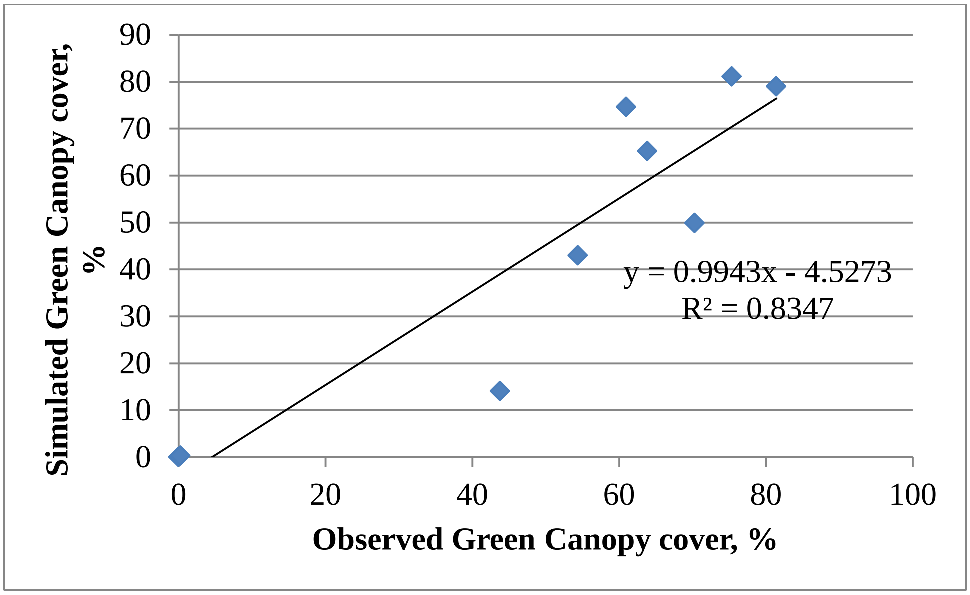

Figure 4.26 (c): Correlation of Green Canopy cover trends for $F_{60}W_{65}$ treatment

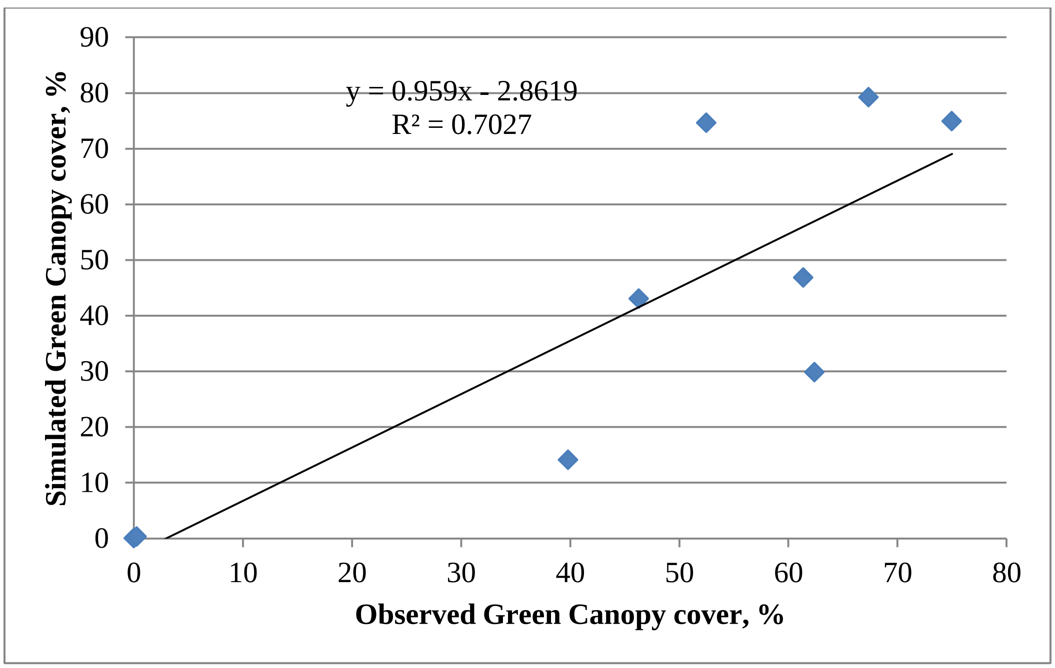

Figure 4.26 (d): Correlation of Green Canopy cover trends for $F_{60}W_{50}$ treatment

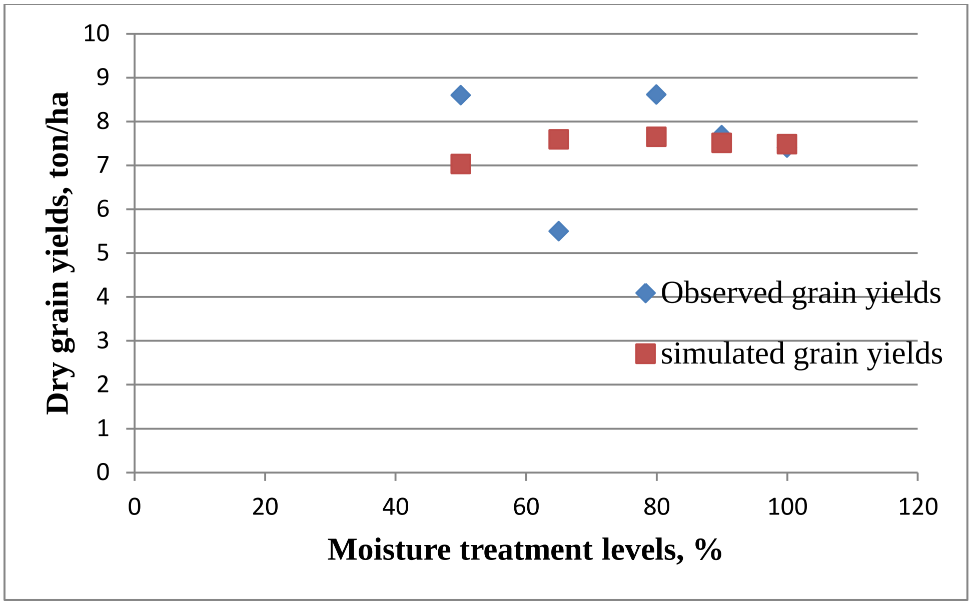

Figure 4.27 (a) Validation results of dry grain yields for treatment levels of $F_{60}W_{90}$, $F_{60}W_{80}$, $F_{60}W_{65}$ and $F_{60}W_{50}$

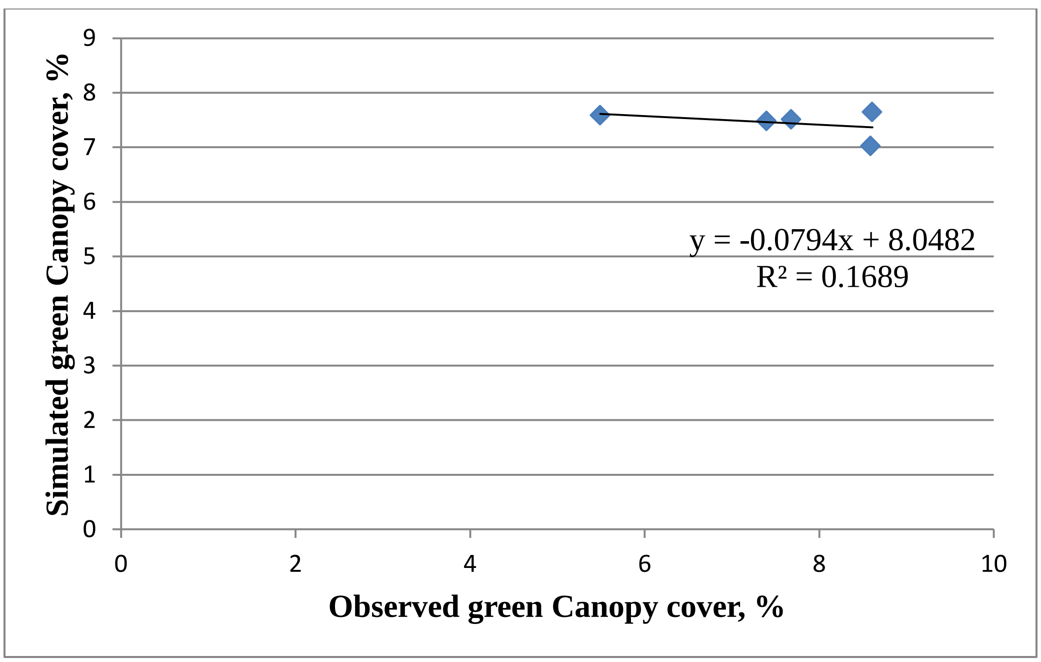

Figure 4.27 (b) Correlation results of observed and simulated dry grain yields for treatment levels of $F_{60}W_{90}$, $F_{60}W_{80}$, $F_{60}W_{65}$ and $F_{60}W_{50}$

Calibration of nutrient fertilizer levels $F_{40}W_{100}$ results of canopy cover simulation and their correlation trends are presented in Figure 4.28 (a) and (b).

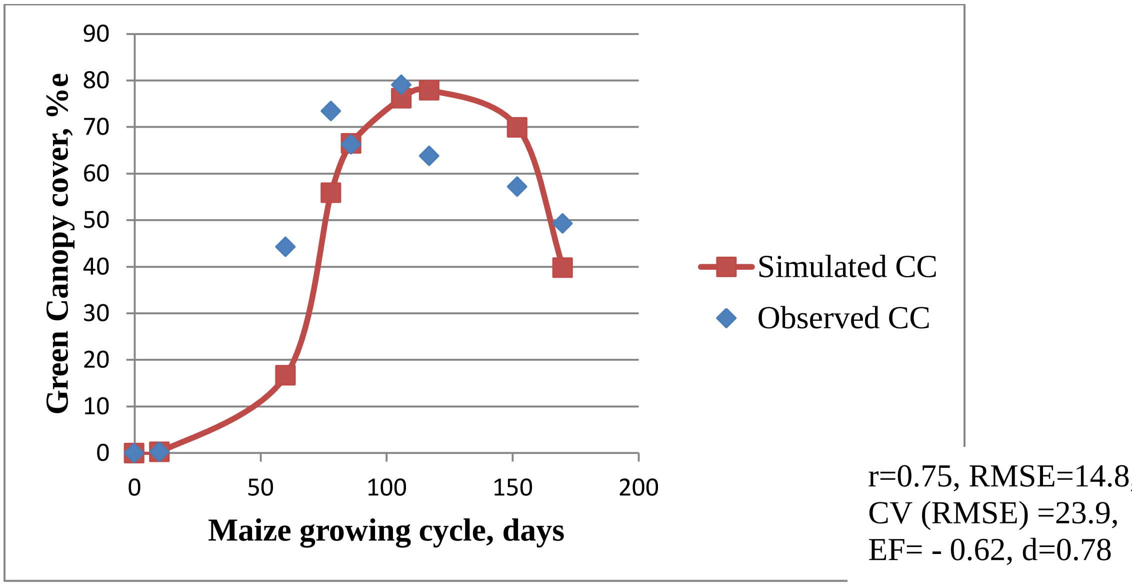

Figure 4.28 (a): Green Canopy cover trends for $F_{40}W_{100}$ treatment

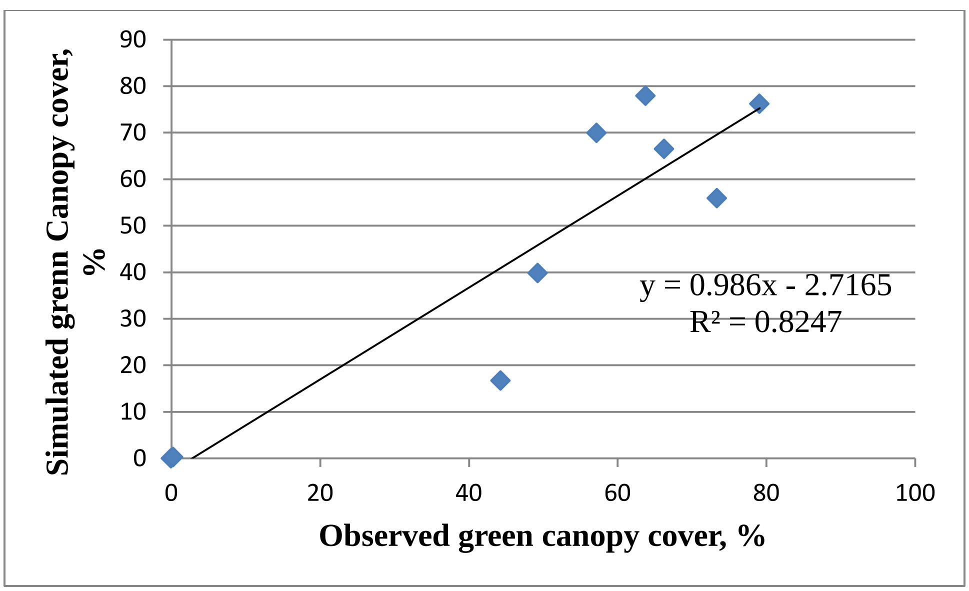

Figure 4.28 (b): Correlation of Green Canopy cover trends for $F_{40}W_{100}$ treatment

Validation simulation results of $F_{40}W_{100}$ using $F_{40}W_{90}$, $F_{40}W_{80}$, $F_{40}W_{65}$ and $F_{40}W_{50}$ Canopy cover correlations and maize grain yields are presented in Figure 4.29 (a) – (d) and Figure 4.30 (a) and (b).

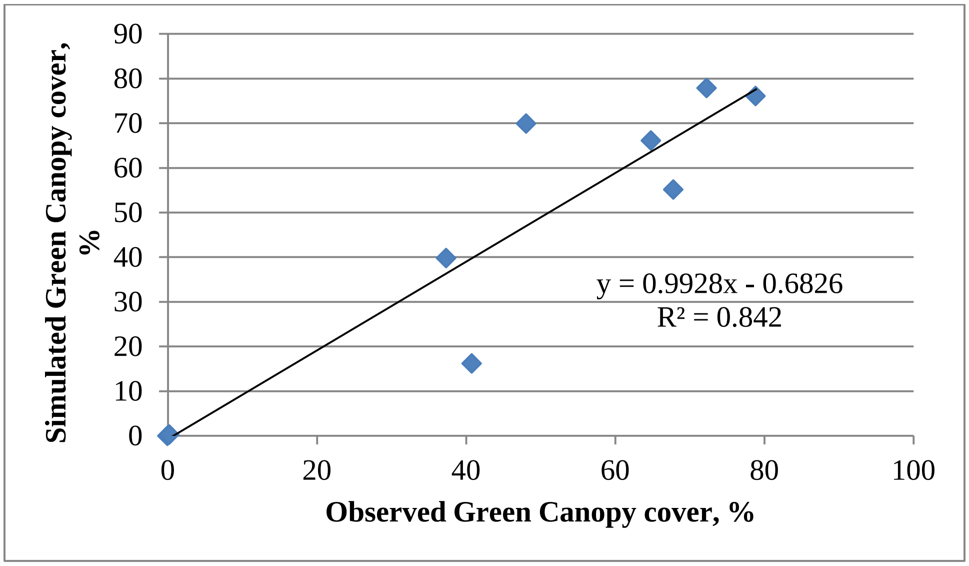

Figure 4.29 (a): Correlation of Green Canopy cover trends for $F_{40}W_{90}$ treatment

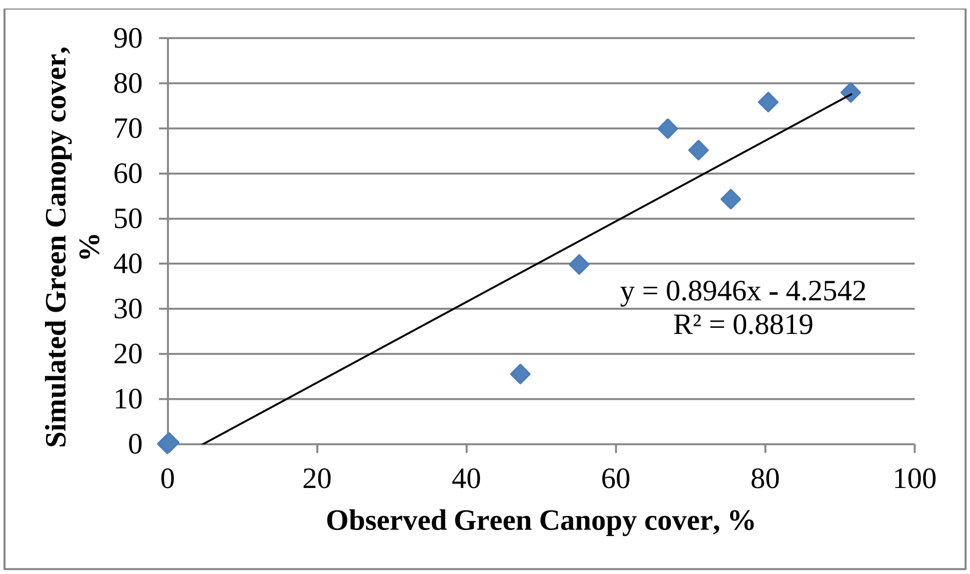

Figure 4.29 (b): Correlation of Green Canopy cover trends for $F_{40}W_{80}$ treatment

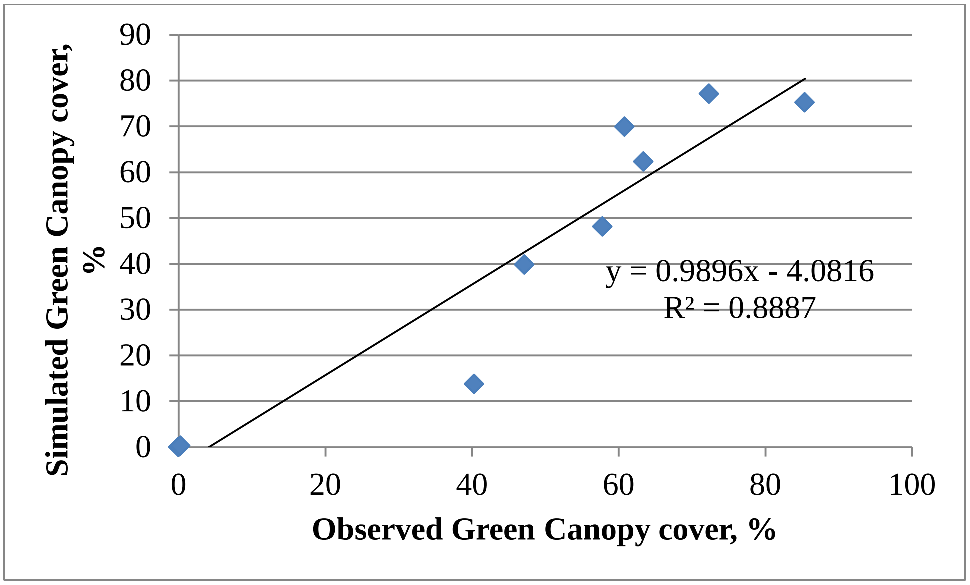

Figure 4.29 (c): Correlation of Green Canopy cover trends for $W_{65}F_{40}$ treatment

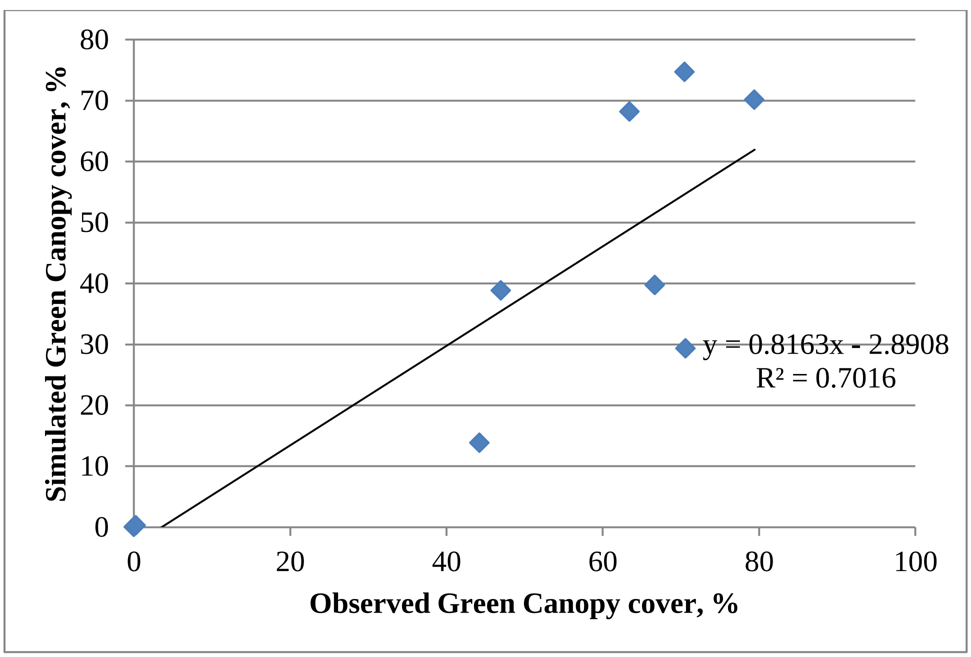

Figure 4.29 (d): Correlation of Green Canopy cover trends for $F_{40}W_{50}$ treatment

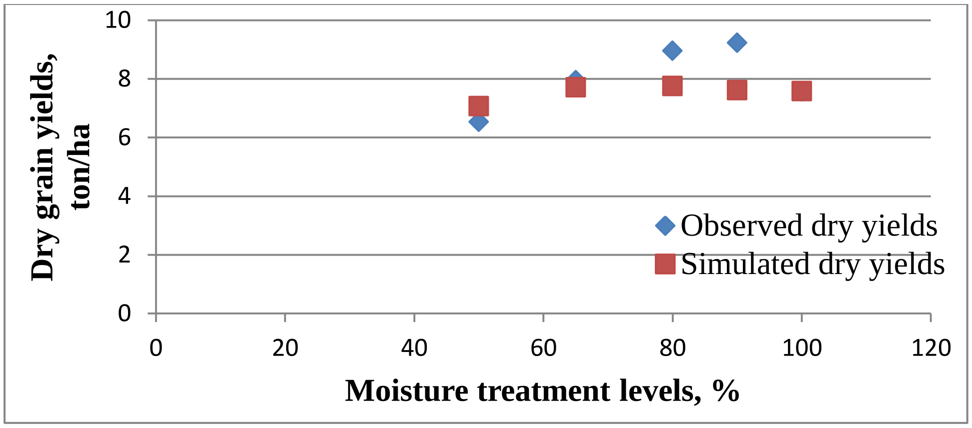

Figure 4.30 (a) Validation results of dry grain yields for treatment levels of $F_{40}W_{90}$, $F_{40}W_{80}$, $F_{40}W_{65}$ and $F_{40}W_{50}$

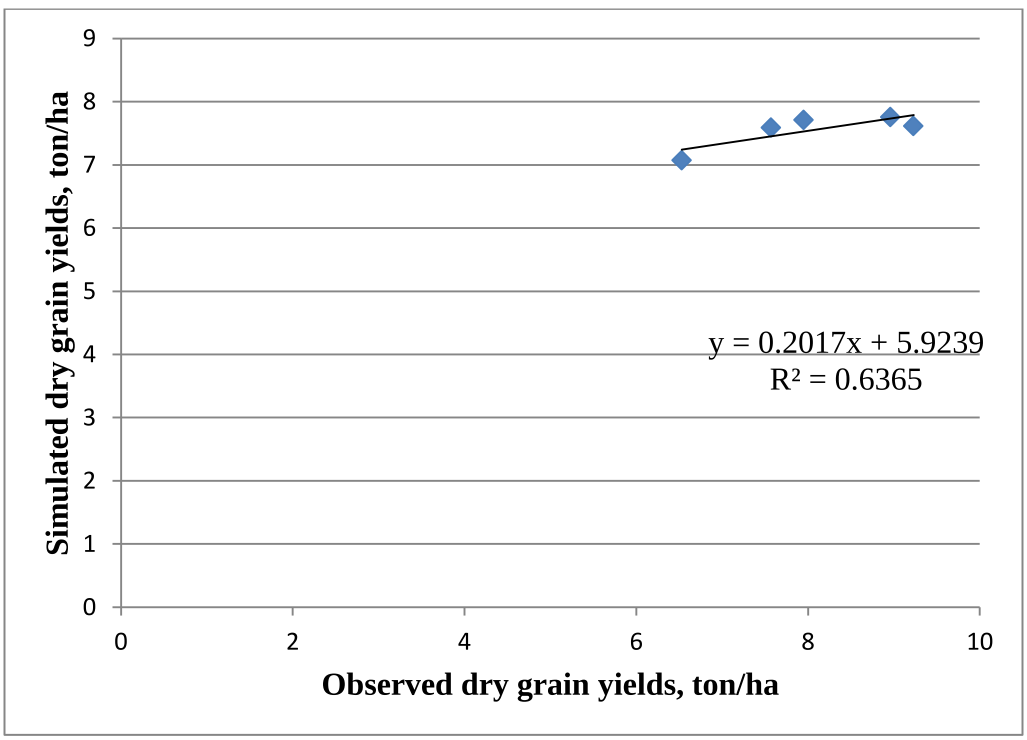

Figure 4.30 (b) Correlation results of observed and simulated dry grain yields for treatment levels of $F_{40}W_{90}$, $F_{40}W_{80}$, $F_{40}W_{65}$ and $F_{40}W_{50}$

Calibration of nutrient fertilizer levels $F_{20}W_{100}$ results of canopy cover simulation and their correlation trends are presented in Figure 4.31 (a) and (b).

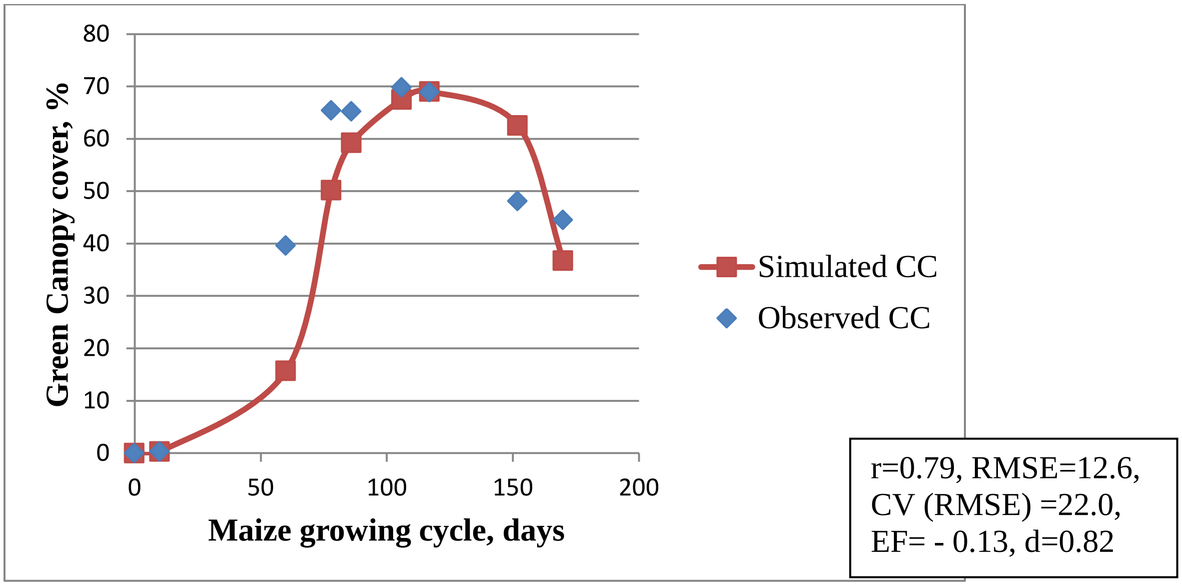

Figure 4.31 (a): Green Canopy cover trends for $F_{20}W_{100}$ treatment

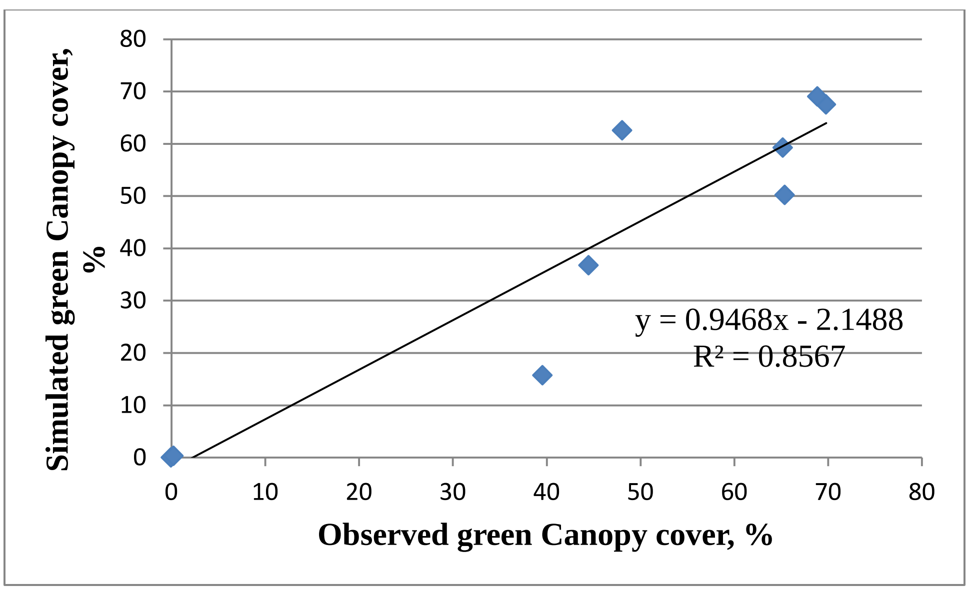

Figure 4.31 (b): Correlation of Green Canopy cover trends for $F_{20}W_{100}$ treatment

Validation simulation results of $F_{20}W_{100}$ using $F_{20}W_{90}$, $F_{20}W_{80}$, $F_{20}W_{65}$ and $F_{20}W_{50}$ Canopy cover correlations and maize grain yields are presented in Figure 4.32 (a) – (d) and Figure 4.33 (a) and (b).

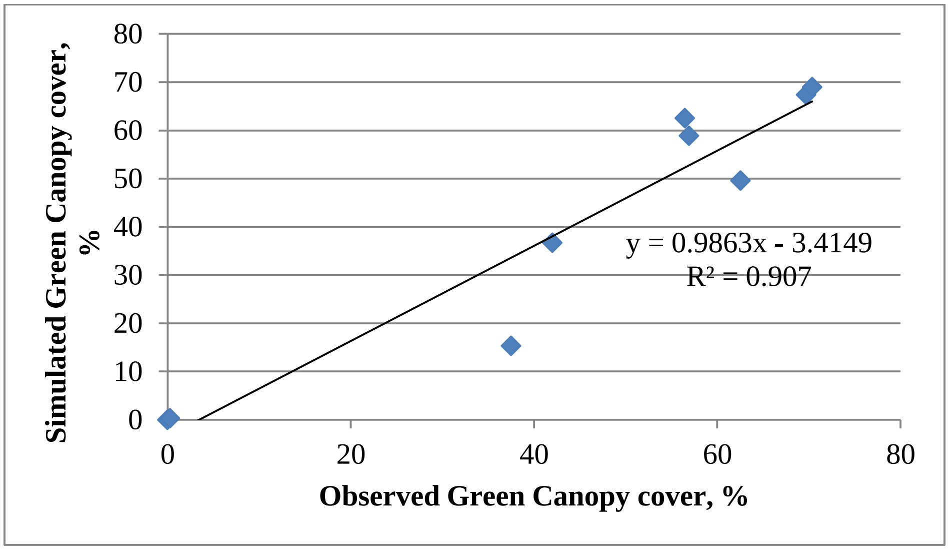

Figure 4.32 (a): Correlation of Green Canopy cover trends for $F_{20}W_{90}$ treatment

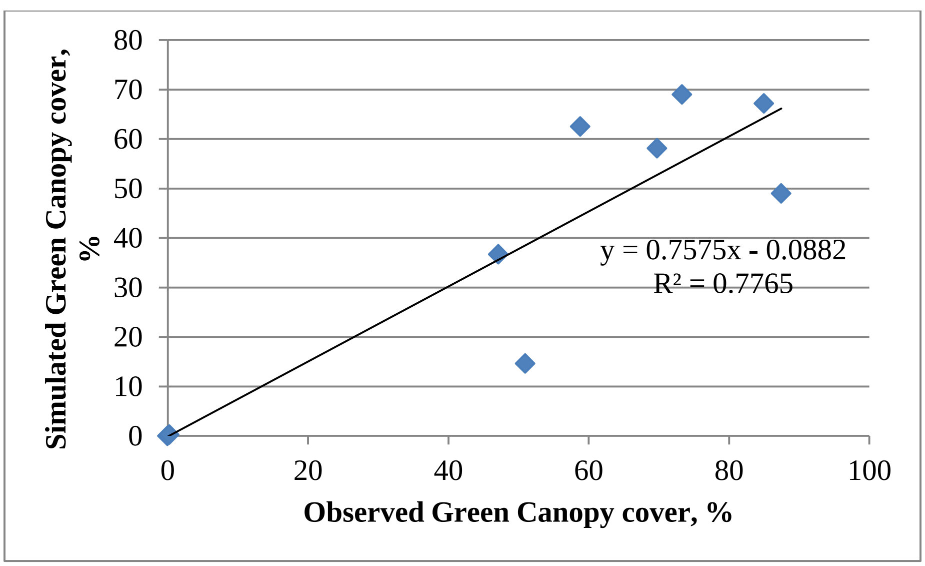

Figure 4.32 (b): Correlation of Green Canopy cover trends for $F_{20}W_{80}$ treatment

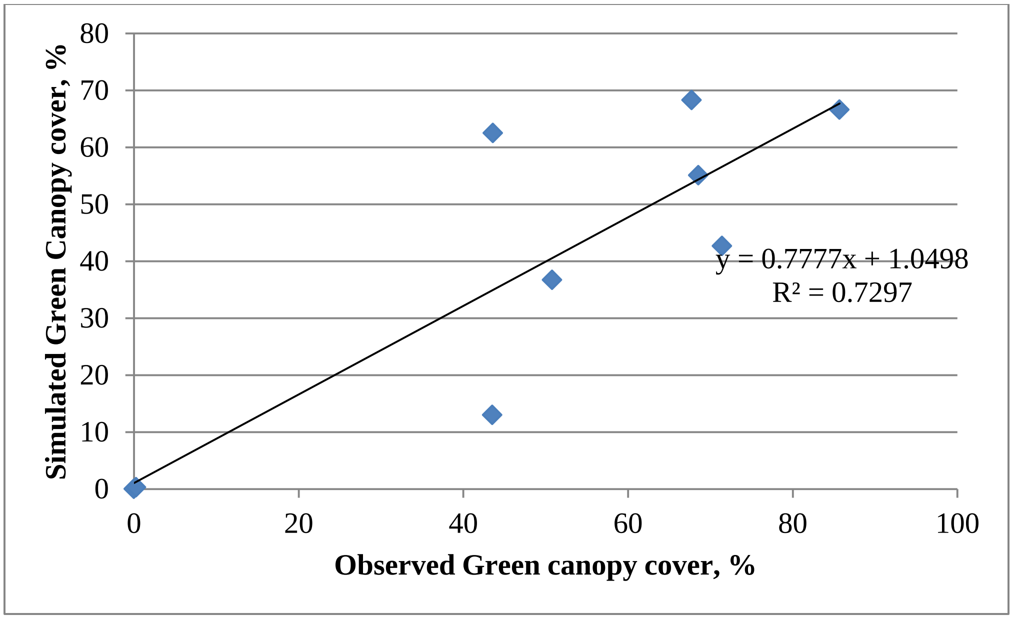

Figure 4.32 (c): Correlation of Green Canopy cover trends for $F_{20}W_{65}$ treatment

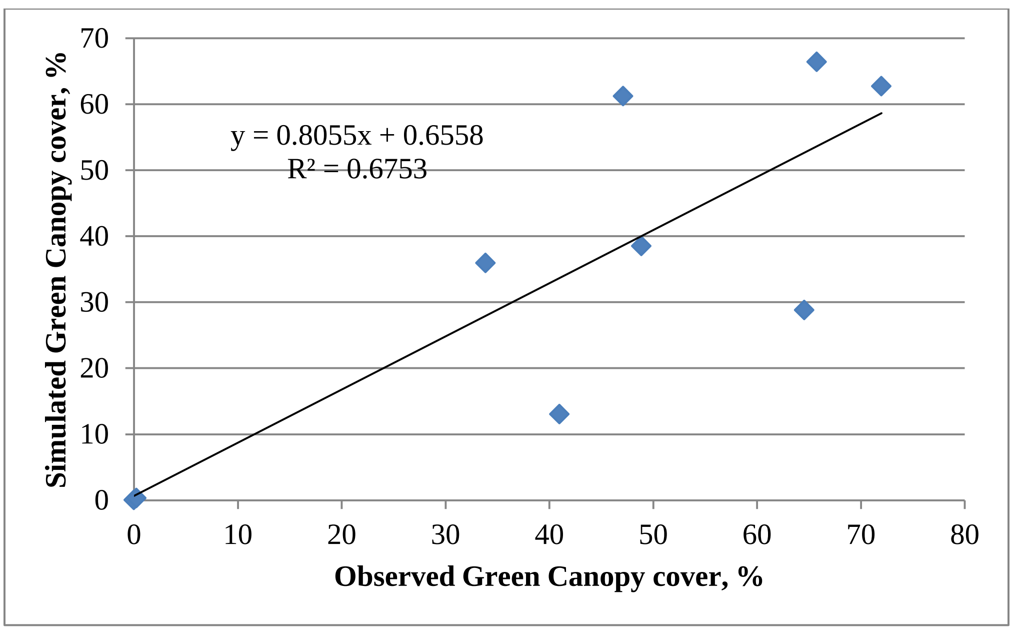

Figure 4.32 (d): Correlation of Green Canopy cover trends for $F_{20}W_{50}$ treatment

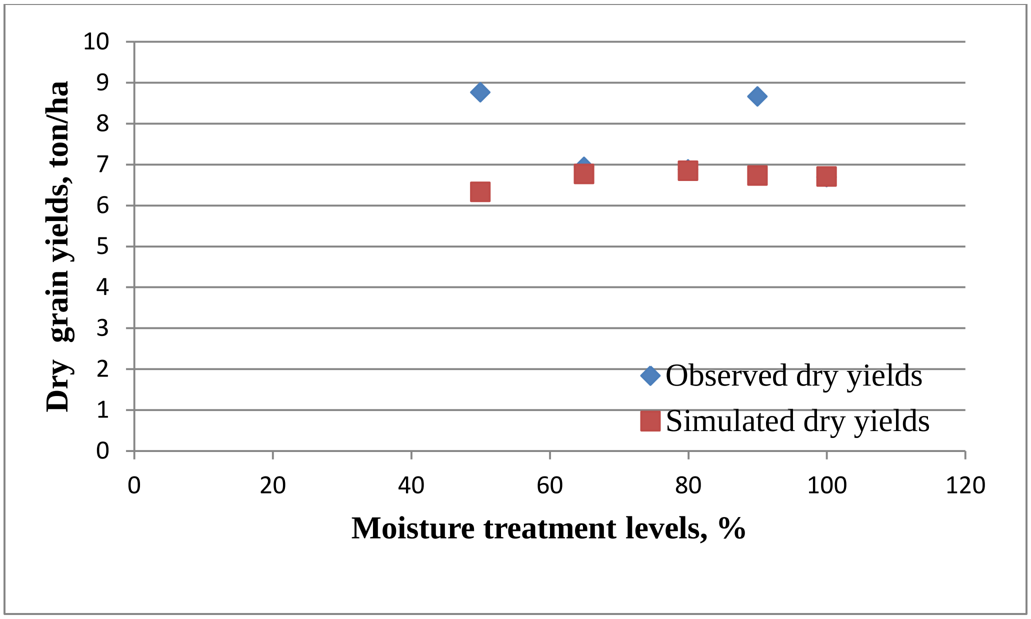

Figure 4.33 (a) Validation results of dry grain yields for treatment levels of $F_{20}W_{90}$, $F_{20}W_{80}$, $F_{20}W_{65}$ and $F_{20}W_{50}$

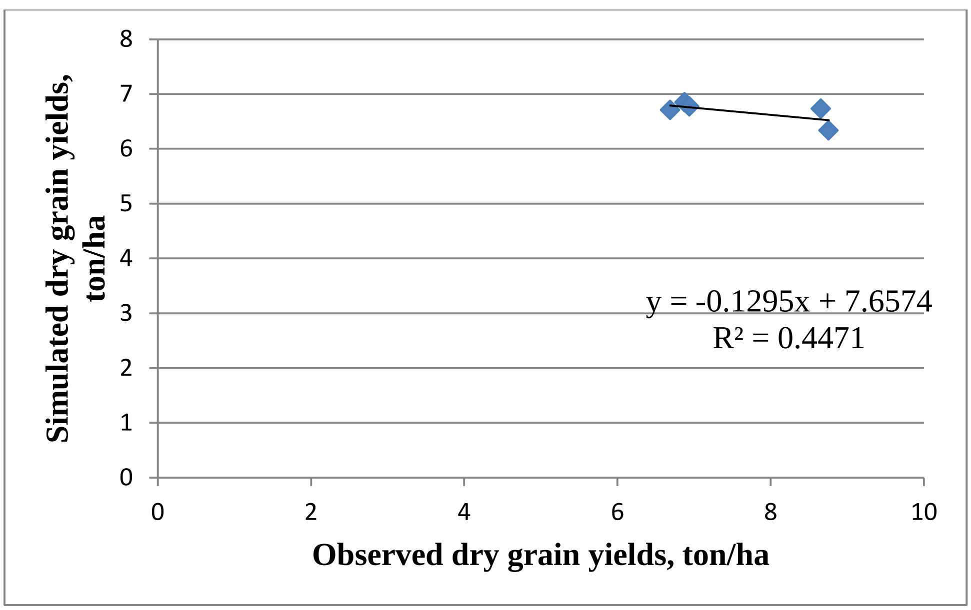

Figure 4.33 (b) Correlation results of observed and simulated dry grain yields for treatment levels of $F_{20}W_{90}$, $F_{20}W_{80}$, $F_{20}W_{65}$ and $F_{20}W_{50}$

The performance of AquaCrop in simulating canopy cover, soil water content and maize grain yield statistical indices are provided in a matrix format and presented in Table 4.22 (a). The results are obtained from the model calibration using actual field demonstration data of canopy cover, soil water content and maize grain yields for moisture and nutrient fertilizer treatment levels of $F_{100}W_{100}$, $F_{80}W_{100}$, $F_{60}W_{100}$, $F_{40}W_{100}$ and $F_{20}W_{100}$.

Table 4.22 (a): AquaCrop model Calibration simulation of Canopy cover and Soil water content statistics (W=100%)

Nutrient Fertilizer (F) treatment (%)	Model calibration correlation statistics					Correlation trend (R^2)
	r	RMSE	CV(RMSE)	EF	d	
100	0.73	15.1	23.9	- 0.15	0.81	0.826
80	0.92	10.2	16.7	0.35	0.90	0.916
60	0.85	11.8	19.1	0.50	0.90	0.898
40	0.75	14.8	23.9	- 0.62	0.78	0.824
20	0.79	12.6	22	- 0.13	0.82	0.856
Soil water Content	0.35	42.6	9.5	- 0.57	0.43	0.471

Validation results for the correlation trend statistics (R^2) of observed and simulated data for canopy cover growth and maize grain yields are presented in Table 4.22 (b).

Comparative results of AquaCrop model calibration and validation simulation results of nutrient fertilizer treatment levels are presented in Figure 4.34. The plot of dry grain yields against moisture treatment levels show consistent similar graphical curves for the respective nutrient fertilizer treatments.

Table 4.22 (b): AquaCrop model Validation simulation of Canopy cover and dry Maize grain yield

Nutrient Fertilizer (F) treatment (%)	Validation correlation of moisture treatments (R^2)				Correlation trend (R^2)
	W_{90}	W_{80}	W_{65}	W_{50}	
100	0.868	0.794	0.870	0.736	0.510
80	0.825	0.905	0.934	0.827	0.632
60	0.827	0.846	0.834	0.702	0.168
40	0.842	0.881	0.888	0.701	0.636
20	0.907	0.776	0.729	0.675	0.447

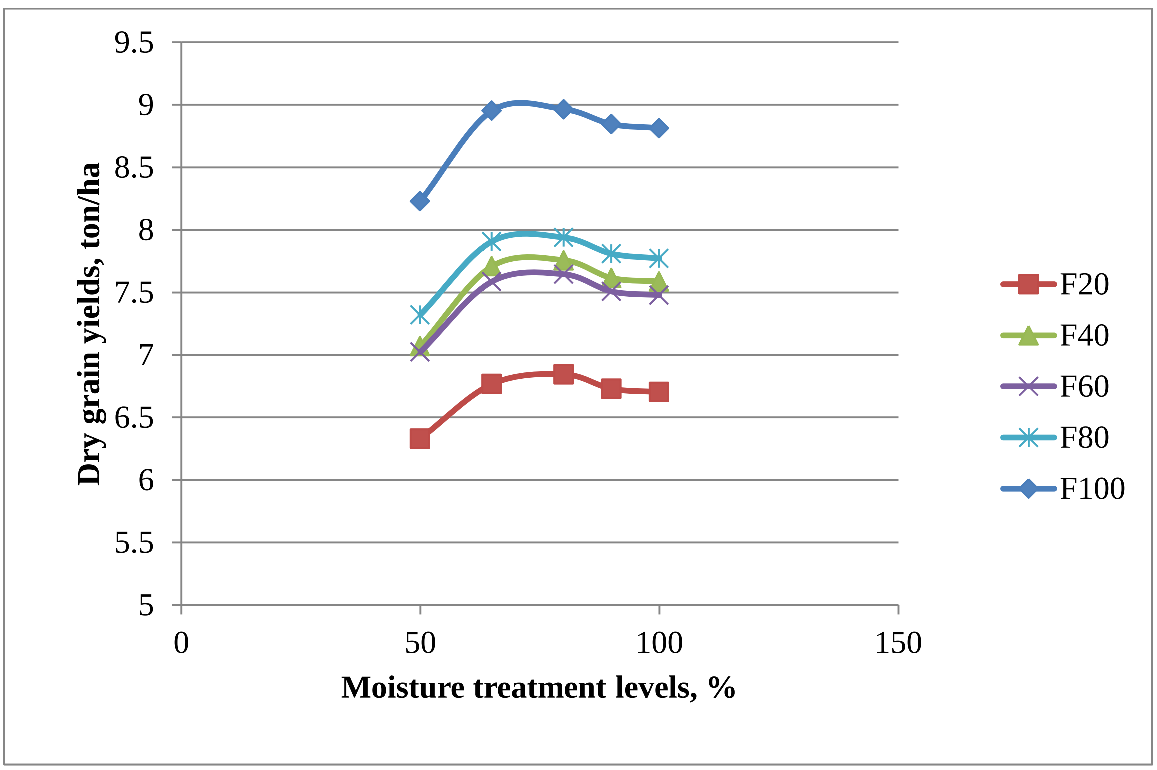

Figure 4.34: Comparison of AquaCrop model simulation results of dry grain yields and deficit irrigation (W %) application levels.

Simulation results of F_{20} and F_{100} are discreet at low and high levels of dry grain yields respectively. Dry grain yield values of nutrient levels F_{40} and F_{60} are comparatively close and those of F_{80} are slightly distinct and higher.

AquaCrop model simulation of dry grain yields against nutrient fertilizer for different levels of moisture treatment is presented in Figure 4.35.

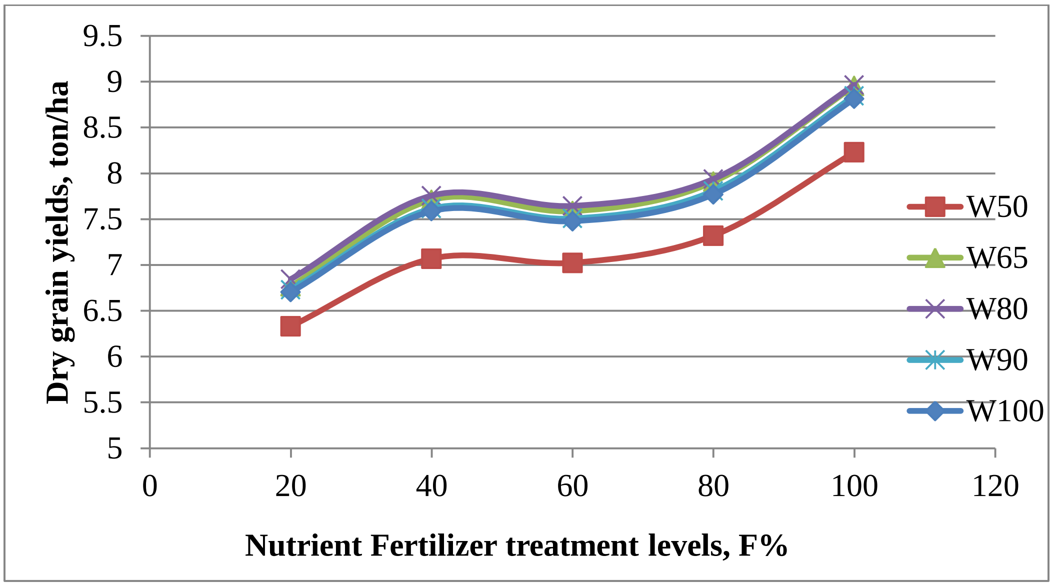

Figure 4.35: Comparison of AquaCrop model simulation results of dry grain yields and nutrient fertilizer (F %) treatment levels.

The general trend of the graph is similar to Figure 4.7 and Figure 4.8 showing the characteristics of increasing yield from F_{20} to F_{40} and F_{80} to F_{100} but decreasing values from F_{40} to F_{80}. Dry grain yields for W_{80} moisture treatment level is higher for all nutrient levels and similar trend was noted during calibration and validation process.

4.4.6 AquaCrop model water productivity simulation results for maize crop production

AquaCrop is a water productivity model that is applied in optimization of water resources in crop production under deficit moisture conditions in the soil. The model registers actual crop parameters experienced at the growing site climatic conditions by specifying the crop growing cycle (day 1 after sowing and the maturity dates). The simulation process is either linked to the growing cycle or not and the current research simulation period is the growing cycle (15th April to 11th October 2015). The available climatic data imported into the model are used to create the climate file that forms the basis of the crop growing characteristics and creation of the project simulation data.

Records of field measurements of canopy cover, above ground dry biomass and soil water content are entered then the model is run to process the crop water productivity simulation. Maize Production simulation results for different levels of deficit irrigation and nutrient fertilizer levels under non-stressed conditions of F=100% and W=100% respectively are presented in Table 4.23 (a) and (b).

Table 4.23: (a) AquaCrop model maize (H629) production simulation results (F=100%)

Parameter	Unit	Simulation results for respective deficit irrigation levels and 100% nutrient fertilizer application				
		W_{100}	W_{90}	W_{80}	W_{65}	W_{50}
Biomass	ton/Ha	28.124	28.053	27.928	27.247	25.553
Dry Yield	ton/Ha	8.815	8.845	8.965	8.953	8.230
WP_{ETo}	kg/m^3 H_2O	2.21	2.26	2.31	2.36	2.31
HI	%	31.3	31.5	32.1	32.9	32.2
Irrigation, IRR	mm	426.0	400.6	394.8	388.5	371.6
IWUE	kg/m^3 H_2O	2.069	2.208	2.271	2.305	2.215
Evaporation, E	mm	48.9	43.4	40.6	40.4	37.6
Transpiration, Tr	mm	349.3	348.5	347.1	339.3	319.4

Table 4.23 (b): AquaCrop model maize (H629) production simulation results (W=100%)

Parameter	Unit	Simulation results for respective nutrient fertilizer levels and 100% irrigation application				
		F_{100}	F_{80}	F_{60}	F_{40}	F_{20}
Biomass	ton/Ha	28.124	28.275	28.631	27.603	25.785
Dry Yield	ton/Ha	8.815	7.771	7.478	7.587	6.703
WP_{ETo}	$kg/m^3\ H_2O$	2.21	1.96	1.87	1.95	1.81
HI	%	31.3	27.5	26.1	27.5	26.0
Irrigation, IRR	mm	426.0	413.4	412.4	414.2	411.7
IWUE	$kg/m^3\ H_2O$	2.069	1.880	1.813	1.832	1.628
Evaporation, E	mm	48.9	44.0	43.7	44.8	47.9
Transpiration, Tr	mm	349.3	352.1	357	343.7	321.5

General variation trend of the parameter results indicate biomass, dry maize grain yields irrigation, evaporation and transpiration increase with increasing deficit irrigation application levels while water productivity, harvest index and IWUE are decreasing. Values of WP_{ETo} and IWUE are closely similar and represent production of maize grain yields per unit amount of water used (kg/m^3H_2O).All parameters increase with increasing nutrient fertilizer application levels. Values of WP_{ETo} and IWUE are near equal with minimal difference though both represent production of maize grain yields per unit amount of water used (kg/m^3H_2O) under different conditions.

4.5 Application of AquaCrop model in yield gaps prediction under water and fertility stress in Uasin Gishu County

AquaCrop is a water productivity model used to simulate maize crop grain yields under different local environmental conditions and nutrient treatment levels. Calibrated model utilize has the capacity to predict specific food crop yields and their variations under different production environments and management. Variations in field crop yields occur as a result of site-specific growing environments, in-situ soil properties and the prevailing local weather conditions. Actual farm yields deviate from the maximum possible (potential) yields and constitute to yield gap as the difference (FA0, 2017). The level of potential yields for a given location is achieved through simulation modeling, field experimental trials and/or documented records of highest yields of the site.

4.5.1 Comparative strategies of deficit irrigation and water productivity analysis

Reduction in the amount of water applied in irrigation implies the amount of moisture available in the soil for plant growth is less than the threshold for readily available water and the plant would be subjected to stressful depletion of the limited deficit water. However, the deficit irrigation strategy causes the crop to develop resistance characteristics and become efficient in its water use hence its water productivity (yield in kg per unit m^3 of water used) is increased. Ultimate results create an opportunity for saving the limited amount of water used in irrigation that would be rescheduled for an increased area under crop production and increased yield per unit amount of available water.

Table 4.24(a): Analysis of strategic parameter results of AquaCrop model simulation

Strategic Parameter	Units	Comparative results under deficit irrigation application levels				
		W_{100} Full irrigation	W_{90}	W_{80}	W_{65}	W_{50}
Amount of deficit irrigation applied	mm	426.0	400.6	394.8	388.5	371.6
Irrigation events	No.	9	9	8	8	7
Amount of water saved	mm	0	25.4	31.2	37.5	54.4
	%	0	6.0	7.3	8.8	12.8
Simulated dry yield	ton/ha	8.815	8.845	8.965	8.953	8.230
Water Productivity (WP_{ET})	kg/m^3-H_2O	2.21	2.26	2.31	2.36	2.31
Comparative area achieved under deficit irrigation	ha	1.0	1.06	1.08	1.10	1.15
Relative increase in area	%	0	6	8	10	15
Total dry yield obtained for the increased irrigated area	ton	8.815	9.38	9.68	9.85	9.46

Table 4.24(b): Comparison with rain-fed controlled plot in the research site (ton/ha)

Nutrient fertilizer treatment levels for rain-fed controlled plot in the research site (ton/ha)						Average rain-fed yield (ton/ha)
Fertility levels	F=100%	F=80%	F=60%	F=40%	F=20%	
Rain-fed dry yield	9.75	7.75	11.43	7.47	9.81	9.24

Table 4.24(c): Area covered and dry yield obtained from the water saving

Strategic Parameter	Unit	Results of increased area and dry yield for the water saved				
		W_{100} Full irrigation	W_{90}	W_{80}	W_{65}	W_{50}
Amount of water saved	m^3/ha	0	254	312	375	544
Area increased for irrigation	ha	0	0.06	0.08	0.10	0.15
Yield increased	ton	0	0.535	0.715	0.897	1.230
Relative increase in dry yield	%	0	6.0	8.0	10.0	15.0

Comparative analysis are given in Table 4.24 (a) - (c) showing increase in crop yields due to variable cropping area under deficit irrigation of maize production.

4.5.2 Prediction of maize yields under field demonstration plots

Field demonstration results of maize crop (Hybrid H629) grown at Saroiyot research site and sheltered from rainfall was subjected to deficit irrigation using drip irrigation system. Harvested dry grain yields of maize from the respective water application levels were compared with AquaCrop model simulated yields and the analysis tabulated in Table 4.25 (a) and (b). Controlled demonstration plot ($F_{100}W_{100}$) yield of 8.81 ton/ha is considered the field potential yield under no-stress condition and not affected by unpredictable local environmental changes.

Table 4.25(a): Yield Gap Analysis of farm and AquaCrop model simulated yields under deficit irrigation

Deficit irrigation level	Maize grain yield (ton/ha)		Controlled plot yield (ton/ha)	Yield gap (ton/ha)	
	Farm yield	Simulated yield		Farm yield	Simulated yield
$F_{100}W_{100}$	8.81	8.815	8.81	0.0	0.005
$F_{100}W_{90}$	10.99	8.845		2.18	0.035
$F_{100}W_{80}$	9.07	8.965		0.26	0.155
$F_{100}W_{65}$	8.97	8.953		0.16	0.143
$F_{100}W_{50}$	7.08	8.230		- 1.73	- 0.580

The findings give a record of dry maize grains attained in the farm demonstration plots for non-stressed nutrient fertilizer level of F_{100} and AquaCrop model simulated yields during validation process and their yield gaps. Harvested maize grain yields increase from low value of 7.08 ton/ha to a maximum value of 10.99 ton/ha at deficit irrigation moisture levels of W_{50} and W_{90} respectively. Non-stressed controlled plot at W_{100} moisture level recorded a decreased yield value of 8.81 ton/ha. The trend follows the general crop production function that attains a maximum value below 100% moisture application level. The maximum yield recorded the highest positive yield gap of 2.18 ton/ha (24.7%) and the lowest yield recorded the only negative yield gap value of -1.73 ton/ha (- 19.6%).

Simulated maize grain yields are expected to replicate fully harvested farm yields but since calibration involves fine tuning of the model and avoiding outlier values result in slight variations in their values. Maximum positive yield gap of 0.155 ton/ha (1.8%) was recorded at deficit irrigation level of W_{80} and indicates an optimum moisture application level where production is optimized. The only negative yield gap of - 0.580 ton/ha (-6.6%) occurred at the lowest moisture application level of W_{50}.

Table 4.25(b): Yield Gap Analysis of farm and AquaCrop model simulated yields for different nutrient fertilizer levels

Nutrient fertilizer level	Maize grain yield (ton/ha)		Controlled plot yield (ton/ha)	Yield gap (ton/ha)	
	Farm yield	Simulated yield		Farm yield	Simulated yield
$F_{100}W_{100}$	8.81	8.815	8.81	0.0	0.005
$F_{80}W_{100}$	10.08	7.771		1.27	- 1.039
$F_{60}W_{100}$	7.4	7.478		- 1.41	- 1.332
$F_{40}W_{100}$	7.57	7.587		- 1.24	- 1.223
$F_{20}W_{100}$	6.69	6.703		- 2.12	- 2.107

Results of farm maize grain yields attained were used in the calibrations of nutrient fertilizer simulated yields. Yields increase from F_{20} to F_{40} followed by a minimal drop from F40 to F_{60} then increases to a maximum at F_{80}. Yields reduced to the level of non-stressed controlled plot value of 8.81 ton/ha. Maximum yield of 10.08 ton/ha recorded the only positive yield gap of 1.27 ton/ha (14.4%). Other values of maize grain yields were lower than reference plot value and recorded negative yield gaps and the highest was - 2.12 ton/ha (- 24.1%) at the lowest nutrient fertilizer treatment level of F_{20}.

4.5.3 Prediction of maize yield distribution in Uasin Gishu climate zones

Forecast of Uasin Gishu plateau climate trend was studied using 34 years daily historical climate data (1981-2014) from Kapsoya meteorological station. Results of frequency analysis for the maize cropping season (March – October) rainfall data were obtained using RAINBOW software (Raes *et al*., 1996). The data were found to be normally distributed with mean statistic of 898.2 and standard deviation of 189.8. Magnitude summary of their events and their probability of exceedance are tabulated in Table 4.26.

Table 4.26: Uasin Gishu plateau rainfall frequency analysis (1981 – 2014)

Probability of Exceedance (%)	Return period (year)	Magnitude Event (mm)
10	10	1141.4
20	5	1057.9
30	3.33	997.6
40	2.5	946.2
50	2.0	898.2
60	1.67	850.2
70	1.43	798.8
80	1.25	738.5
90	1.11	655.0

Probability of exceedance limits of 20% and 80% in frequency analysis results were considered to predict wet and dry weather conditions of Uasin Gishu plateau climate. Results of frequency analysis and categorizations of the climate were presented in dry, normal and wet weather conditions. Results of seasonal (15th April to 11th October) rainfall events used in AquaCrop model maize yield prediction for each weather condition are presented in Table 4.27.

The study findings of RAINBOW frequency analysis categorized rainfall data into more homogeneous weather conditions with improved standard deviations lower than for the global data. The data in the three weather groups were used in AquaCrop model to predict maize yield for the crop cycle season covered during demonstration plots. The model was calibrated for conditions under no fertility stress and applied to simulate the results of dry grain yield for climate data variations in the dry, normal and wet weather conditions. Further investigation was carried out for model calibration of the nutrient fertilizer levels with W_{100} moisture application levels and used for dry grain yield simulation for the three weather conditions.

Table 4.27: Seasonal weather conditions data and maize yield prediction

Parameter		**Rainfall data under weather conditions**		
		Dry	**Normal**	**Wet**
Probability of Exceedance (%)		> 80	20 ≤ rainfall ≥ 80	< 20
Seasonal rainfall events (15th April to 11th October)	Minimum (mm)	390.3	556.3	977.3
	Maximum (mm)	624.2	923.1	1056.6
	Mean (mm)	514.94	719.47	1013.43
	Standard Deviation	75.06	95.39	29.48
Average yield prediction under no stress condition (ton/ha)		7.02	9.46	11.17
Standard Deviation (simulated yield)		4.84	2.35	0.30

Yield gap results of the model prediction of average maize yields given in Table 4.25 are presented by comparing with the farm non stressed demonstration plot ($F_{100}W_{100}$) yield results given in Table 4.28.

Table 4.28: Yield gap analysis of maize grain yields in Uasin Gishu plateau

Parameter	Unit	Weather conditions			Uasin Gishu average maize yield
		Dry	Normal	Wet	
Average maize yield prediction of AquaCrop model	ton/ha	7.02	9.46	11.17	9.22
Farm yield in the $F_{100}W_{100}$ plot	ton/ha	8.81	8.81	8.81	8.81
Yield gap	ton/ha	- 1.79	0.65	2.36	0.41
Variation	%	-20.32	7.38	26.79	4.65

Findings of AquaCrop model simulation in Table 4.28 indicate a difference in dry grain yields of 2.44 ton/ha between dry and normal and 1.71 ton/ha between normal and wet weather conditions respectively. A loss of 4.15 ton/ha of dry grain yields occur between dry and wet weather conditions of Uasin Gishu plateau. The model prediction of dry grain yields are above farm observations under drip irrigation system by 0.65 ton/ha and 2.36 ton/ha for the normal and wet weather conditions respectively. Dry weather simulation gave a lower dry grain yield difference of 1.79 ton/ha. The results suggest that maize grown under normal and wet weather conditions achieve higher dry grain yields compared to drip irrigation fields which show relevance under dry weather conditions and additional costs of irrigation. These results are supported by maize dry grain yields of rain-fed demonstration plot given in Table 4.24 (b) which produced an average of 9.24 ton/ha for the 5 nutrient fertilizer treatment plots.

Further analysis was considered for model calibration of nutrient fertilizer (F = 80, 60, 40 and 20) values under W_{100} moisture treatment level for the three weather conditions and the results are presented in Table 4.29.

Table 4.29 (a): Simulation of maize grain yields for different nutrient fertilizer treatment under Uasin Gishu plateau weather conditions

Nutrient fertilizer level	Maize yield (ton/ha) prediction for nutrient fertilizer (F) treatment levels and weather condition					
	Dry season	STDEV	Normal season	STDEV	Wet season	STDEV
F_{100}	7.02	4.84	9.46	2.35	11.17	0.30
F_{80}	7.06	4.86	9.88	1.03	11.22	0.31
F_{60}	6.76	4.66	9.46	1.01	10.79	0.29
F_{40}	6.87	4.73	9.60	1.04	10.95	0.30
F_{20}	6.43	4.43	8.97	0.95	10.23	0.28
Average	6.83	4.70	9.47	1.28	10.87	0.30

Variable nutrient fertilizer treatment given in Table 4.29 (b) influences maize crop yields and yield gap obtained when compared with the farm yield of the control plot ($F_{100}W_{100}$).

Table 4.29 (b): Yield gap analysis for different nutrient fertilizer treatment under Uasin Gishu plateau weather conditions

Nutrient fertilizer level	Maize yield gap (ton/ha) prediction for nutrient fertilizer (F) treatment levels and weather condition						
	Dry season	Normal season	Wet season	Farm yield ($F_{100}W_{100}$)	Yield gap (Dry)	Yield gap (Normal)	Yield gap (Wet)
F_{100}	7.02	9.46	11.17		- 1.79	0.65	2.36
F_{80}	7.06	9.88	11.22		- 1.75	1.07	2.41
F_{60}	6.76	9.46	10.79	8.81	- 2.05	0.65	1.98
F_{40}	6.87	9.60	10.95		- 1.94	0.79	2.14
F_{20}	6.43	8.97	10.23		- 2.38	0.16	1.42
Average	6.83	9.47	10.87		- 1.98	0.66	2.06

A general trend of yield gap increase occurs for the normal and wet weather conditions from lower values at F_{20} to a maximum at F_{80} and a reduction at F_{100}. Similar trend occur for the maize crop yields for various levels of nutrient fertilizer treatments. Simulation findings of the dry weather condition indicate that maize crop yields are lower than farm yield unlike for the normal and wet weather conditions which are all higher with positive yield gaps. Nutrient fertilizer level of F_{20} recorded highest negative yield gap and generally degreases to F_{80}. Dry weather condition with limitation of nutrient fertilizer in the soil lowers the vigour of maize growth and the ultimate dry grain yield and yield gap trends are influenced depending on the contribution of nutrition.

Yield gap predictions under normal weather condition recorded the lowest average value of 0.66 ton/ha compared to -1.98 ton/ha and 2.06 ton/ha for the dry and wet weather conditions respectively. This result suggest that maize grain yield under normal weather condition in Uasin Gishu plateau compares closely with the results of drip irrigated crop under no fertility stress. Any variation in the yield gap is attributed to available residual nutrients in the soil that influenced calibration process of the respective nutrient fertilizer levels.

4.5.4 Influence of soil distribution on the maize yield prediction

Distribution of soil types and their prediction of maize yield presented in Table 4.30 and Figure 4.36 provided unique similarities for each of the weather conditions. The simulation findings indicate that soil texture mix strongly influence maize grain yields under different weather conditions. Fine grains in mineral clay soils are affected by low water levels in dry weather conditions with strong bonding in their lattice. Maize crop roots in clay content soils are limited in propagation and imbibing nutrients in dry conditions. The crop growth is impaired and zero yields are recorded in clay, sandy clay, silt clay loam and silt clay soils. Soils with coarse fraction mix in the clay texture recorded variable maize yields depending on the proportion of mixture components. This behavior is attributed to the unique hydraulic characteristics of fine grained soils that exhibit plastic behavior and low water conductivity.

Under dry conditions sandy clay loam, clay loam and the demonstration plots soils at Saroiyot recorded 10.05 ton/ha, 4.21 ton/ha and 6.03 ton/ha respectively. This result support that Saroiyot soils are clay loams with some fraction of sand which was proven by the laboratory results of Kericho Tea Research Foundation (KTRF) presented in Table D.

Table 4.30: Maize yields prediction under different types of soils and weather conditions

Soil types	Dry season		Normal season		Wet season	
	Average Yields (ton/ha)	STDEV	Average Yields (ton/ha)	STDEV	Average Yields (ton/ha)	STDEV
Clay	0.00	0.00	0.39	0.67	1.26	0.14
Clay Loam	4.21	3.82	8.89	2.23	10.48	0.52
Loam	10.81	0.52	10.85	0.60	11.02	0.32
Loamy Sand	10.39	0.23	10.87	1.05	11.11	0.41
Sand	10.13	0.25	10.77	1.20	11.11	0.38
Sandy Clay	0.00	0.00	6.39	5.55	10.02	1.10
Sandy Clay Loam	10.05	1.31	11.01	0.87	11.04	0.34
Sandy Loam	10.71	0.38	10.90	0.66	11.04	0.34
Saroiyot soils	6.03	5.22	10.18	0.66	11.12	0.39
Silt	10.88	0.58	10.74	0.66	10.66	0.32
Silt Clay Loam	0.00	0.00	5.34	4.68	8.59	1.14
Silt Loam	10.92	0.56	10.84	0.60	11.02	0.31
Silt Clay	0.00	0.00	2.76	2.41	4.49	0.60

Maize yields predicted below controlled demonstration plot value for normal and wet weather conditions were recorded in soils of pure clay and when mixed with other textural soils under normal and wet weather conditions. Clay recorded 0.39 ton/ha and 1.26 ton/ha while silt clay recorded 2.76 ton/ha and 4.49 ton/ha respectively. Plastic properties of fine grained soils allow plant roots to penetrate but suffer from waterlogging when water fills the voids. The presence of loamy soils improved the drainage in the silt clay loam that recorded 5.34 ton/ha and 8.59 ton/ha under normal and wet weather. This result suggests that clay dominance is lower and more porous soil environment is created that support maize crop production.

Soil textural classes containing sand, silt and loam recorded maize yields above the controlled plot value and registered positive yield gaps. Lower yields are recorded under dry weather and increase to higher values in wet condition while normal weather registered the average of the two levels. This achievement is attributed to favourable hydraulic properties of the soil and capacity to store sufficient plant nutrients in their porosity.

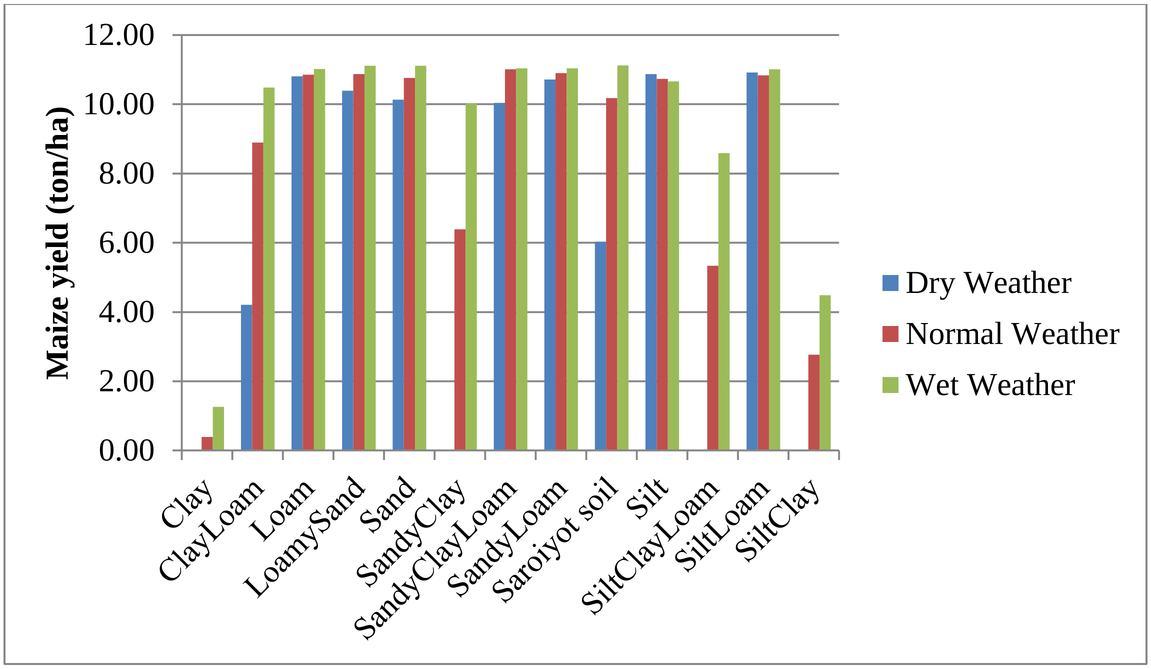

Figure 4.36: Maize yields prediction for Uasin Gishu plateau on different soils

Predicted yields of soils in Saroiyot demonstration plots recorded 6.03 ton/ha, 10.18 ton/ha and 11.12 ton/ha under the dry, normal and wet weather conditions respectively. The controlled plot ($F_{100}W_{100}$) attained a maximum of 8.81 ton/ha. This result explains the limitation of application of drip irrigation system that wets about 30% (FAO, 2018) of the cropping area and limit root growth both vertically and horizontally therefore result in shallow crop rooting system and limited space for getting stored nutrients.

Table 4.31: Maize yields prediction and yield gaps for different soils and weather conditions

Soil types	Model yield prediction (ton/ha)			Farm plot (F_{100} W_{100}) yield (ton/ha)	Yield gap calculation (ton/ha)		
	Dry season yield	Normal season yield	Wet season yield		Dry season yield gap	Normal season yield gap	Wet season yield gap
Clay	0.00	0.39	1.26	8.81	-8.81	-8.42	-7.55
Clay Loam	4.21	8.89	10.48		-4.60	0.08	1.67
Loam	10.81	10.85	11.02		2.00	2.04	2.21
Loamy Sand	10.39	10.87	11.11		1.58	2.06	2.30
Sand	10.13	10.77	11.11		1.32	1.96	2.30
Sandy Clay	0.00	6.39	10.02		-8.81	-2.42	1.21
Sandy Clay Loam	10.05	11.01	11.04		1.24	2.20	2.23
Sandy Loam	10.71	10.90	11.04		1.90	2.09	2.23
Saroiyot soils	6.03	10.18	11.12		-2.78	1.37	2.31
Silt	10.88	10.74	10.66		2.07	1.93	1.85
Silt Clay Loam	0.00	5.34	8.59		-8.81	-3.47	-0.22
Silt Loam	10.92	10.84	11.02		2.11	2.03	2.21
Silt Clay	0.00	2.76	4.49		-8.81	-6.05	-4.32

Results of yield gap calculation for the three weather conditions are given in Table 4.31 and Figure 4.37. Variation in yield in the different soil types compared to the reference controlled plot imply that potential maize crop yields are influenced by the in-situ soil properties, prevailing environmental climate conditions and the level of nutrition.

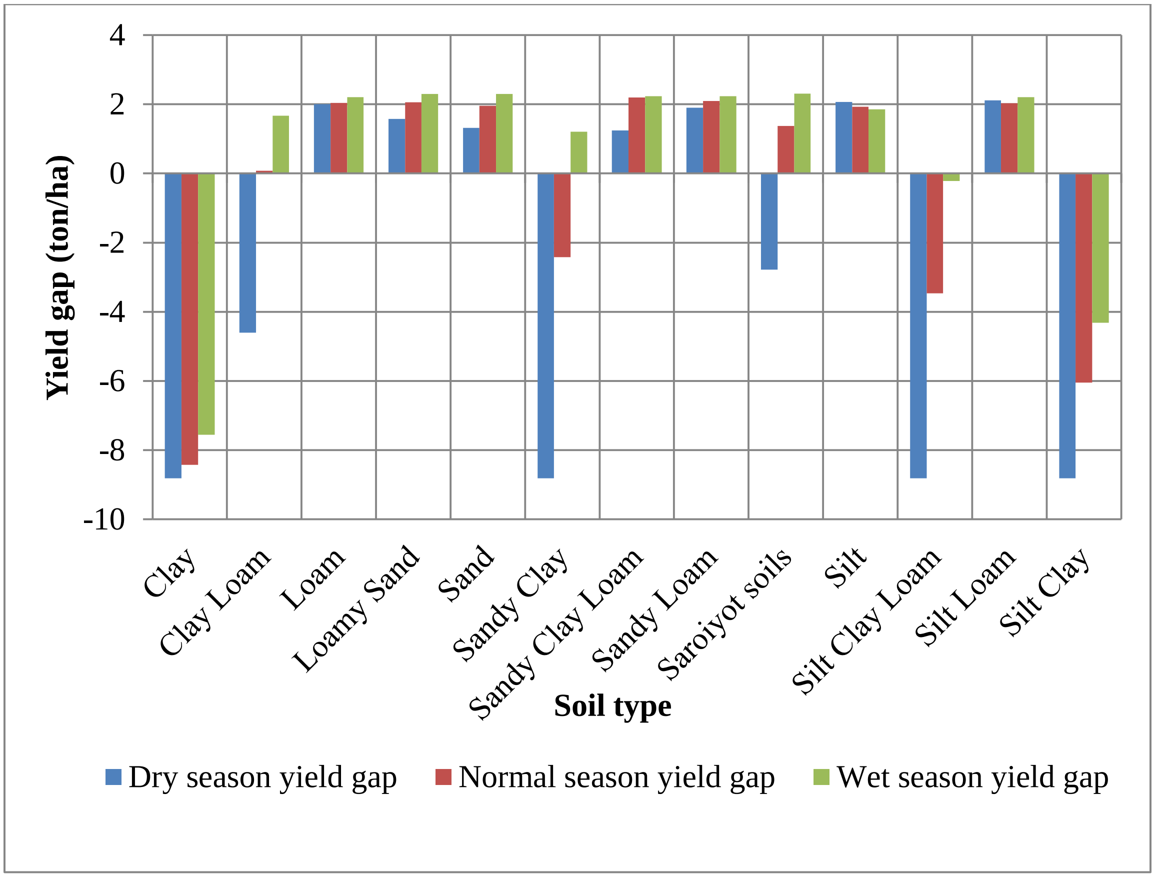

Figure 4.37: Maize yield gap prediction for Uasin Gishu plateau on different soils

4.5.5 Effects of soil fertility stress on maize yield prediction

Results of maize yield under fertility stressed conditions were predicted using AquaCrop model by comparing a reference non- fertility stressed field with a stressed condition based on the proportions of their measurable parameters. Fertility stress level in the field reduces the amount of biomass produced and maximum canopy cover attained. The reference field data used was from the controlled demonstration plot ($F_{100}W_{100}$) calibration of the model.

Soil fertility module in AquaCrop model derives and calibrates specific level of stress crop parameters as a proportion of the reference plot data. Various levels of soil fertility stress and their crop calibration parameters are given in Table 4.32 and are used in tuning the model for maize crop yield prediction.

Table 4.32: Calibration of crop parameters due to soil fertility stress on the reference plot

Soil Fertility Stress (%)	Crop parameters due to soil fertility stress				
	CC_x (%)	DAS (days)	WP* (g/m^2)	CGC (% per day)	CDC (% per day)
0 ($F_{100}W_{100}$)	81	109	30.7	8.0	6.5
5	75	110	29.8	7.92	0.02
20	57	109	29.8	7.76	0.03
40	49	123	29.8	6.64	0.19
50	49	132	29.8	6.16	0.25
60	49	134	19.3	6.08	0.19
80	36	134	9.0	5.9	0.33
95	11	134	12.9	4.9	0.45

The model predicts the amount of biomass produced as a difference between the potential value at 100% and the level of soil fertility stress and the amount of predicted maize grain yields follow the model regression formula of yield given in Equation 2.8. Maize yield results tabulated in Table 4.33 were predicted for various levels of soil fertility stress from 5% to 95% corresponding to biomass production levels of 95% to 5% respectively.

Maximum canopy cover (CC_x) achieved was lower than that of the reference plot value of 81% and vary from 75% to 11% (model minimum value) applied under conditions of dry, normal and wet climate of Uasin Gishu plateau.

Maize crop yield findings indicate a general decrease with increase in the soil fertility stress under the three weather conditions of dry, normal and wet categories. Similarly canopy growth coefficient (CGC) parameters decreased from 7.92% to 4.0% and an increase in the length of growth to maximum canopy cover from 109 to 134 (DAS). This implies that a decrease in the rate of canopy growth take longer to maturity and lead to reduced utilization of available nutrients, diminished biomass manufacture and lower maize grain yield production.

Table 4.33: Soil fertility stress and climate based prediction of maize yields

Soil Fertility Stress (%)	Climate based maize yields (ton/ha)							
	Dry season	STDEV	Normal season	STDEV	Wet season	STDEV	Average yield	Average STDEV
0 ($F_{100}W_{100}$)	7.02	4.84	9.46	2.35	11.17	0.30	9.22	2.50
5	6.67	4.60	9.32	1.0	10.61	0.29	8.87	1.96
20	5.68	3.90	7.89	0.83	8.96	0.25	7.51	1.66
40	4.67	3.21	6.27	1.57	7.41	0.21	6.12	1.66
50	4.32	2.98	5.84	1.47	6.93	0.19	5.70	1.55
60	2.96	2.05	4.03	1.03	4.82	0.13	3.94	1.07
80	1.40	0.98	1.93	0.52	2.36	0.07	1.90	0.52
95	1.00	0.69	1.37	0.19	1.57	0.04	1.31	0.31
Average	4.22	2.91	5.76	1.12	6.73	0.19	5.57	1.41

Prediction of maize dry grain yield under dry weather condition recorded values below controlled demonstration plot ($F_{100}W_{100}$). Results of normal and wet weather conditions recorded positive yield gap values for soil fertility stress below 15% and 25% respectively, and all other levels of predictions are below $F_{100}W_{100}$ yield level. This finding presented in Table 4.34 suggest that optimal level of soil fertility nutrition recommended for maize crop application when the soil does not have any residual nutrient content is approximately 85% and 75% under normal and wet weather conditions respectively. Previous statistical analysis of demonstration plots yield data under conditions of available residual soil nutrient content gave approximate fertilizer application level of 65% (Figure 4.10) for Uasin Gishu plateau. The difference is attributed to soil nutrients and productivity sustained by nutrient transfers from different holding sources in the soil. The simulation results support the recommendation of fertilizer application level less than 100% to achieve optimal maize crop yield production achieved in the controlled demonstration plot yield value of 8.81 ton/ha.

Maize dry grain yields reduction vary gently for soil fertility stress range from 0% to 50% levels but greater variation occurs for values above 50% in all the weather conditions.

Table 4.34: Yield gap (ton/ha) range prediction for Uasin Gishu plateau climatic seasons

Soil Fertility Stress (%)	Predicted maize yields under soil fertility stress and their Yield gaps							
	Predicted maize yields (tons/ha)			Non-stressed farm yield ($F_{100}W_{100}$)	Yield gap (ton/ha) analysis			
	Dry season	Normal season	Wet season		Dry season	Normal season	Wet season	Average yield gap
0 ($F_{100}W_{100}$)	7.02	9.46	11.17	8.81	- 1.79	0.65	2.36	0.41
5	6.67	9.32	10.61		- 2.14	0.51	1.8	0.06
20	5.68	7.89	8.96		- 3.13	- 0.92	0.15	-1.30
40	4.67	6.27	7.41		- 4.14	- 2.54	- 1.4	-2.69
50	4.32	5.84	6.93		- 4.49	- 2.97	- 1.88	-3.11
60	2.96	4.03	4.82		- 5.85	- 4.78	- 3.99	-4.87
80	1.40	1.93	2.36		- 7.41	- 6.88	- 6.45	-6.91
95	1.00	1.37	1.57		- 7.81	- 7.44	- 7.24	-7.50

Comparison of grain yield results simulated under soil fertility stress and soil nutrient application levels used in the demonstration plots are given in Table 4.35 for similar range of 20% to 80% maize nutrition levels.

Table 4.35: Comparison of maize yields (ton/ha) under climate based simulation of soil fertility stress and field nutrient application level

Fertilizer nutrition level (%)	Dry season			Normal season			Wet season		
	Soil fertility stress	Field nutrient level	Variation	Soil fertility stress	Field nutrient level	Variation	Soil fertility stress	Field nutrient level	Variation
80	5.68	7.06	1.38	7.89	9.88	1.99	8.96	11.22	2.26
60	4.67	6.76	2.09	6.27	9.46	3.19	7.41	10.79	3.38
40	2.96	6.87	3.91	4.03	9.60	5.57	4.82	10.95	6.13
20	1.40	6.43	5.03	1.93	8.97	7.04	2.36	10.23	7.87

The results indicate that maize yields achieved under calibrated field nutrient fertilizer application levels get boosts of supplemental residual soil nutrients from mineral, organic and biological sources commonly available in Uasin Gishu plateau soils. The amount of soil nutrients made available for maize crop assimilation and production is also influenced by the amount of water in the root zone and the difference is shown by the yields delineated under dry, normal and wet weather conditions. Simulation of yields results under soil fertility stress assumes no other source of nutrition is available compared to those of field nutrient application and therefore lower values justify the difference in the crop nutrition.

Determination of yield gaps values under AquaCrop model fertility stress conditions does not take into account the amount of available residual nutrients reserve in the field soil conditions that contributes to the final maize crop nutrition and production yields.

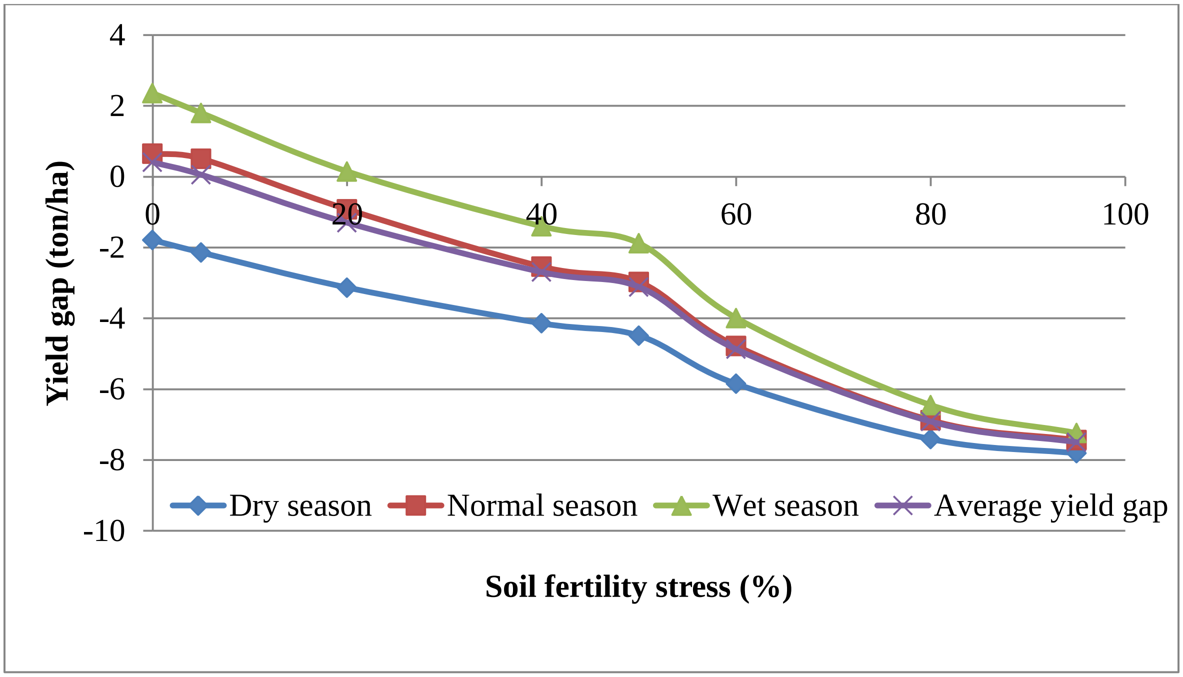

Fig. 4.38: Effect of soil fertility stress and climate on prediction of maize yield gaps in Uasin Gishu plateau

Comparative prediction of maize yield gaps for various soil fertility stresses and weather conditions are given in Figure 4.38. The findings indicate that maize yields and yield gaps drop as fertility stress increases. AquaCrop model simulation partitioned maize yields under fertility stress grouped into dry, normal and wet season conditions. Normal weather results are approximately the average of both dry and wet season data. The difference in yield gap results for the three weather conditions above 50% soil fertility stress are closer with smaller margins than for stress less than 50%. This is attributed to stronger influence of reduced nutrition levels compared to the effect of the amount of water and weather conditions.

CHAPTER FIVE

DISCUSSIONS

5.1 Introduction

Randomized complete block design plots provided a set up for applying statistical analysis and conclusions based on sampled data. The data was closely monitored on daily basis and therefore represent the climate and maize production requirements at Saroiyot farm. Mobile steel framed rainfall shelter was constructed on site and facilitated control of deficit irrigation application.

Analysis of the research data incorporated various statistical techniques to obtain the results of the respective research objectives and the questions presented. AquaCrop model simplified the design of deficit irrigation water application rates. Prediction of maize yields and analysis of yield gaps for Uasin Gishu county weather were achieved by applying AquaCrop model. Partitioning of the climate using meteorology data was achieved by applying RAINBOW software.

5.2 Statistical analysis of the field demonstration plots data

Statistical tools are employed to guide in the explanation and interpretation of the field demonstration plot results for maize production under deficit irrigation and nutrient fertilizer application levels.

5.3 Response of maize yield to various levels of moisture and nutrient fertilizer applications

Average maize yield data are considered to establish their response to the amount of applied deficit irrigation and the trend is presented by Figure 4.6. There is a general increase in maize yield as the level of regulated amount of moisture is increased. Maize yields achieved at 100% readily available moisture in the soil was slightly less than the maximum amount at 90% moisture application. This implies that optimal level of production of maize is not necessarily at maximum availability of water.

The average amount of dry above ground biomass level comprises of dry maize grain yield and the stover dry matter and their trend is presented in Figure 4.8. The result is proportionately similar to Figure 4.6 showing average grain yield is derived from the average biomass production. AquaCrop model simulates crop yields as a function of the dry biomass depending on crop harvest index as a coefficient of proportionality.

Maize crop growth demands utility of both moisture and nutrient fertilizer in the soil under favourable conditions. The analysis of the standard crop production function normally dependent on only moisture as an independent variable is modified by considering additional parameter. The right amount of water is required to dilute and enable the nutrients to be abstracted by the crop and conversely, the right level of nutrients are required to meet the crop demands and to minimize effects of salinity and high salt concentrations.

Statistical analysis applied ANOVA to consider the variation of dry grain yields with both available levels of moisture and nutrient fertilizer applied. Yield data from the 75 plots were grouped into low, medium and high yields. Graphical presentation of the data derived average values of optimal nutrient fertilizer and moisture application.

Variations of dry maize grain yields under treatment levels of nutrient fertilizer and moisture were considered by applying average trend of their standard deviations. Standard deviation values of maize grain yields were derived for every treatment level of nutrient fertilizer in the field for moisture variation from W_{50} to W_{100} and the results are presented in Figure 4.11.

Further analysis of the three variables of maize grain yield, nutrient fertilizer and moisture was carried out by studying maize grain yield coupled with each of the other parameters separately. Yield variations with each of the variable nutrient fertilizer and moisture are considered at non-stressed application level of F_{100} or W_{100}. Optimal value of maize grain yield was established by plotting their correlation trends together and results are presented in Figure 4.12. Both input treatments are saved when lower application in the field takes place at optimum levels. Considering previous statistical average values of 65% nutrient fertilizer and 80% moisture application levels presented in Figure 4.12 gave maize grain yield of 8.4 ton/ha and 9.3 ton/ha respectively. Their yield variations with the controlled demonstration plot value of 8.81 ton/ha are - 0.41 ton/ha (- 4.7%) and 0.49 ton/ha (5.6%). The value of variation is approximately equal below and above the optimal yield value of 8.8 ton/ha. This result suggest the use of variable combination of nutrient fertilizer and moisture application levels between 65% and 80% respectively that ultimately give the average of the optimum value of 75% when both variables apply concurrent level.

Further analyses of the correlations extrapolation show that 0% nutrient fertilizer application level resulted in dry maize grain yield of 4.9 ton/ha and 0% moisture application attain 0.9 ton/ha. This result confirms that maize crop production record minimal yield when supported by only residual plant nutrient reserves in the soil and close to zero yield when no moisture is applied and dependent only on atmospheric dew or available soil moisture.

5.4 Correlation of the soil residual nutrients with maize yield, nutrient fertilizer and deficit irrigation levels

Crop nutrients in the soil are part of the soil components or introduced through decomposition of crop residue and addition of inorganic fertilizers. Their presence and concentrations in the soil influence availability of nutrients for plant growth and soil microbial activity. Accumulation of residual nutrients may increase after every cropping season and become environmental and economic concern in crop production.

5.4.1 Correlation between residual nutrients with maize grain yields

Interpretations of the analysis consider the levels of major plant nutrients at the beginning before maize sowing and at harvest to assess their variation. The nutrients considered are; Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), Manganese (Mn) and soil pH.

Variations of maize grain yield results from the demonstration replica plots inferred that some level of crop nutrients in the soil root zone were boosting the crop growth and development. Correlation results in Table 4.15 confirm that residual nutrients (Phosphorus, Potassium, Calcium, Magnesium and Manganese) had significant relationship with maize yield levels. The amount of these nutrients in the soil influences the level of yield to be achieved and therefore explains why maize grain yield varied in the replica plots.

Plots with high levels of residual amounts of calcium, magnesium and manganese had the highest yield levels and suggests that the nutrients were sufficient in the soil.

5.4.2 Correlation between residual nutrients with nutrient fertilizer levels

Nutrient fertilizer added to the soil during sowing of maize contains nitrogen and inorganic phosphorus required by plants as macro elements and interacts with the available residual nutrients in the soil and influence ultimate yields and biomass production of maize. The inorganic fertilizer contain zero content of potassium which is sufficiently found in the soil and because it is highly reactive forms compounds with input fertilizer.

Favourable plant growth and most soil processes occur when soil pH range is 5.5 – 8.0 (Saweda *et al.*, 2017). Soil acidity occurs when pH is less than 5.5 which is considered an optimal level. The demonstration site average level soil pH measurement was 5.0 (Appendix IV) and the soils were categorized as acidic.

The value of pH is measured by the amount of hydrogen ions in the soil. Ionization level requires water and therefore pH reading is dependent on the amount of moisture in the soil. Soil acidifies because of increased concentrations of hydrogen ions caused by inefficient use of nitrogen majorly in Ammonium based fertilizers and removal of plant materials (Alkaline) through grazing or harvest. Organisms contributing in decomposition of organic materials cause release of hydrogen ions, and in addition to high rainfall seasons make soils more acidic. Low pH causes reduced crop yields and increase in availability of micronutrients (Manganese, Aluminum and Iron), their toxicity and decrease in the availability of essential (macro) nutrients (N, P, K, S, Ca and Mn), Molybdenum and water intake by plant roots.

Levels of available residual nutrients in the soil at harvest were correlated with the applied nutrient fertilizer and the relationship is presented in Table 4.17.

5.4.3 Correlation between residual nutrients with moisture levels

Availability of moisture in the soil play a key role in the ionization of the plant nutrients, assimilation process and transpiration. Interaction processes of soil residual nutrients are dependent on the level of moisture applied. The amount of nutrients left in the soil was correlated with the applied moisture content levels under deficit irrigation strategies. Sufficient moisture in the soil was necessary for plant nutrients to be assimilated.

5.5 Calibration and Validation of AquaCrop model using field data

AquaCrop is a mathematical model developed to measure water productivity of different crops. The model was developed through simulations using default values of various crops and climate. The model has the capacity to simulate water productivity of all the crops in the system crop file. This is made possible by calibrating the model for the prevailing local climate and its accuracy is confirmed by validating using data of green canopy cover, soil moisture regime, biomass production during the cropping season and the crop yield.

AquaCrop model was calibrated for the Kenya seed company hybrid H629 maize cultivar parameters tabulated in Table 4.19. Statistical analysis of simulation (FAO, 2018) is applied by the model to evaluate its performance using Pearson's coefficient of determination (r), normalized root mean square error CV (RMSE), Nash-Sutcliffe model efficiency coefficient (EF) and Willmott's index of agreement (d).

Comparison of Pearson's correlation coefficient of determination (r), Willmott's index of agreement (d) and correlation trend (R^2) are approximately equal where r= 0.85 to 0.92, d = 0.90 and R^2 =0.898 to 0.916 given in Figure 5.1. Recoded values are rated good between 0.80 and 0.89 and very good from 0.90 and therefore the model simulation was in good agreement with observed field data.

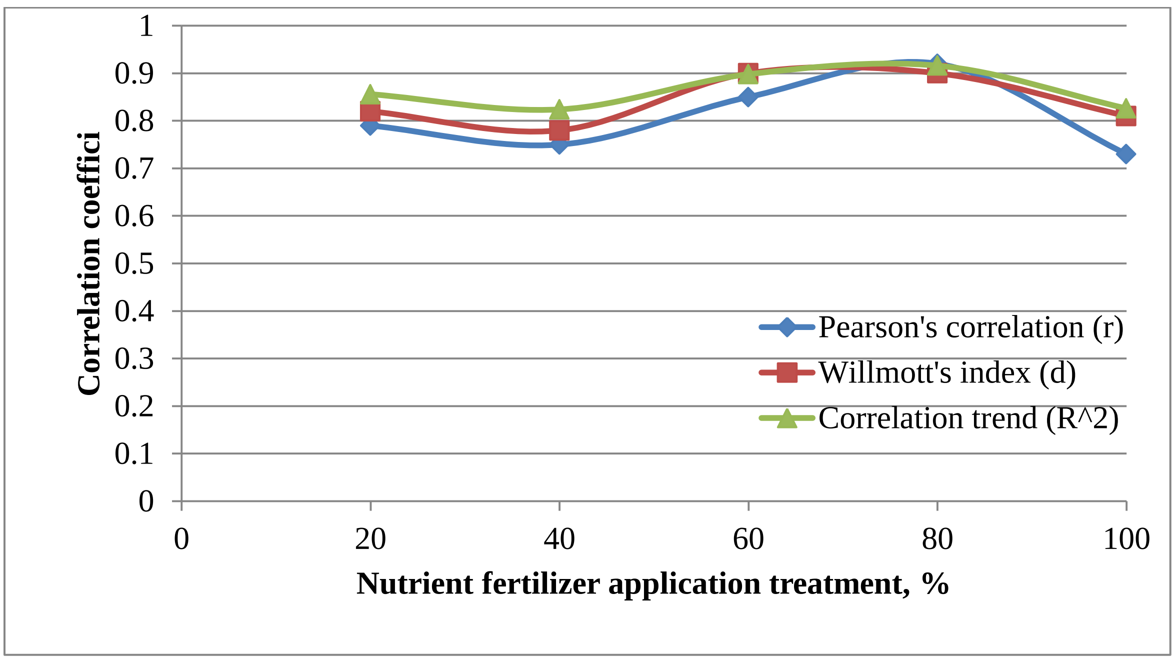

Figure 5.1: Evaluation of AquaCrop model calibration correlation coefficients

Normalized CV (RMSE) values (19.1 – 16.7) are in the range of moderately good (16% to 25%) while EF values of (0.35 – 0.50) also fall into moderately good (0.40 to 0.59) category. All other parameter values for F_{20}, F_{40} and F_{100} deviate slightly lower but above average.

Statistical evaluations confirms that AquaCrop model correlations responds strongly to maize crop growth at nutrient fertilizer treatments between 60% and 80% using canopy cover and grain yields simulation when moisture is not limiting (W_{100}). The calibration results agree with the statistical analysis given in Figures 4.10 and 4.12 that give average optimal nutrient fertilizer levels of 65% when considered independent of moisture and 75% when both parameters are coupled in the analysis.

Results of AquaCrop model validation of calibrated parameters and using actual field demonstration data of canopy cover, soil water content and maize grain yields compare observed and simulated values. Simulations are run for moisture treatment levels not used in calibrations of W_{90}, W_{80}, W_{65} and W_{50} for the respective nutrient fertilizer treatment levels of F_{100}, F_{80}, F_{60}, F_{40} and F_{20}.

Validation correlation results indicate that nutrient fertilizer application levels between F_{40} and F_{80} are distinct from those in the range of F_{20} to F_{40} and F_{80} to F_{100}. Graphical representation of correlations trends in Figure 5.2 show that moisture application label of W_{65} and W_{80} recorded similar values above 80% and higher than those of W_{90} in the nutrient fertilizer range of F_{40} to F_{80}. Other moisture levels recorded slightly lower values but correlation coefficient is above 70%.

Correlation of maize grain yields of observed and simulated values recorded lower coefficients than those of the canopy cover. Values recorded at F_{40} (0.64) and F_{80} (0.63) are similar and those of F_{20} (0.45) and F_{100} (0.51) are average values. F_{60} (0.20) recorded the lowest value that explains the yield graph given in Figure 4.7 which showed reduction in yields under this treatment.

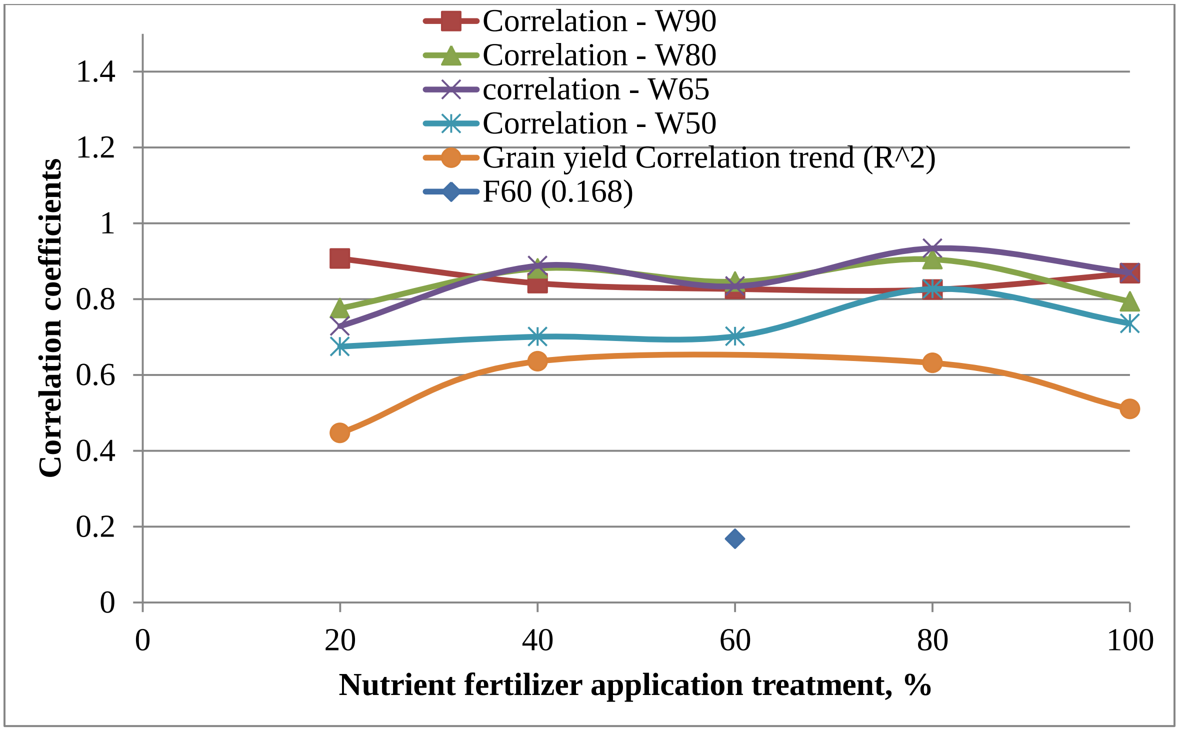

Figure 5.2: Evaluation of AquaCrop model validation correlation coefficients

Moisture levels of W_{65} and W_{80} recorded the highest correlation coefficients at nutrient fertilizer level of F_{80}. The levels of moisture with highest correlation indicate that maize crop is growing at optimal rate and its parameters agree with those of the model calibration.

5.4.1 AquaCrop model water productivity simulation results

Interpretation of water productivity results from AquaCrop simulation modeling is considered by comparing the harvest index variations with biomass and grain yield. Generalized trends presented in Figure 5.3 (a) – (d) are used to deduce possible actual results that occur in the field under influence of moisture and fertilizer treatment levels.

Biomass is one of the products of plant food manufacture that result in the dry matter and therefore it increases when the food processing green vegetative matter increases. The amount of maize grain yield is directly proportional to the biomass growth and the coefficient of proportionality is the harvest index which is expected to be constant in an environment when all plant growth parameters are not limiting.

Simulation modeling results under deficit irrigation treatment recorded biomass increase from 25.553 ton/ha at low moisture level of W_{50} to a maximum value of 28.124 ton/ha at non-stressed moisture level of W_{100} (R^2=0.917). Maize grain yields increased from 8.230 ton/ha at W_{50} to a 8.815 ton/ha at W_{100} (R^2=0.7378). Maximum maize grain yields are attained at W_{80} moisture level. This result implies that maximum grain yields do not necessarily occur at maximum biomass level and therefore harvest index coefficient is not constant. Values of the harvest index decreased from 32.9 at W_{65} to 31.3 at W_{100} as moisture application and biomass production increased. Similar trend is recorded for water productivity (WP) and IWUE values decrease from 2.36 to 2.21 and from 2.305 to 2.069 respectively. High level of moisture application in maize production lead to delay in the crop maturity and maximum use of the available nutrients cause flourishing of the dry matter and less conversion into grain yield.

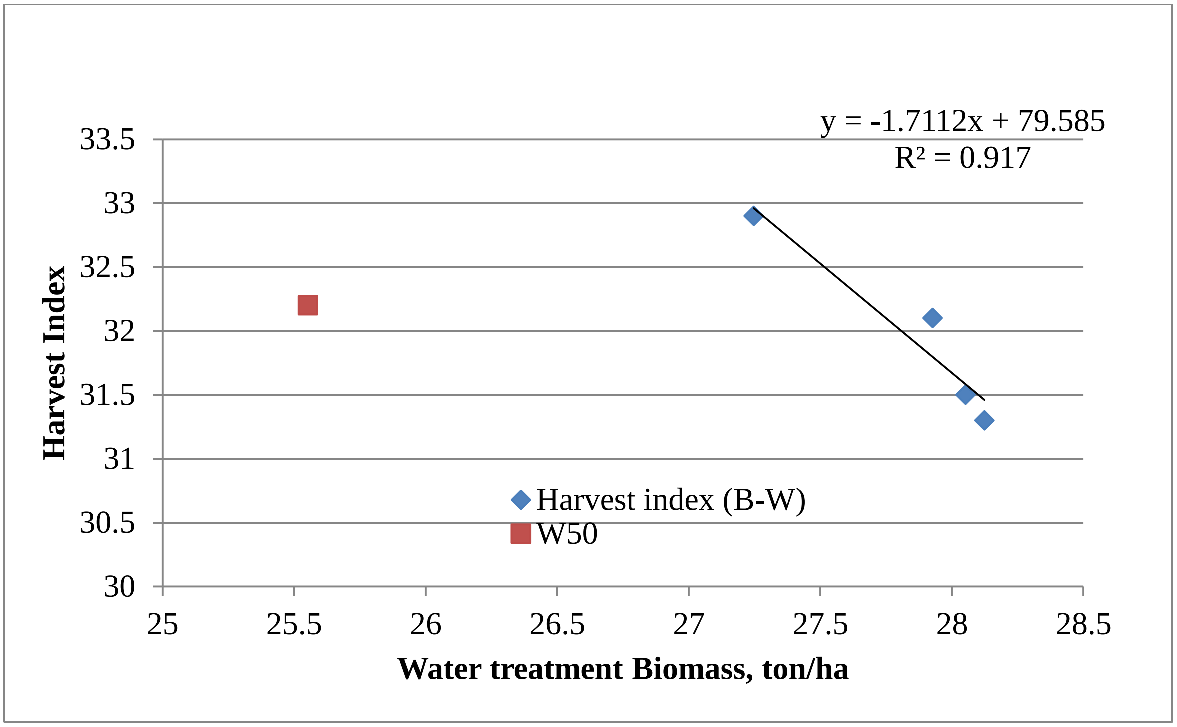

Figure 5.3: (a) Variation of the harvest index with biomass under deficit irrigation treatment

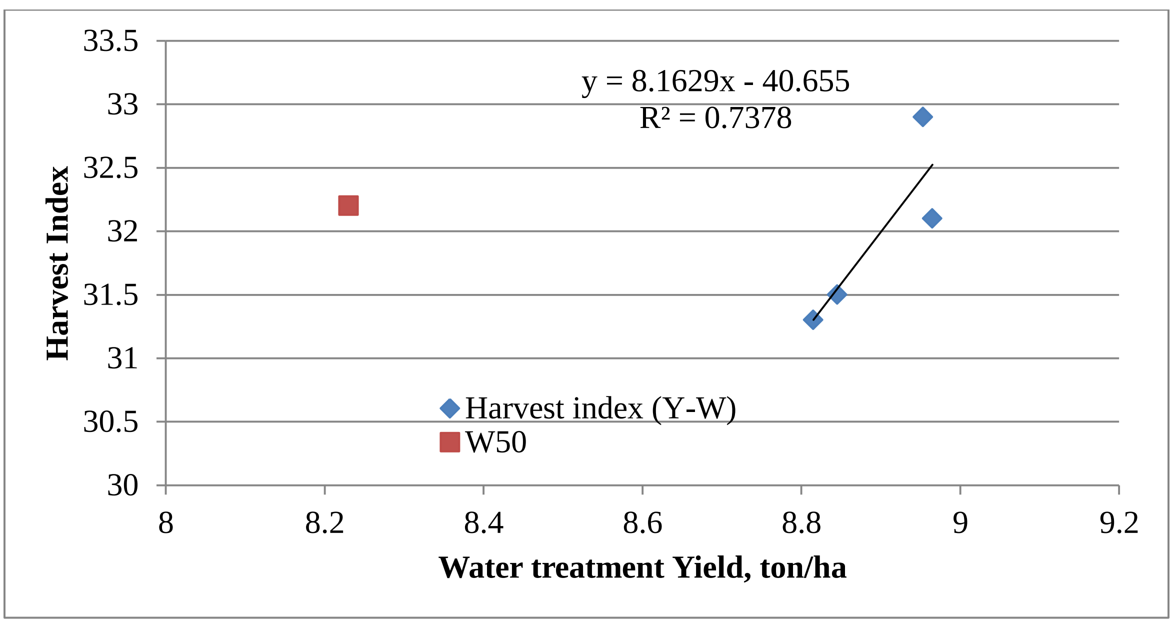

Figure 5.3: (b) Variation of the harvest index with maize yield under deficit irrigation treatment

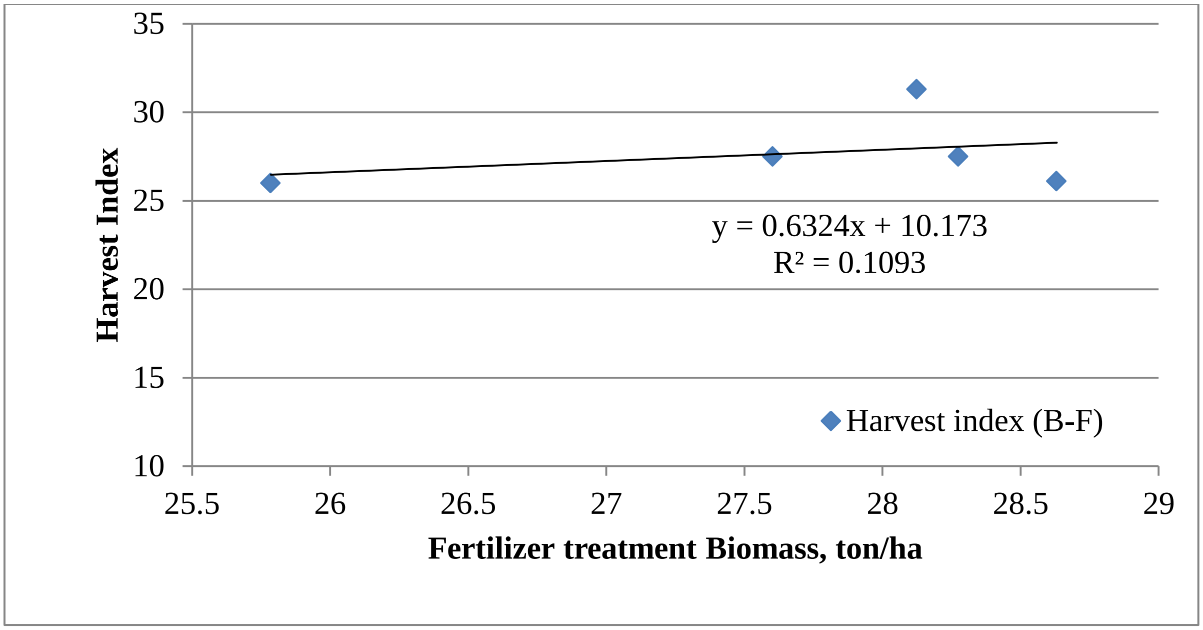

Figure 5.3: (c) Variation of the harvest index with biomass under nutrient fertilizer treatment

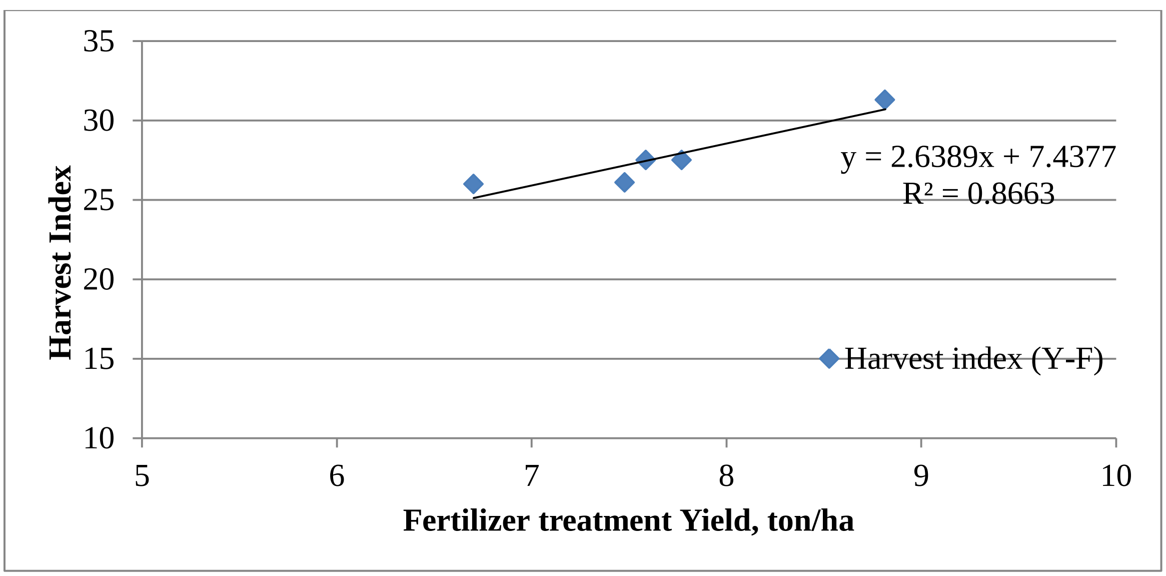

Figure 5.3: (d) Variation of the Harvest index with maize yield under nutrient fertilizer treatment

Simulation results based on the nutrient fertilizer treatment recorded low correlation trend of biomass production and the harvest index (R^2=0.1093). However extreme low of 26.0 and high of 31.3 values of harvest index occurred under low (F_{20}) and high (F_{100}) nutrient fertilizer treatment levels but near constant values at F_{40} – F_{80}. Biomass increased from 25.785 ton/ha to 28.124 ton/ha and grain yield increased from 6.703 ton/ha to 8.815 ton/ha from F_{20} to F_{100} respectively. Positive correlation between grain yield and the harvest index of R^2=0.8663 indicate a strong relationship of increase in HI causes increase in water productivity, IWUE and grain yield when nutrient fertilizer application levels increased from F_{20} to F_{100} when moisture is maintained at W_{100}. Maximum biomass value of 28.631 ton/ha occurred at F_{60} and at the same nutrient fertilizer level recorded unique reduction of grain yield, water productivity, harvest index and IWUE.

5.5 Application of AquaCrop model in yield gaps prediction under water and fertility stress in Uasin Gishu County

The challenges of attaining food self sufficiency and security in Uasin Gishu county demands that accurate prediction of food crop yields are essential in order to obtain early forecasts of expected production surplus and deficit amounts. Production capacity of land area utilized for food production is diminishing because of change in use and reduction in the fertility levels. AquaCrop is a handy water productivity model that guides in food policy development and interpretations of optimal yields of food crops under prevailing field environmental conditions. The model utilizes local climate parameters for calibration in the production of sustainable crop yields.

The results of maize yield from Saroiyot demonstration site are the farm yields used as the basis for comparing with the crop maximum potential yields.

Different methods are used for yield gap assessment and each approach is subject to possible limitations. The methods are distinctly divided into actual field-based yield data collection and crop model simulations. Field data are either collected from controlled experiments or survey of farmers documented records. Reliable results from field data are achieved through well-managed methodology that eliminates erroneous variations in the yield gaps. Benchmarking of the cropping season and replications should be maintained to reduce yield-limiting and reducing factors (Cassman, 2003 and *Lobell et al., 2009*). Crop simulation models, such as AquaCrop simplify the interactions of the soil-water-plant and environment processes into a mathematical representation that is calibrated for the local prevailing conditions. The models are flexible to simulate various crop yields and are validated for their reliability using controlled field data under non stressed conditions.

5.5.1 Comparative strategies of deficit irrigation and water productivity analysis

Implementation of deficit irrigation design of 50%, 65%, 80%, 90% and 100% of the crop water requirement (ET_c) have shown that production of maize grain yields in the replica plots may not necessarily reduce adversely with decreasing moisture applied. Decreasing moisture application level from W_{100} to W_{50} causes maize grain yields increase from 8.815 ton/ha to a maximum of 8.965 ton/ha at W_{80} then decreased to 8.230 ton/ha at W_{50}. Water productivity values followed the trends of grain yields and varied from 2.21 kg/m^3-H_2O at W_{100} to a maximum of 2.36 kg/m^3-H_2O at W_{65} then dropped to

2.31 kg/m^3-H_2O at W_{50}. Lower deficit irrigation at W_{50} had better utilization of moisture applied and saved 54.4 mm more than 31.2 mm saving at W_{100}.

Reduction of the yields and water productivity at W_{100} imply that the efficiency of the crop growth and yield production is affected by applying full amount of readily available moisture. The balance between the exchange of gases during aeration and crop nutrient assimilation is lower and therefore not recommended for optimal water application and maize crop yield assessment.

5.5.2 AquaCrop model prediction of maize yields under field demonstration plots

The results of maize grain yields from the demonstration plots recorded a general increase from low level at W_{50} of 7.08 ton/ha to a maximum yield at W_{90} of 10.99 ton/ha moisture levels. Maximum moisture application level of W_{100} recorded reduced yield to 8.81 ton/ha (controlled plot) and the value was used in the calibration of AquaCrop model calibration for maize crop parameters under non-stressed conditions. Yield results for moisture application levels of W_{50} to W_{90} were used in the validation of the model and recorded minimal variations.

Apart from the nutrient fertilizer and moisture requirements for maize crop growth, other factors such as aeration and residual soil fertility may alter the level of yields attained. The farm used for the demonstrations has been utilized for maize production for over two decades under mechanized land preparations. The level of farm yields and their yield gaps recorded indicate that more studies are required of possible soil profile modifications as a result of soil erosion and compaction. Controlled rain-fed plots at demonstration site experienced normal cropping season and sufficient moisture for maize crop production recorded an average of 9.24 tons/ha and the yield gap was 0.43 ton/ha (4.9 %) with the non-stressed irrigated plot of W_{100}. The average rain-fed yield value is about 84% of the maximum attained under drip irrigation moisture application of W_{90}. This result support earlier recommendation that optimal level of moisture application is about 80%.

Findings of yield gap variations under nutrient fertilizer levels displayed three unique trends from F_{20}-F_{40}, F_{40}-F_{60} and above F_{60}. For this analysis, the trends are categorized into low, moderate and higher levels of fertilizer application respectively to explain that maize crop responds differently with the available levels of nutrient fertilizer in the soil. Low levels of nutrient with sufficient available moisture triggers plant roots to grow further in search for plant nutrition. Under this category, yields increase for every increase in nutrient fertilization from negative lowest yield gap of 2.12 ton/ha (24.1%) obtained at F_{20} to a value of 1.24 ton/ha (14.1%) at F_{40}. The yield gap is reduced by about 50% in this category when maize is surviving under low applied nutrition but utilize more in the soil storage reserves (residual nutrients). Average level of nutrient fertilizer application occurs at moderate category. Fertilizer amounts would seem sufficient for initial root growth development of maize causing concentration around wetted area of drip irrigation application points. Maize crop demand for nutrients and water is high during development growth before flowering and silking but amount available at moderate levels does not satisfy crop development with shallow rooting system and mature with reduced yields. Minimal increase in yield gap occurred from 1.24 ton/ha (14.1%) to 1.41 ton/ha (16.0%) showing a reduction of maize crop yield from 7.57 ton/ha to 7.4 ton/ha. The two categories recorded lower farm yields compared to model simulated value and therefore not recommend for management of an economical maize production.

Application of sufficient moisture and enhanced higher nutrient fertilizer levels above F_{60} caused maize crop yields to increase sharply to 10.08 ton/ha at F_{80} and a yield gap of 1.27 ton/ha (14.35%) higher than controlled plot (F_{100}) yield value of 8.81 ton/ha. Maize grain yields reduced when maximum nutrient supply is applied and therefore support the expected trend of nutrition turning poisonous to crop production when available in large quantities in the soil.

5.5.3 AquaCrop model prediction of maize yield distribution under Uasin Gishu climate

Maize crop requires rainfall amounts between 500mm and 800mm of water per season (Tekwah and Bwade, 2011, *Abirdew et al., 2018*) and the amount of moisture is within rainfall recommendation by FAO, 2006 of 600 mm – 1150 mm during growing period.

Analysis of maize cropping season (March - October) rainfall data for 34 years categorized Uasin Gishu weather into dry, normal and wet seasons. Dry conditions had rainfall occurrence with magnitude of events less than 738.5mm (80% probability of exceedance). The condition had a minimum of 390.3mm and a maximum of 624.2mm of seasonal rainfall.

Normal season rainfall data had a minimum of 556.3mm and a maximum 923.1mm, while wet season condition recorded a minimum of 977.3mm and a maximum of

1056.6mm. Both weather conditions recorded amounts higher than the seasonal requirements of maize. The amounts provided sufficient water for the crop production and excess is lost back into the environment through both surface water runoff and soil water percolation into groundwater storage. Yield gap for wet conditions was the highest at 2.36 ton/ha (26.79%) compared to – 1.79 ton/ha (- 20.32%) and 0.65 ton/ha (7.38%) for dry and normal weather conditions respectively.

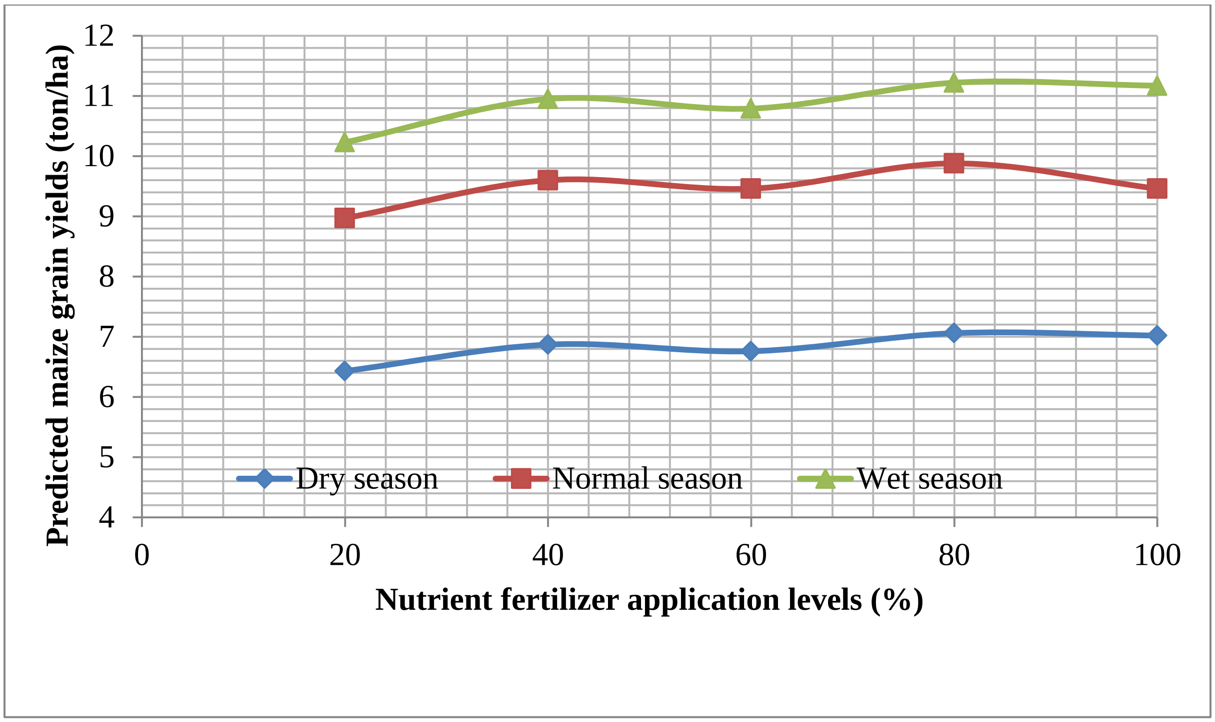

Figure 5.4: Trends of maize yield prediction for nutrient fertilizer application levels

Results of maize grain yield when moisture is sufficient are considered for different nutrient fertilizer levels (F_{80}, F_{60}, F_{40}, and F_{20}) in the three weather seasons. Grain yield prediction in the three seasons recorded general increase from lower values at F_{20} to maximum yields at F_{80} and reduction occurred for F_{100}. Predicted grain yields at F_{20} are

6.43 ton/ha, 8.97 ton/ha and 10.23 ton/ha and their yield gaps are – 2.38 ton/ha (- 27.0%), 0.16 ton/ha (1.82%) and 1.42 ton/ha (16.12%) in dry, normal and wet seasons respectively. Maximum grain yields at F_{80} are 7.06 ton/ha, 9.88 ton/ha and 11.22 ton/ha and their yield gaps are – 1.75 ton/ha (- 19.86%), 1.07 ton/ha (12.15%), and 2.41 ton/ha (27.36%) for dry, normal and wet weather conditions.

AquaCrop model predicted smoothened grain yield variation profiles similar to the trends recorded in the demonstration plots. Yields increase from F_{20} to F_{40} followed by a decrease F_{60} then increased to a maximum in F_{80}. A decrease is recorded in F_{100} yields similar to crop production trend at maximum input applications.

Statistical analysis of demonstration plot data on variations of maize grain yields gave an optimum yield of nutrient fertilizer application at 65% in Uasin Gishu plateau. Residual nutrient reserves in the soil provide the balance requirements for optima maize production. Results of AquaCrop model prediction given in Figure 5.4 recorded at 65% nutrient fertilizer application optimal maize grain yields of 6.8 ton/ha, 9.6 ton/ha and 10.8 ton/ha in dry, normal and wet weather conditions and their yield gaps are – 2.01 ton/ha (-22.8%), 0.79 ton/ha (9.0%) and 1.99 ton/ha (22.6%). The results are closely related to grain yield prediction results of 7.02 ton/ha, 9.46 ton/ha and 11.17 ton/ha based on the rainfall data for Uasin Gishu plateau for dry, normal and wet seasons respectively.

5.5.4 Influence of soil distribution and weather conditions on maize yield prediction

Soil comprises mineral particles of various particle sizes, organic matter and the voids holding water and air. AquaCrop model incorporate soil types and their physical characteristics module in its calibration. Influence of the soil characteristics on maize production was considered during maize grain yield predictions. The model was calibrated for non-fertility stress condition so that water and nutrient holding capacities are what generates the results given in Figure 4.17.

Maize yield predictions in various soil textures for the three weather conditions gave unique and consistent trends. The difference in yield levels is attributed to the climatic conditions that prevailed in dry, normal and wet seasons.

Influence of individual weather condition resulted on different levels of yields recorded. Under wet weather condition all the soil types having a combination of loam, clay, silt and sand recorded yield gap values between 25.1% and 26.2% except sandy clay (13.7%), clay loam (19%), silt (21%) and silt clay loam (- 2.5%). Soil types which are prone to waterlogging and low yield values are Clay (- 85.7%) and silt clay (- 49.0%). Under normal weather low yield gap was recorded for clay loam (0.91%) and Saroiyot soil (15.6%), otherwise all other soil types recorded positive values between 21.9% and 25.0%. Negative yield gaps are recorded in clay (- 95.6%), sandy clay (- 27.5%), silt clay loam (- 39.4%) and silt clay (- 68.7%). These soils with negative yield gap have clay content and prone to poor drainage.

Prediction of maize grain yield under dry weather condition recorded low yield gaps for loamy sand (17.9%), sand (15.0%) and sandy clay loam (14.1%) while other soils values ranged from 21.6% to 24.0%. Negative yields recorded large value for clay (- 100%), clay loam (- 52.2%), sandy clay (- 100%), Saroiyot soil (- 31.6%), silt clay loam (- 100%) and silt clay (- 100%). Soils with negative yield gaps recorded low yield are affected by drought and impede plant roots from scavenging into the soil.

Yield prediction results are further considered based average results of group characteristics of similar textural derived soil types that include; clay (clay, clay loam), silt (silt, silt clay loam, silt loam, silt clay), sand (sand, sandy clay, sandy clay loam, sandy loam) and loam (loam, loamy sand). Average maize grain yields, standard deviation and their respective yield gaps are presented in Table 5.1

Analysis of the soil textural groups gave average results of grain yield, standard deviations and their yield gaps for the three weather seasons. Clay derived soils in dry season record average yields of 38.6% of the controlled plot value of 8.81 ton/ha with an average yield gap of -61.3% but when sufficient moisture is available during wet season increased to an average yield of 86.3% and improved yield gap of -13.6%. Silty group of soils recorded yields of 62.4% and yield gap of -38.6% in dry season and increased to 98.8% and yield gap of -1.1%. Yields of the controlled plot are closely approximate to the average value attained by silty soils during wet season. Sandy soils group average yields attained 87.4% and yield gap of -12.5% in dry season and increases to 122.6% and positive yield gap of 22.7%. Loamy soils attained yield of 120.3% and yield gap of 20.4% in dry weather and increased to 126.0% and yield gap of 26.1% during wet conditions. Prediction results suggest that maize production is favourable in soils with balanced mix of the textural classes and non-plastic course textured soils.

Table 5.1: Average maize grain yields predicted for group soil textural characteristics

Soil textural group	Dry season			Normal season			Wet season		
	Average yields (ton/ha)	STDEV	Yield gap	Average yields (ton/ha)	STDEV	Yield gap	Average yields (ton/ha)	STDEV	Yield gap
Clay (Clay, Clay loam, Saroiyot soils)	3.4	3.1	-5.4	6.5	5.3	-2.3	7.6	5.5	-1.2
Silt (Silt, Silt clay loam, Silt loam, Silt clay)	5.5	6.3	-3.4	7.4	4.0	-1.4	8.7	3.3	-0.1
Sand (Sand, Sandy clay, Sandy clay loam, Sandy loam)	7.7	5.2	-1.1	9.8	2.3	1.0	10.8	0.5	2.0
Loam (Loam, Loamy sand)	10.6	0.3	1.8	10.9	0.0	2.1	11.1	0.1	2.3

The group results indicate a general increase in yields and their yield gaps as weather changes from dry to wet conditions and from clay to loam textural group of soils. This imply that increased moisture in the soil boost the capacity of maize crop to mobilize abstraction of plant nutrients and that course textured group of soils allow sufficient moisture and nutrient storage and unlimited root development.

5.5.5 Effect of soil fertility stress on maize yield prediction for different weather conditions

Soil fertility stress is a form of soil degradation that cause stagnation or decreasing crop yields (FAO, 2006) and variations in yield gaps. The problem is experienced in the field as a result of multiple activities in the soil that include; plant nutrient depletion due to soil erosion, inactivation of nutrients, reduced retention and loss of organic matter, soil acidity and toxicity. The amounts of plant nutrients held in the soil reserve describe fertility level in a given ecological zone. Different soils exhibit different storage capacity and result in varied productivity categories.

Maize production yields continuously decreased for every increase in soil fertility stress level as a response to slower canopy expansion, reduced maximum canopy cover, and decreased biomass water productivity. Similar results were recorded by Van Gaelen et al., (2015). Considering agro-ecological zones, observations by Yusuf, (2018) found that soil fertility had a much larger effect on crop yield than climate change factors and concluded that crop yields responded positively by increasing soil fertility in any agro-ecological zone.

Simulation of yields under fertility stressed soil conditions affected both biomass production and maximum canopy cover achieved. Calibration of the model to simulate changes in fertility levels in the soil is achieved by varying both biomass production levels and maximum canopy cover. Canopy cover profile coefficients (FAO, 2017) are defined and used to predict maize yields for the tuned levels of stress.

The three weather conditions partitioned by RAINBOW displayed different and unique trends of the amount of available rainfall water and the crop yield. Results of maize grain yields from each category of weather condition indicate that biomass production level and maximum canopy cover have direct influence of their quantities. This implies that any increase in fertility stress in the soil affected maize crop biomass production and result in depressed yields.

Depending on the production levels in the reference plot (non-stressed condition), AquaCrop model was calibrated to simulate biomass production under fertility stress between 5% (near optimal production) and 95% (very poor production). Reduction in canopy cover from 75% (close to reference level) to 11% (very strongly reduced) is registered by biomass water productivity (WP*) reduction process from 30.7 g/m^2 to 12.9 g/m^2 and interpreted by the achieved maize grain yield ranges of 6.67 ton/ha - 1.0 ton/ha, 9.32 ton/ha – 1.37 ton/ha and 10.61 ton/ha – 1.57 ton/ha for the dry, normal and wet weather conditions respectively. Similar model calibration findings were reported by Van Gaelen et al. 2015 as soil nutrient reservoir becomes depleted.

Uasin Gishu plateau weather at normal and wet conditions given in Figure 4.38 achieved break-even maize grain yield of 8.81 ton/ha recorded at the control plot ($F_{100}W_{100}$) at soil fertility stress levels of 15% and 25% or nutrient fertilizer application levels of 85% and 75% respectively and adequate water supply. Maximum maize grain yield under dry weather conditions at zero (0%) fertility stress level recorded lower value with a yield gap of -1.79. Minimum nutrition levels in terms of major plant nutrient quantities of Nitrogen (N), Phosphorus (P) and Potassium (K) applied in 18:46:0 D:A:P and 27% N

C:A:N fertilizers are derived from the field recommended application amount of 187.5 kg/ha (75 kg/acre) for each type and the consumption amounts per hectare are given in Table 5.5 for the break-even or zero yield gap values.

Table 5.2: Minimum amounts of Nitrogen and Phosphorus in fertilizer application

Field Category	Fertilizer level (%)	N:P:K (kg/acre)		N:P:K (kg/ha)		N (kg/ha)		P (kg/ha)		N (kg/ha)
		DAP	CAN	DAP	CAN	DAP	CAN	DAP	CAN	Total
Wet	75	56.0	56.0	140.6	140.6	25.3	38.0	64.7	0	63.3
Normal	85	63.8	63.8	159.4	159.4	28.7	43.0	73.3	0	71.7
Non-stressed	100	75.0	75.0	187.5	187.5	33.8	50.6	86.3	0	84.4

General recommendation by FAO, 2006 of N application rates for irrigated maize grouped crop varieties into 60–80 kg N/ha for early-maturing varieties, 80–100 kg N/ha to medium-duration varieties, and 90–150 kg N/ha to late-maturing varieties. Conditions of unreliable rainfall (dry weather) are associated with low yields and salinity problems recommend about 50 kg N/ha application. However, recommends application on the basis of prevailing local growing conditions and variations in soil Nitrogen (N) reserves and supply of other inputs and management are optimal. Amount of Phosphate (P) is in the range of 30–100 kg P_2O_5/ha and recommend application based on soil tests. Uasin Gishu plateau soils have sufficient amounts of Potassium (K) and therefore fertilizer contains zero formulation.

CHAPTER SIX

CONCLUSIONS

6.1 Introduction

The compilation of the demonstration plots results and analysis have generated important conclusions. Presentations of the research conclusions include; the evaluation of the demonstration plots set up and measurements, response of maize yields and correlations of residual nutrients to applied deficit irrigation and nutrients fertilizer, calibration, validation, simulations of maize grain yields and application of AquaCrop model in yield gap analysis of Uasin Gishu County.

Statistical tools were employed to explain achieved results. Individual plot results explained the trends of maize grain yields for the whole farm by applying their average mean, symmetry skewness and normal distribution kurtosis. Optimal yield values and the levels of application of both moisture and nutrient fertilizers are derived from their statistical outcome.

6.2 Response of maize yield to various levels of moisture and nutrient fertilizer applications

Maize yield data from the three replica plots were subjected to statistical analysis and found to fit to a symmetrical normal distribution presented in Figure 4.1 and had the lowest yield of 2.03 ton/ha and the highest yield of 13.5 ton/ha. The mean of maize yield data of the three replica plots were evaluated and found to be 7.71 ton/ha, 7.94 ton/ha .and 6.31 ton/ha in replicas 1, 2 and 3 respectively presented in Table 4.3 and Figure 4.2. The results of the mean show variations that were statistically proven to have significance level of $p=0.0$ given in Table 4.4. The treatments of replica plots were the same and therefore the difference realized in the mean of the maize yields was attributed to the difference in the level of residual nutrients available in the soil.

Data on above ground dried biomass show similar trends with maize grain yields. Analysis of their variations indicates lower grain yields result in higher percentage of biomass change and vice versa. Further statistical results show strong relation at significance level of $p=0.0$ between yield and biomass.

Design configuration of moisture and nutrient fertilizer application levels were considered concurrently in their response to maize crop yields in the demonstration plots. The results presented in Figure 4.10 yielded optimal maize grain yields at optimal application levels of 65% of nutrient fertilizer and 80% of moisture as a proportion of the practiced recommended application levels. These results suggests there will be savings in both the nutrient fertilizers and the amount of deficit irrigation applied and provides more increase in maize grain yields by increasing land area under the crop.

Results of correlation trends between dry maize grain yields and each of the treatment parameters of nutrient fertilizer and moisture (Figure 4.12) recorded an optimal yield value of 8.8 ton/ha at a concurrent application level of 75%. The same level of yield was attained at the controlled demonstration plot at non-stressed application level of $F_{100}W_{100}$.

6.3 Correlation of residual nutrients with maize yield, nutrient fertilizer and deficit irrigation levels

Agents of variations of maize grain yields in the three replica plots considered the levels of residual nutrients left in the soil after harvest. The amounts of residual nutrients indicated significant correlations with maize yield, nutrient fertilizer and moisture application levels.

6.3.1 Correlation between residual nutrients with maize grain yields

The amounts of residual nutrients in the soil were tested for their significance levels using Levene statistic, descriptive ranking and Pearson correlation at significant level of $p=0.05$.

Test of homogeneity of variances using Levene statistic indicated varying amounts of Nitrogen ($p = 0.021$), Phosphorus ($p = 0.000$), Calcium ($p = 0.000$), Magnesium ($p = 0.000$) and Manganese ($p = 0.001$). Variations of the amounts of nutrients in replica plots resulted in the nutrition and maize grain yields levels to vary.

Descriptive significance ranking have compared and shown that sufficiency of residual nutrient levels in the soil reflects the level of maize grain yields. Description of residual nutrients levels of high, average and low conforms to their occurrence and implied to the level of maize grain yields attained.

Pearson correlation between maize grain yield and residual nutrients shown in Table 4.15 indicate significant correlation exists for phosphorus, potassium, calcium, magnesium and manganese in the soil. The amounts of nitrogen ($p=0.320$) and the soil pH (0.251) indicate no significance with maize grain yield. The result explain that nitrogen is converted into compounds that is consumed or lost as gaseous and the average pH level of 5.0 in the soil caused minimal variations of maize grain yield.

6.3.2 Correlation between residual nutrients with nutrient fertilizer levels

Applied nutrient fertilizer had a strong correlation coefficient of p=0.04 (2-tailed) with residual potassium only in the soil (Table 4.17). The relationship is that potassium reacts and form compounds with input fertilizer. Other residual nutrients (calcium, magnesium, and manganese and soil pH) do not react with nitrogen and inorganic phosphorus contained in nutrient fertilizer.

Results of maximum application of nutrient fertilizer (F_{100}) level with variable levels of moisture (Figure 4.13) indicate high levels of residual nutrients left in the soil after harvest. This scenario explains build up of nutrients in the soil that lead to increased prevalence of low pH and transportation into large water masses.

6.3.3 Correlation between residual nutrients with moisture levels

Moisture content is important in order to allow the soil compounds release the amount of hydrogen ions commensurate with the level of pH measurements.

The findings between residual nutrients and moisture application levels (Table 4.17) indicate strong correlation exist with both the residual nitrogen (p=0.007) and pH (p=0.001). Nitrogen compounds require moisture content to be assimilated by the crop roots, otherwise lost into gaseous form. Moisture facilitates other elements in the soil which vary pH.

Application of maximum moisture (W_{100}) level for various levels of nutrient fertilizer (Figure 4.14) recorded low levels of residual nutrients in the soil after harvest. High level of moisture causes nutrients to be leached or transported out of the soil profile into large water masses.

6.4 Calibration and Validation of AquaCrop model using field data

AquaCrop model calibration and validation statistics are given by Pearson's correlation (r), Willmott's index of agreement (d) and correlation trend (R^2). The results presented in Table 4.22 have shown strong correlation trends are recorded between simulated and observed parameter values (R^2) with a minimum of 0.824 (F_{40}) and a maximum of 0.916 (F_{80}). Values of the correlation statistics r, d and R^2 are similar.

Significantly distinct higher correlation values occur between F_{60} ($R^2 = 0.898$) and F_{80} ($R^2 = 0.916$) and indicate the optimal values of calibration correlation statistics. Presented results support AquaCrop model efficiency in the simulation of maize crop growth and using canopy cover growth in assessing maize grain yield simulation process.

6.4.1 AquaCrop model water productivity simulation results

After calibration and validation process, the model is used to simulate water productivity strategies for the F=100% and W=100% respectively. The results support the correlation that production of maize grain yields are directly proportional to biomass yield and the coefficient of proportionality is the Harvest index (HI), a ratio that measure amount of grain yield to the amount of biomass produced.

Values of HI vary depending on water productivity, the amount of biomass and grain yield production. Average values of harvest index (kg/kg) of 0.25 – 0.58 were documented by *Guo et al., 2004; D'Andrea et al., 2008* for maize production. Simulation modeling results varied from 31.3 – 32.2 for W_{50} and W_{100} respectively under deficit irrigation treatment and 26.0 – 31.3 for F_{20} and F_{100} respectively under nutrient fertilizer treatment.

Graphical presentation results showed significant correlation of HI with both Biomass (R^2=0.917) and grain yield produced (R^2=0.7378) under deficit irrigation treatments. Production levels in either excess or dry moisture conditions are associated with low maize grain yields. Wet conditions cause excess vegetative development but minimum production of the biomass in dry conditions.

6.5 Application of AquaCrop model in yield gaps prediction under water and fertilizer stress in Uasin Gishu County.

Forecast of maize grain yields of Uasin Gishu County was achieved by applying calibrated AquaCrop model prediction for specific environmental conditions. Categories of the results achieved include; water productivity analysis, predictions of maize yields obtained in the field demonstration plots, Uasin Gishu County climate zones of dry, normal and wet zones, and the effects of soil distribution and fertility stress.

6.5.1 Comparative strategies of deficit irrigation and water productivity analysis

The model considers strategies to maximize utilization of every unit amount of water to optimize maize grain yield production and protect the environment from nutrient transport to large water masses. Results of AquaCrop model simulation given in Table 4.23(a) show that application of reduced water in deficit irrigation has impact on the economic use of water and land resources.

Considering a unit area of land and decreasing deficit irrigation application level from W_{100} to W_{50} is indicated by amount of irrigation water decreasing from 426.0 mm- to 371.6 mm of water. The amount of maize grain yield increased from 8.815 ton/ha to a maximum of 8.965 ton/ha at W_{80} then decreases to a low value of 8.230 ton/ha at W_{50}. Similar trend was noted in the model simulation of water productivity increase from 2.21 kg/m^2-H_2O at W_{100} to 2.36 kg/m^2-H_2O at W_{65} and decrease to 2.31 kg/m^2-H_2O at W_{50}.

AquaCrop model water productivity strategies allow saving of water utilization to be used in expansion of more irrigable area. Results of model simulation considering 1.0 ha of irrigable land recorded water saving of 54.4 mm at W_{50} and increased irrigable area of 0.15 ha (15%) which is twice as much as at W_{90} which saved 25.4 mm and irrigable area of 0.06 ha (6.0%).

6.5.2 Prediction of maize yields under field demonstration plots

Results of the actual farm yields had the highest of 10.99 tons/ha at W_{90} and the lowest at W_{50} 7.08 tons/ha under non-stressed nutrient fertilizer application of F_{100} and a maximum of 10.08 ton/ha at F_{80} and lowest of 6.69 ton/ha at F_{20} when maximum moisture of W_{100} is maintained. Maize grain yield for the controlled demonstration plot at $F_{100}W_{100}$ is constant at 8.81 ton/ha for both moisture and nutrient fertilizer variations. Considering similar range of input application levels, dry maize grain yields dropped by 3.91 ton/ha (yield gap change) from a maximum of 10.99 ton/ha to 7.08 ton/ha for moisture variations from W_{90} to W_{50}, a reduction of 40% moisture application level. Grain yield reduced by 2.51 ton/ha (yield gap change) from a maximum of 10.08 ton/ha to 7.57

ton/ha for nutrient fertilizer variations from F_{80} to F_{40}, a reduction of 40% nutrient fertilizer application level.

This finding suggests that moisture variations cause greater maize yield loss (yield gap) compared to similar range variations by nutrient fertilizer supported by the residual nutrients available in the soil. Moisture is a critical parameter because all plant growth processes depend on it and any variation cause stress that is reflected in the grain yield level especially during flowering and silk formation.

6.5.3 Prediction of maize yield distribution in Uasin Gishu climatic zones

AquaCrop model is used to predict maize yields for Uasin Gishu climatic zones categorized into dry, normal and wet weather conditions using 34 years seasonal rainfall data presented in Table 4.25. Dry weather conditions was forecast based on 80% exceedance of rainfall (< 738.5 mm) and simulated the lowest maize yield predictions of 7.02 tons/ha and yield gap of – 1.79 ton/ha (- 20.32%) from the reference plot farm yield of 8.81 ton/ha. Forecast of wet weather conditions of 20% exceedance (> 1057.9 mm) had the highest yield predictions of 11.17 tons/ha and yield gap variation of 2.36 ton/ha (26.79%) above the reference value. Normal weather conditions between exceedance level of 20% and 80% had an average yield prediction of 9.46 tons/ha and yield gap variations of 0.65 ton/ha (7.38%). Low yields of 7.02 ton/ha were recorded under dry weather condition and imply that distribution of received amount of seasonal rainfall is not sufficient to meet the water requirement for maize production in Uasin Gishu plateau and to attain maximum yields, extra moisture demands are needed for environmental losses.

Comparison results of calibrated nutrient fertilizer application levels and maize grain yields generated similar trends with recorded field data. Recommended optimal nutrient fertilizer application level of 65% predicted grain yields of 6.8 ton/ha, 9.6 ton/ha and 10.8 ton/ha under dry, normal and wet weather conditions. These results under normal weather condition compare closely but higher than the model prediction of 9.46 ton/ha (100% nutrient fertilizer application) for Uasin Gishu plateau weather and the average yields of 9.24 tons/ha achieved under rain-fed plots at Saroiyot demonstration plots site. The record suggest that maize production season of 2015 received rainfall amounts categorized under normal weather conditions.

These findings suggest that soils of Uasin Gishu plateau are receiving excess nutrient fertilizer when application is at 100% causing soil environment get modified by inorganic fertilizer, especially D:A:P causing reduction in the pH level.

6.5.4 Influence of soil distribution on the maize yields prediction

AquaCrop model prediction categorized soils according to their group characteristics and maize grain yield follow a general increase from low to high yields when weather changes from dry to wet conditions. Grain yield attained at the controlled demonstration plot separated soils with lower or higher yields and their yield gaps.

Soils with clay texture recorded zero or lower yields (ton/ha) under the three weather conditions of dry, normal and wet as enclosed in brackets for each level of clay texture: clay (0.0, 0.39, 1.26), silt clay loam (0.0, 5.34, 8.59) and silt clay (0.0, 2.76, 4.49). These soils recorded zero yields during dry season but changes and supported maize crop production as moisture increased to wet conditions. Clay soil with proportion of course textured fraction in clay loam (4.21, 8.89, 10.48), Saroiyot soils (6.03, 10.18, 11.12) and sandy clay (0.0, 6.39, 10.02) recorded lower yields in dry season but increased and recorded higher yields under wet conditions (Figure 4.37).

Similarly soils which attained higher yields than controlled plot value are: sand (10.13, 10.77, 11.11), sandy clay loam (10.05, 11.01, 11.04), sandy loam (10.71, 10.90, 11.04), silt (10.88, 10.74, 10.66), silt loam (10.92, 10.84, 11.02), loam (10.81, 10.85, 11.02) and loamy sand (10.39, 10.87, 11.11).

Maximum yields (ton/ha) predicted by AquaCrop model for the respective weather condition are: 10.92 (silt loam), 11.01 (silt loam), and 11.12 (clay loam) for dry, normal and wet weather conditions respectively. FAO, 2006 recommend maize production under well-drained light loam or alluvial soil with pH of 5.5 – 7.0.

AquaCrop prediction results compare well with FAO recommendation for the silt loam under dry and normal weather conditions.

6.5.5 Effect of soil fertility stress on maize yield prediction

The level of soil fertility stress on maize yields was evaluated using AquaCrop model simulations for the three weather conditions of dry, normal and wet seasons. The results show that soil as a foundation of plant roots and devoid of plant nutrients does not support crop yield production. Plants growth and level of yield production responds to nutrient supply stored or transferred from holding sources in the soil.

Calibration of soil fertility stress module of AquaCrop model was done for maize crop response to stress levels from 5% to 95% using reference crop parameters of non-stressed demonstration plot ($F_{100}W_{100}$) at Saroiyot farm.

Reduction of maize grain yield occurred proportionately according to climatic categorization of the RAINBOW software. Increasing soil fertility from 5% to 95% and comparing with the reference plot yield, maize grain yields increased by 64.4%, 90.2% and 102.6% for dry, normal and wet weather conditions. For managerial guidance, dry weather conditions with seasonal rainfall range of 390.3 mm – 624.2 mm is in the category of dry semi-arid area with rainfall range of 250 mm – 700 mm associated with critical water supply and low fertility (FAO, 2006).

Average maize yield increase during years of dry weather is low to break-even and not profitable to invest in growing maize. Both the normal and wet weather ranges of 556.3 mm – 923.1 mm and 977.3 mm – 1056.6 mm respectively fall within the recommended requirement for maize growing rainfall regime of 600 mm – 1150 mm. Increase in yield is significant in both weather conditions and therefore justify investment in maize production with the cost of increasing soil fertility.

Results of maize grain yield for soil fertility stress simulation are compared with those recorded for field nutrient fertilizer application in the demonstration plots for similar application levels of 80% to 20%. Dry grain yields prediction under field nutrient fertilizer application levels recorded higher values than soil fertility stress levels. The variation differences are lower for higher nutrient fertilizer application and increases with reduction in nutrition. Differences in the yield value ranges are 1.38 ton/ha – 5.03 ton/ha, 1.99 ton/ha – 7.04 ton/ha and 2.26 ton/ha – 7.87 ton/ha for dry, normal and wet weather seasons. Comparison of the variation range with reference plot grain yield gave 41.4%, 57.3% and 63.7% when nutrition decreases from 80% to 20% for the dry, normal and wet seasons respectively.

Prediction amount of grain yield variations is positive when nutrition level decreases towards zero indicate maize crop production is utilizing residual soil nutrients reserves. Production of maize crop grain yields are sustained by residual crop nutrient reserves available depending on the amounts in different sites.

The simulation findings of yield gap results of maize crop production cycle are influenced by soil fertility stress and weather conditions. Dry weather conditions that received seasonal rainfall of 390.3mm – 624.2mm recorded lower yields than the reference value of drip irrigated demonstration plot for all levels of stress values between 5% and 95%. Consequently wider yield gaps were recorded than observed under normal and wet weather conditions. Values of yield gap ranged from 1.79 ton/ha (20.3%) to 7.81 ton/ha (88.6%) at 0% and 95% soil fertility stress respectively.

Soil fertility stress levels above 40% resulted in yield gaps greater than 50% and near complete crop failure occur for stress levels above 75% when yield gaps are above 80%.

Maize crop yields attained positive yield gaps of 0.65 ton/ha (7.38%) to 0.51 ton/ha (5.79%) for soil fertility stress between 0% and 15% under normal weather condition that received seasonal rainfall range of 556.3mm – 923.1mm. The range of negative yield gaps of 0.92 ton/ha (10.44%) to 7.44 ton/ha (84.45%) occurred for stress levels above 15%.

High level of moisture in the soil during wet weather conditions received seasonal rainfall of 977.3mm – 1056.6mm and registered stronger resistance to soil fertility stress up to 25% and positive yield gap of 2.36 ton/ha (26.79%) to 0.15 ton/ha (1.70%). Simulated yields below the reference value recorded negative yield gaps that grew from 1.4 ton/ha (15.89%) to 7.24 ton/ha (82.18%) above 25% stress level.

Results of optimal nutritional level and nutrient fertilizer saving considered 25% and 15% stress levels for wet and normal weather conditions respectively to attain break-even maize grain yield value of 8.81 ton/ha. The condition of production using Nitrogen and Phosphorus nutrition under wet weather saved 21.1 kg N/ha (25%) and 21.6 kg P/ha (25%) and achieved nutrient productivity of 139 kg/ha / kg-N and 136 kg/ha / kg-P instead of non-stressed conditions of 132.3 kg/ha /kg-N and 129.4 kg/ha / kg-P respectively. Production under normal weather achieved a saving of 12.7 kg N/ha (15%) and 13.0 kg P/ha (15%) and nutrient productivity of 122.9 kg/ha / kg-N and 120 kg/ha / kg-P instead of non-stressed condition value of 112.1 kg/ha / kg-N, and 109.6 kg/ha / kg-P respectively. Production at optimal yields saves on soil environment with excess use of nitrogenous fertilizer which increases salinity levels and common in Uasin Gishu soils.

CHAPTER SEVEN

RECOMMENDATIONS

7.1 Introduction

The research design and results have provided insight information in water productivity of maize production and that AquaCrop model is a versatile tool in crop production management and policy delivery. The model capacity to simulate local climate, cropping pattern of various crops and deficit irrigation enables researchers, farmers and policy administrators to access quick solutions to their problems in crop water productivity. Incorporation of soil fertility simulation management allows the model to provide crop productivity results of all agro-ecological zones.

7.2 Recommendations

The following recommendations are derived from the analysis of the research data and outcomes achieved for the set objectives and questions under considerations.

(1) The research has provided useful information on deficit irrigation and nutrient fertilizer application levels for moisture between 50% and 100% of readily available moisture. In order for a complete assessment of deficit crop water requirements, research on moisture levels below 50% are necessary. There is need to investigate ability for the crops to be sturdy and survive under minimal available moisture content and compare with the behavior and capacity of the rooting system to scavenge for moisture far and deeper into the root zone.

(2) AquaCrop model simulates soil fertility stress derived from biomass production and green canopy cover results. There is need to improve the model to balance actual nutrients applied and available residual nutrients in the soil before sowing the crop in order to quantify better the problems caused by plant nutrients in the quality of water resources.

(3) The research findings of optimal amount of nutrient fertilizer application of 65% of the commercial recommendation (Ref CropNuts laboratories) of 190 kg/ha (75 kg/acre) is important to be implemented by the policy administrators and agricultural extension managers. FAO, 2006 recommend combination of mineral fertilizer with organic and biological sources of nutrients because of environmental and economic concerns. Most crops and plant nutrients are available to plants under neutral soil pH and therefore implementation of the research findings will save the soils from further acidity and minimize reduction in crop yields.

(4) AquaCrop model adequately provides reliable information on maize yields, water productivity and yield gaps data of Uasin Gishu County when calibrated and validated for the different agro-ecological zones. The data may be used to derive specific maps for yield gaps and soil fertility in correlation with prevailing climate.

(5) Soil moisture depletion rates and irrigation application amounts result in a zig-zag moisture profile. Sampling and measurement of soil moisture content require at least 3 measurements for every irrigation interval in order for AquaCrop model to

accurately simulate. Use of soil moisture measuring equipments installed on site may reduce moisture variations when soil is transported to a remote laboratory.

7.3 Recommendations for further research areas

The following areas have research gaps which need to be addressed using AquaCrop model simulation.

(1) Most cereal growing zones of Uasin Gishu County have used mechanized land preparation for more than three decades and there is possibility of soil profile compaction that affect maize growth and level of yields obtained. There is need to study the effect of soil compaction on maize yields and yield gap simulations of AquaCrop model.

(2) Use of field data from non-stressed plots assumes the inputs applied into the soil root zone are fully assimilated by the crop roots and utilized for crop production without losses. However some fraction of losses occurs and the model simulates mathematically an environment with zero losses. A research design should be carried out using no losses environment by using technologies such as hydroponics.

(3) Maize crop consumptive use of water increases to peak demand during vegetative development growth stage. A research is required to investigate the effect of maximum canopy cover on reduction of soil water evaporation resulting in unutilized moisture in the soil.

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APPENDICES

APPENDIX I: Project site Soil Analysis report (Saroiyot farm)

Soil Analysis
Basic Soil Analysis

KENYA ACCREDITATION SERVICE KENAS ISO/IEC 17025:2005 ACCREDITED

CROPNUTS Daktari wa Udongo

Customer:	John langat	**Crop:**	Maize	**Date Received:**	16-Apr-15
Address:	+254722684880	**Crop Stage:**		**Analysis Date:**	15-May-15
Farm Name:	Langat farm	**Comments:**		**Report Date:**	16-May-15
Contact Person:	John langat	**Condition:**		**Sample ID:**	AGD301-154SA0001

Field: Saroyot Top Soil

To maintain the correct history ensure that the next sample sent from this Field is labelled: Saroyot

History (Last 3 analysis)

Parameter	Unit	Result	Guide Low	Guide High	Low	Optimum	High	Symbol	Current	Method
pH (H2O)		**5.00**	5.80	7.00				pH	5.00	Potentiometric
Phosphorus	ppm	**7.42**	40.0	100				P	7.42	Spectroscopy
Potassium	ppm	**720**	138	692				K	720	Spectroscopy
Calcium	ppm	**863**	2130	2660				Ca	863	Spectroscopy
Magnesium	ppm	**262**	213	341				Mg	262	Spectroscopy
*Sodium	ppm	**26.1**		< 204				Na	26.1	Spectroscopy
*Organic Matter	%	**4.46**	2.50	8.00				OM	4.46	Colorimetric
*Nitrogen	%	**0.21**	0.20	0.50				N	0.21	Colorimetric
*C.E.C	meq/100g	**17.7**	15.0	30.0				C.E.C	17.7	Calculated
***PERCENTAGES AND RATIOS**										
Calcium %	%	**24.2**	60	75				Ca%	24.2	
Magnesium %	%	**12.2**	10	16					12.2	
Potassium %	%	**10.3**	2	10				K%	10.3	
Sodium % (ESP)	%	**0.63**	0	5					0.63	
Other Bases %	%	**7.40**	3	10					7.40	
Hydrogen %	%	**45.0**	10	15				H%	45.0	
Total	**%**	**100.00**								
Ca:Mg Ratio	%	**1.97**	4	7					1.97	

COMMENTS #
>Very Low pH in this Top Soil>Very Low Phosphorus in this Top Soil>High Potassium in this Top Soil>Very Low Calcium in this Top Soil>Very Low Calcium % in this soil.>High Potassium % in this soil.>Very High Hydrogen % in this soil.>Very Low Ca:Mg Ratio in this soil.

APPENDIX II: Irrigation scheduling and deficit irrigation design

Table II-A: Schedule amount of designed deficit irrigation (α %) applied to respective levels

Date	DAS	ETc (mm/day)	Deficit Irrigation levels and amount applied (mm)				
			W_{100}	W_{90}	W_{80}	W_{65}	W_{50}
14 April 2015	0		11.40	11.40	11.40	11.40	11.40
17 April 2015	3	3.12	9.27	9.27	9.27	9.27	9.27
21 April 2015	7	2.73	11.32	11.32	11.32	11.32	11.32
25 April 2015	11	2.76	11.03	11.03	11.03	11.03	11.03
03 May 2015	19	2.78	22.49	22.49	22.49	22.49	22.49
11 May 2015	27	2.45	20.67	20.67	20.67	20.67	20.67
21 May 2015	37	3.61	32.93				
22 May 2015	38	3.68		33.71			
23 May 2015	39	3.75			33.80		
25 May 2015	41	3.68				33.72	
30 May 2015	46	3.93					33.13
02 June 2015	49	3.97		37.51			
05 June 2015	52	3.83			39.79		
11 June 2015	58	3.80	43.00				
12 June 2015	59	3.80				45.11	
15 June 2015	62	3.90		45.56			
20 June 2015	67	3.87			47.16		45.19
22 June 2015	69	3.81					
23 June 2015	70	3.97	47.33				
29 June 2015	76	4.11		50.25			
30 June 2015	77	3.97				46.49	
05 July 2015	82	4.12	47.93				
06 July 2015	83	4.01			50.90		
13 July 2015	90	3.81		52.35			
15 July 2015	92	3.97					48.07
16 July 2015	93	3.96				52.69	
19 July 2015	96	3.78	51.48				
20 July 2015	97	3.94			53.79		
26 July 2015	103	3.78		50.66			
28 July 2015	105	3.71					51.26
30 July 2015	107	3.72				54.35	

Table II-B: Schedule amount of designed deficit irrigation (α %) applied to respective levels

Date	DAS	ETc (mm/day)	Deficit Irrigation levels and amount applied (mm)				
			W100	**W190**	**W80**	**W65**	**W50**
02 August 2015	110	3.69	54.11				
03 August 2015	111	3.72			53.88		
09 August 2015	117	3.96		52.29			
11 August 2015	119	3.75					52.27
13 August 2015	121	3.86				52.87	
16 August 2015	124	3.97	53.17				
17 August 2015	125	3.67			53.12		
23 August 2015	131	3.97		53.58			
25 August 2015	133	4.22					53.62
27 August 2015	135	3.93				54.21	
30 August 2015	138	4.20	55.19				
31 August 2015	139	4.18			55.70		
05 September 2015	144	4.25		54.03			
07 September 2015	146	4.53					53.29
09 September 2015	148	4.21				55.47	
12 September 2015	151	4.40	55.87				
13 September 2015	152	4.53			54.44		
18 September 2015	157	4.02		52.69			
26 September 2015	165	3.18	Cut-off	Cut-off	Cut-off	Cut-off	Cut-off
27 September 2015	166	3.07					
01 October 2015	170	2.62					
10 October 2015	179	1.71					

APPENDIX III: Root zone soil moisture measurements

Date	DAS (days)	Irrigation application level (%)	Soil moisture content		Available soil moisture	
			θ_m % (mass basis)	θ_v % (volumetric basis)	mm/m	mm
5/6/2015	52	W100	24.5	34.3	343	445.9
		W90	23.8	33.3	333.2	433.2
		W80	23.1	32.3	323.4	420.4
		W65	24.1	33.7	337.4	438.6
		W50	25	35	350	455
17/6/2015	64	W100	23.7	33.2	331.8	431.3
		W90	24.9	34.9	348.6	453.2
		W80	23.7	33.2	331.8	431.3
		W65	23.9	33.5	334.6	435.0
		W50	23.9	33.46	334.6	435.0
2/7/2015	79	W100	25	35	350	455
		W90	27	37.8	378	491.4
		W80	26.8	37.5	375.2	487.8
		W65	28.2	39.5	394.8	513.2
		W50	28.7	40.2	401.8	522.3
14/7/2015	91	W100	23.5	32.9	329	427.7
		W90	22.4	31.4	313.6	407.7
		W80	25.5	35.7	357	464.1
		W65	31.5	44.1	441	573.3
		W50	24.5	34.3	343	445.9
6/8/2015	114	W100	22.7	31.8	317.8	413.1
		W90	25.2	35.3	352.8	458.6
		W80	26.6	37.2	372.4	484.1
		W65	26.2	36.7	366.8	476.8
		W50	21.9	30.7	306.6	398.6
2/9/2015	141	W100	28.9	40.5	404.6	526.0
		W90	29.3	41.0	410.2	533.3
		W80	28.8	40.3	403.2	524.2
		W65	26.9	37.7	376.6	489.6
		W50	28	39.2	392	509.6
29/9/2015	168	W100	24.1	33.7	337.4	438.6
		W90	27.7	38.8	387.8	504.1
		W80	23.9	33.5	334.6	435.0
		W65	27.6	38.6	386.4	502.3
		W50	23	32.2	322	418.6

APPENDIX IV: Laboratory results of residual soil fertility content (Kericho Tea Research Foundation)

Table IV-A: Amount of residual nutrient measurements of the three replica plots

Deficit irrigation water application levels	**Residual nutrient elements in the soil**	**Amount of residual nutrient measurements (ppm) and pH for the respective nutrient fertilizer application levels and replica plots**														
		F=20%			**F=40%**			**F=60%**			**F=80%**			**F=100%**		
		R-1	**R-2**	**R-3**	**R-1**	**R-2**	**R-3**	**R-1**	**R-2**	**R-3**	**R-1**	**R-2**	**R-3**	**R-1**	**R-2**	**R-3**
W=50%	N	278	130	129	213	87	63	58	107	352	435	66	100	193	372	231
	P	13	16	26	18	16	16	18	19	16	18	18	27	21	20	30
	K	872	874	841	1060	872	644	921	934	651	881	898	615	952	1070	633
	Ca	1200	623	651	1130	610	647	1160	621	625	1270	665	582	956	683	527
	Mg	467	290	308	476	296	291	466	312	286	479	349	276	414	378	253
	Mn	162	116	89	165	94	99	170	101	103	202	88	76	172	138	102
	pH	4.93	4.76	4.88	4.79	5.11	5.08	4.85	5.04	4.42	4.58	5.26	5.31	4.57	4.63	4.89
W=65%	N	146	123	90	219	123	138	82	123	155	175	72	137	342	128	294
	P	13	20	29	18	17	19	18	17	17	20	20	19	11	20	24
	K	984	1070	820	905	830	703	790	729	627	940	844	658	924	900	662
	Ca	1090	699	593	961	1180	564	956	1110	597	1080	1360	541	1020	1290	557
	Mg	453	370	288	390	514	276	383	443	271	410	558	261	461	544	262
	Mn	154	133	95	160	120	101	141	142	103	174	129	94	164	161	107
	pH	4.73	4.89	5.04	4.59	5.27	4.86	4.86	5.21	4.95	4.5	5.31	5.21	4.63	5.28	4.64
W=80%	N	228	136	82	201	96	100	150	111	158	165	106	129	137	122	129
	P	19	21	18	23	19	23	16	17	25	14	22	44	13	23	11
	K	954	1070	661	871	1060	789	918	777	753	782	863	735	846	764	571
	Ca	970	725	676	1060	718	577	1280	1140	592	945	1110	582	908	1040	577
	Mg	430	368	299	461	363	268	513	482	276	405	498	286	396	458	270
	Mn	154	100	88	136	86	94	153	129	86	138	145	87	138	180	97
	pH	4.75	5.05	5.29	5.23	5.02	4.93	5.42	5.03	4.83	5.34	5.33	5.19	4.86	5.02	5.25
W=90%	N	336	78	74	125	63	81	156	128	116	48	101	109	57	129	225
	P	17	21	28	17	16	18	13	16	26	15	28	26	14	20	26
	K	993	889	858	930	752	690	915	904	815	810	846	803	774	862	787
	Ca	1170	647	654	1110	610	626	948	1260	585	1180	1290	634	1210	603	694
	Mg	468	308	311	450	287	305	408	530	279	456	542	302	492	305	338
	Mn	160	79	94	149	97	144	144	153	110	159	173	90	161	129	101
	pH	4.84	5.35	5.07	5.28	5.04	5.34	4.88	5.27	4.76	5.42	4.78	5.5	5.1	5.43	4.9

Table IV-B: Amount of residual nutrient measurements of the three replica plots

Deficit irrigation water application levels	Residual nutrient elements in the soil	Amount of residual nutrient measurements (ppm) and pH for the respective nutrient fertilizer application levels and replica plots														
		F=20%			F=40%			F=60%			F=80%			F=100%		
		R-1	R-2	R-3	R-1	R-2	R-3	R-1	R-2	R-3	R-1	R-2	R-3	R-1	R-2	R-3
W=100%	N	134	133	61	106	84	55	225	149	59	252	100	92	116	105	128
	P	11	22	26	19	21	19	20	19	28	23	18	10	16	13	27
	K	853	819	804	989	793	737	1010	970	565	847	870	605	945	691	734
	Ca	1080	1120	545	1300	1100	720	1020	709	499	1070	617	571	1390	1150	592
	Mg	446	473	259	479	482	332	427	370	248	426	290	264	556	448	265
	Mn	116	154	74	164	133	99	155	99	84	160	105	86	210	137	99
	pH	5.16	5.38	5.42	5.28	5.35	5.27	4.68	5.05	5.26	5.03	5.04	5.34	4.47	4.97	4.88

APPENDIX V: Descriptive statistics of residual soil fertility and maize yields

Table V-A: Agents of Variations of maize yields in the Three Replicas

Agent and replica plot		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Residual Nutrient Nitrogen in soil	1	25	183.08	94.470	18.894	144.08	222.08	48	435
	2	25	118.88	57.628	11.526	95.09	142.67	63	372
	3	25	129.56	74.321	14.864	98.88	160.24	55	352
	Total	75	143.84	81.010	9.354	125.20	162.48	48	435
Residual Nutrient Phosphorus in soil	1	25	16.72	3.398	.680	15.32	18.12	11	23
	2	25	19.16	3.009	.602	17.92	20.40	13	28
	3	25	23.12	7.079	1.416	20.20	26.04	10	44
	Total	75	19.67	5.476	.632	18.41	20.93	10	44
Residual Nutrient Potassium in soil	1	25	906.64	74.128	14.826	876.04	937.24	774	1060
	2	25	878.04	105.875	21.175	834.34	921.74	691	1070
	3	25	710.44	87.685	17.537	674.25	746.63	565	858
	Total	75	831.71	124.505	14.377	803.06	860.35	565	1070
Residual Nutrient Calcium in soil	1	25	1098.56	129.298	25.860	1045.19	1151.93	908	1390
	2	25	907.20	276.649	55.330	793.01	1021.39	603	1360
	3	25	600.32	52.967	10.593	578.46	622.18	499	720
	Total	75	868.69	271.732	31.377	806.17	931.21	499	1390
Residual Nutrient Magnesium in soil	1	25	448.48	40.639	8.128	431.71	465.25	383	556
	2	25	410.32	93.383	18.677	371.77	448.87	287	558
	3	25	282.96	23.323	4.665	273.33	292.59	248	338
	Total	75	380.59	92.823	10.718	359.23	401.94	248	558
Residual Nutrient Manganese in soil	1	25	158.44	19.440	3.888	150.42	166.46	116	210
	2	25	124.84	27.810	5.562	113.36	136.32	79	180
	3	25	96.08	13.391	2.678	90.55	101.61	74	144
	Total	75	126.45	33.012	3.812	118.86	134.05	74	210
Soil pH level at Harvest	1	25	4.9108	.29590	.05918	4.7887	5.0329	4.47	5.42
	2	25	5.1252	.21221	.04244	5.0376	5.2128	4.63	5.43
	3	25	5.0604	.26403	.05281	4.9514	5.1694	4.42	5.50
	Total	75	5.0321	.27163	.03136	4.9696	5.0946	4.42	5.50

Table V-B: Correlation between Yield and Residual Nutrients

		Yield of Maize	Residual Nutrient Nitrogen in soil	Residual Nutrient Phosphorus in soil	Residual Nutrient Potassium in soil	Residual Nutrient Calcium in soil	Residual Nutrient Magnesium in soil	Residual Nutrient Manganese in soil	Soil pH level at Harvest
Yield of Maize	Pearson Correlation	1	.116	-.404**	.283*	.398**	.387**	.407**	-.134
	Sig.(2-tailed)		.320	.000	.014	.000	.001	.000	.251
	N	75	75	75	75	75	75	75	75
Residual Nutrient Nitrogen in soil	Pearson Correlation	.116	1	-.065	.240*	.148	.143	.360**	-.624**
	Sig.(2-tailed)	.320		.578	.038	.206	.220	.001	.000
	N	75	75	75	75	75	75	75	75
Residual Nutrient Phosphorus in soil	Pearson Correlation	-.404**	-.065	1	-.132	-.346**	-.321**	-.318**	.085
	Sig.(2-tailed)	.000	.578		.260	.002	.005	.005	.471
	N	75	75	75	75	75	75	75	75
Residual Nutrient Potassium in soil	Pearson Correlation	.283*	.240*	-.132	1	.421**	.505**	.453**	-.262*
	Sig.(2-tailed)	.014	.038	.260		.000	.000	.000	.023
	N	75	75	75	75	75	75	75	75
Residual Nutrient Calcium in soil	Pearson Correlation	.398**	.148	-.346**	.421**	1	.975**	.843**	-.022
	Sig.(2-tailed)	.000	.206	.002	.000		.000	.000	.850
	N	75	75	75	75	75	75	75	75
Residual Nutrient Magnesium in soil	Pearson Correlation	.387**	.143	-.321**	.505**	.975**	1	.813**	.001
	Sig.(2-tailed)	.001	.220	.005	.000	.000		.000	.992
	N	75	75	75	75	75	75	75	75
Residual Nutrient Manganese in soil	Pearson Correlation	.407**	.360**	-.318**	.453**	.843**	.813**	1	-.356**
	Sig.(2-tailed)	.000	.001	.005	.000	.000	.000		.002
	N	75	75	75	75	75	75	75	75
Soil pH level at Harvest	Pearson Correlation	-.134	-.624**	.085	-.262*	-.022	.001	-.356**	1
	Sig.(2-tailed)	.251	.000	.471	.023	.850	.992	.002	
	N	75	75	75	75	75	75	75	75

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

APPENDIX VI: Green Canopy Cover measurements

Table VI-A: Canopy Cover (CC) data measurements of the three replica plots

Deficit irrigation water application levels	Maize growth calendar DAS	Canopy size measurements for the respective nutrient fertilizer application levels and replica plots															Average (F) Canopy size (%)
		F=20%			F=40%			F=60%			F=80%			F=100%			
		R-1	R-2	R-3	R-1	R-2	R-3	R-1	R-2	R-3	R-1	R-2	R-3	R-1	R-2	R-3	
W=50%	60	42	41	40	46	45	41.7	38.2	41.5	39.8	39.5	38	46	46.8	36	37.8	41.29
	78	75.3	59.3	59.1	75.9	71.1	64.8	67.9	62.9	56.4	66.2	25.3	77.9	70.9	51.3	51.8	62.41
	86	56.2	21.4	69.1	81.7	35.9	82.4	53.2	69.1	61.8	73.6	69.2	47.5	87.9	39.4	52.7	60.07
	106	71.9	64.3	79.8	90.6	70.2	77.5	77.3	63.7	84	75.4	75.9	57	85.5	64	71.8	73.93
	117	39.5	72.2	85.6	77.1	68.5	65.8	62.9	62	77.2	68.7	90.8	93.5	75	69.4	59.6	71.19
	152	53.9	48.7	38.8	82.3	60	48	51.5	56.8	49.2	61.3	61.7	59	59.1	54.1	33.5	54.53
	170	32	35	34.6	47.3	49.4	44.3	34.3	60.5	44.1	32.1	63.3	44.2	37.3	53.1	24.1	42.37
W=65%	60	40	50	40.6	45	37	39	48	37.5	45.9	42.5	40	38	41.9	38	50	42.23
	78	69.6	81	63.7	80.7	37.7	55.1	85.9	49.8	75.3	77.5	62	59.1	74	44.4	77.3	66.21
	86	56.7	92.9	56.1	78.2	41.5	70.5	80.7	34.1	76.8	76.8	77.8	44	76.8	94.2	83.9	69.40
	106	77.6	97.8	81.7	94.2	79.2	82.9	94	63.9	86.4	89	89.8	58.3	76.4	96.2	80.5	83.19
	117	63	75	65.3	64.2	83.6	69.3	75.8	70.3	80	70	93	90.5	52.5	88.5	82.1	74.87
	152	68.4	26.8	35.7	85.5	35.9	61.1	68.5	60.5	54	87	73.4	58.5	64.5	65.2	64.7	60.65
	170	63.5	60.3	28.6	54.9	35.2	51.5	61.9	53.8	47.6	53	49.3	46.1	49.3	49.3	59.2	50.90

Table VI-B: Canopy Cover (CC) data measurements of the three replica plots

Deficit irrigation water application levels	**Maize growth calendar DAS**	**Canopy size measurements for the respective nutrient fertilizer application levels and replica plots**															**Average Canopy size (%)**
		F=20%			**F=40%**			**F=60%**			**F=80%**			**F=100%**			
		R-1	**R-2**	**R-3**	**R-1**	**R-2**	**R-3**	**R-1**	**R-2**	**R-3**	**R-1**	**R-2**	**R-3**	**R-1**	**R-2**	**R-3**	
=80%	60	49	53	51	53	45	43.8	50.1	48	36.1	55	50.8	34.4	47	49	39.8	47.00
	78	85.7	92.7	84	91	69.5	65.9	52.9	55.8	42.5	86.8	80.3	39	74.5	64	53	69.17
	86	82.7	37.5	89.1	85.9	62.9	64.6	39.8	58.3	71	82.8	75.8	66.5	74.2	87.9	52.4	68.76
	106	95.3	85.4	74.3	86.7	79.7	75	84	75	94.5	92.6	81.1	69.9	93.2	83.7	70.6	82.73
	117	76.6	67.3	76.1	90.8	89.2	94.6	46.5	82.4	90.3	94	65.3	74.4	74.1	55.2	67.8	76.31
	152	67.7	59	49.8	78.1	50.3	72.7	57.9	62.3	52.7	83.7	67.6	49.6	63.5	28.3	43.9	59.14
	170	43.1	54.3	44.1	52.2	56.8	56.5	37.8	57	42.5	52.8	49.5	40.8	42.9	48.8	39.5	47.91
W=90%	60	41.2	40.3	31	43.5	39	40	47	45	51	45	27	35.2	43.8	35	39.5	40.23
	78	84	60.5	43.2	84.5	59.9	59.1	86.5	73.3	75	74.9	36	49.9	79.8	53.4	55.3	65.02
	86	47	66.3	57.5	73.5	49.2	71.8	78.3	89	84.5	80.1	65.3	63.1	70.9	92.3	45.6	68.96
	106	52.1	71.5	85.5	87	77.1	72.6	91.9	86.6	86.2	91.2	39.5	67.1	77.3	74.4	57.2	74.48
	117	48	75.8	87.3	67.3	71.5	78.1	69	71.4	73.8	74.4	60.5	61.1	71.7	59.4	61.9	68.75
	152	60	57	52.4	75.2	47.9	21.3	77.6	70.7	37.8	53.6	41.4	18	74.2	42.7	34	50.92
	170	47.3	35	43.8	43.7	47.4	21	53	56.8	33.4	44.2	40.8	18	41.7	40.8	21.4	39.22
W=100%	60	48.7	30	40	44.9	41	47	41.8	46.8	30	40.7	40.3	38.6	42.1	40.3	46.3	41.23
	78	88.4	44.4	63.5	82	60.3	77.9	79.5	71.2	41.5	70.5	76	55.2	80.1	76	64.6	68.74
	86	77.5	62	56.2	79.7	39.8	79.3	79.3	37.4	91	76.2	51	73.5	67.7	51	60.3	65.46
	106	82.2	54.3	72.8	85.7	68.2	83.5	92.3	64.6	92.5	87.6	75.6	72.6	87.7	75.6	79.4	78.31
	117	79.9	71.6	55.3	46.6	72.1	72.8	84.7	82.3	80.1	81.2	79.1	47.1	75.5	79.1	84.3	72.78
	152	54.5	56.2	33.6	67.5	47.4	56.6	68	55.5	42.4	79.3	52	51	45.4	52	53.4	54.32
	170	54	48.4	31.1	53.5	45.2	49.3	26.6	51.5	41	37.8	56.9	42.3	58.8	56.9	43.5	46.45

APPENDIX VII: Tests of Normality of maize yield, moisture variations and nutrient levels

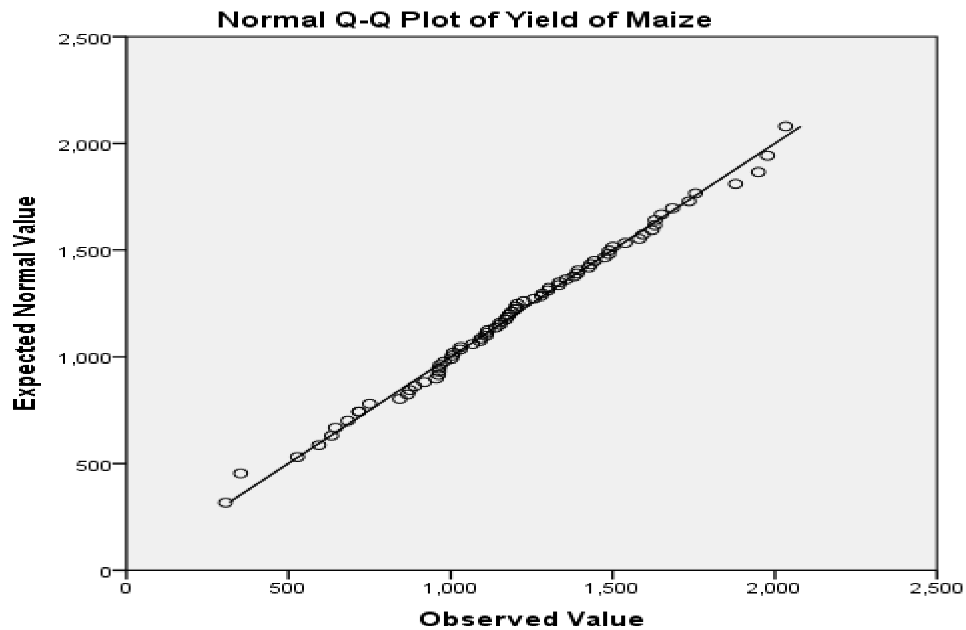

Figure VI-A- Q – Q Plot for Yield of Maize

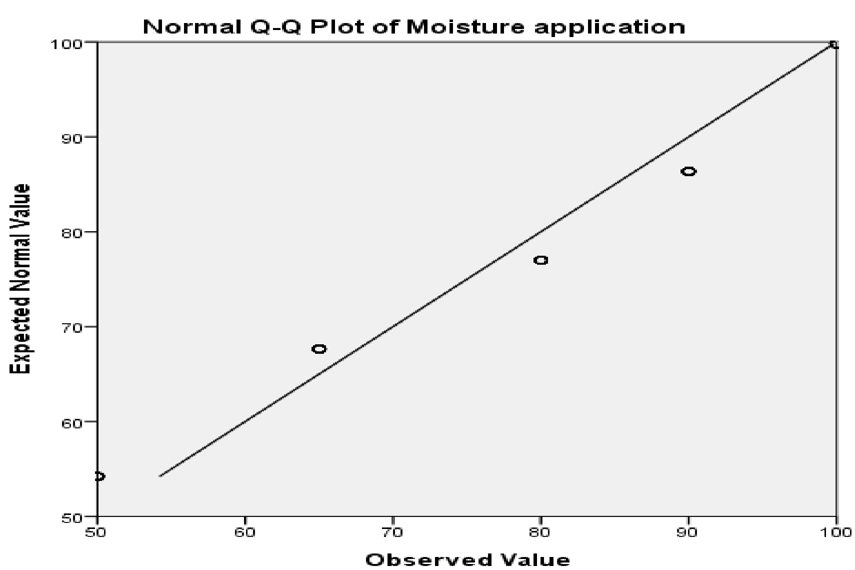

Figure VII-B : Q - Q Plot for moisture application

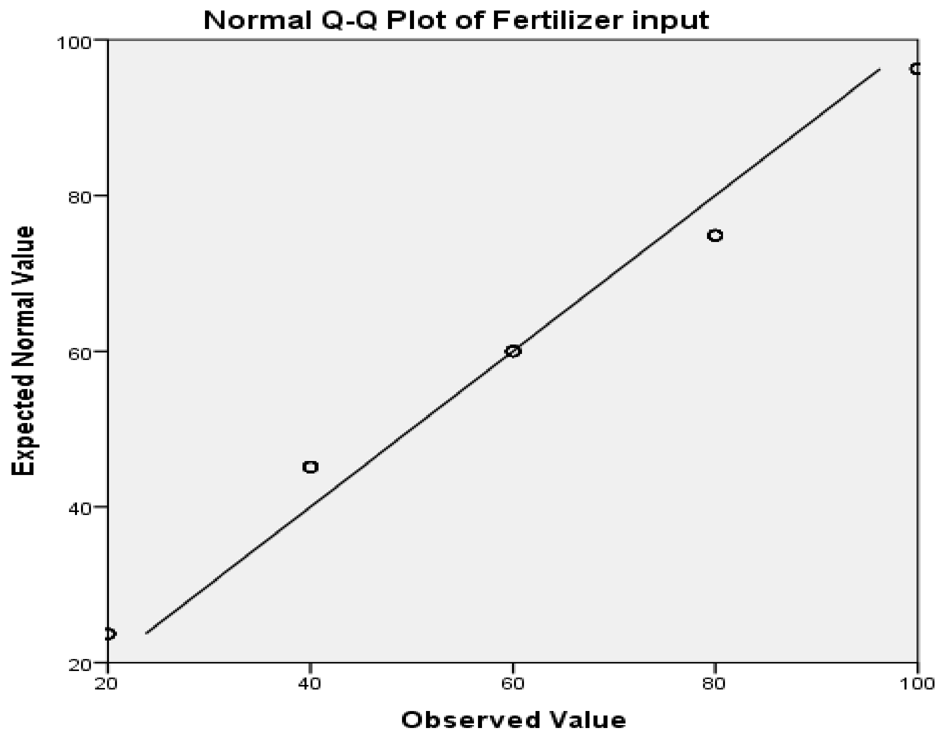

Figure VII-C: Q – Q Plot for fertilizer application

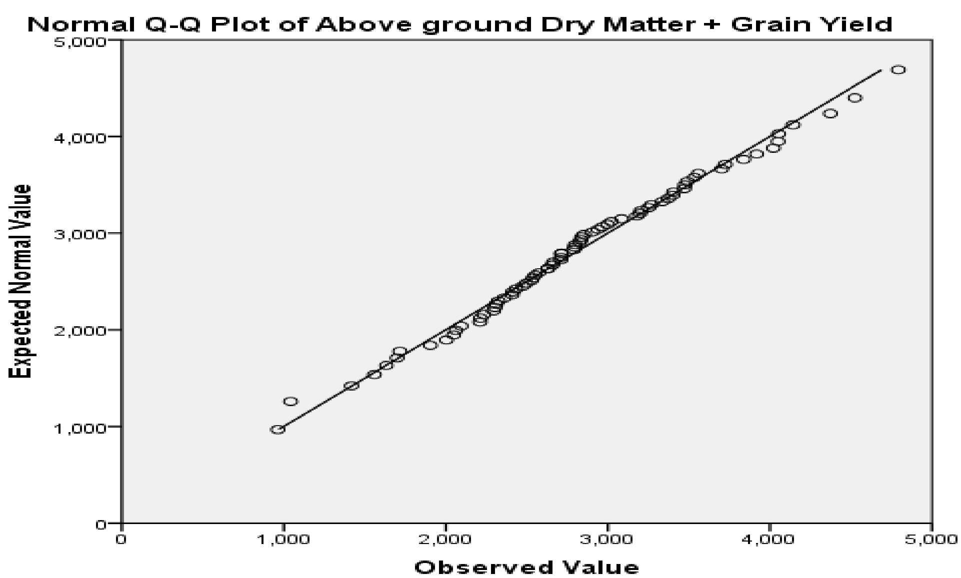

Figure VII-D: Q – Q Plot for Biomass

APPENDIX VIII: Lightweight manually movable ICRISAT rainout shelters

APPENDIX IX: SIMILARITY INDEX/ANTI-PLAGIARISM REPORT

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