EFFECTS OF SOWING DATES ON WHEAT CROP YIELD: APPLICATION OF AQUACROP MODEL UNDER ALTERNATIVE SOIL MOISTURE REGIMES

BY

MARY WANGUI MUTONGA

THESIS SUBMITTED IN PARTIAL FULFILMENT FOR THE AWARD OF DEGREE IN MASTER OF SCIENCE IN AGRICULTURAL & BIOSYSTEMS ENGINEERING IN THE SCHOOL OF ENGINEERING, UNIVERSITY OF ELDORET, ELDORET, KENYA

OCTOCER 2016

DECLARATION

DECLARATION BY STUDENT

This Thesis is my own original work and has not been presented for a degree course in this or any other university. No part of this thesis may be reproduced without the prior written permission of the author and/or University of Eldoret.

Mary Wangui Mutonga Signature……………….…… Date.…………….

PG/ABE/006/14

This thesis has been submitted with our approval as University supervisors.

Prof. Eng. E.C. Kipkorir Signature: ………………..…. Date: ……………

School of Engineering

Moi University

Prof. W. K. Ng’etich Signature: ………………… Date: ………….

School of Agriculture and Biotechnology

University of Eldoret

DEDICATION

I dedicate this study to all those who supported me in one way or the other and encouraged me through the period of this study.

ABSTRACT

Kenya faces numerous challenges against the need to increase food production to feed an increasing population, especially with the setbacks posed by the current enigma of climate change and declining crop productivity. Among the key challenges especially for the farmers who depend on rain-fed agriculture is the inability to accurately predict the optimal sowing onsets. The result is a false start or delayed sowing which shorten the growing period leading to decline in production and crop loss. While zero tillage can better mitigate the problem as compared to conventional tillage there is scanty literature in Kenya on the practice. Therefore, this study was carried out to determine effects of sowing dates and tillage practices (conventional tillage (CT) and zero tillage (ZT)) on soil water content and wheat crop yield. The evaluation was based on field experiment set up at Lengetia farm in Laikipia East sub-County and simulation with calibrated AquaCrop model. The objectives were: to evaluate soil moisture variation between the tillage treatments; to evaluate the impact of onset dates, conventional and zero tillage practices on wheat crop yield; to calibrate and validate AquaCrop model and determine the optimal sowing date(s) for rain-fed wheat in Laikipia County based on optimization analysis of simulated grain yields. Rain-fed trials and a water regime trial (control treatment) were planted on a split plot with the two tillage treatments (ZT) and (CT) as the main plots factors, and four sowing dates (SD1, SD2, SD3, WTSD2) as the sub-plots factors randomized and replicated in three blocks. The data collected was subjected to statistical analysis (ANOVA and T-tests). An approach based on AquaCrop sowing dates simulation with 19 years historic climate data and optimization analysis of simulated yield in Microsoft Excel Solver tool allowed determination of optimal sowing dates based on probability of exceeding the estimated target yields. The key findings were; there was significant moisture variation at $p<0.05$ between the tillage treatments. Under the early onset (SD1), normal (SD2) and late (SD3) the yields were significantly different producing higher yields in zero tillage by 48.9%, 20.6% and 34.1% respectively compared to conventional tillage. AquaCrop model was satisfactorily calibrated and validated in conventional tillage using different data sets. The model performance in simulating canopy cover (CC), biomass (B) and soil water content (SWC) was evaluated using statistical indices, RMSE, d, R^2 and EF. The value of R^2 of 0.95, 0.80, and 0.51 respectively for CC, B and SWC was obtained for calibration in conventional tillage and R^2 of (0.88, 0.87, 0.50) respectively for CC, B and SWC in validation. However, calibration under zero tillage was not satisfactory especially in simulating observed soil water content (R^2=0.13). This limited the application of the model to conventional tillage only in sowing date optimization analysis. First and second week of October was found to be the optimal sowing period for wheat in conventional tillage while in zero tillage all the dates within the sowing window were optimal as confirmed from field observation. Therefore, zero tillage is recommended for use by farmers as a strategy to improve soil moisture conservation and thus maximize wheat grain yield.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

ASAL	Arid and Semi-Arid Land
B	Biomass
CC	Green Canopy Cover
CC_{pot}	Potential Canopy Cover
CIMMYT	International Maize and Wheat Improvement Center
CT	Conventional Tillage
DAS	Days after Sowing
ETo	Reference Evapotranspiration
FAO	Food and Agriculture Organization
FC	Field capacity
Ha	Hectare
HGCA	Home Grown Cereal Authority
HI	Harvest Index
KARI	Kenya Agricultural Research Institute
KARLO	Kenya Agricultural Research and Livestock Organization
KC_{Tr}	Crop Transpiration Coefficient
Kg	Kilogram
KIPPRA	Kenya Institute for Public Policy Research and Analysis
K_{sat}	Saturated Hydraulic Conductivity
Ks_{sto}	Stomata Closure Stress Coefficient
LAI	Leaf Area Index
MAFAP	monitoring African food and agriculture policies
PWP	Permanent wilting point
R^2	Coefficient of Determination

RMSE	Root Mean Square Error
SAT	Saturation
SD	Sowing Date
SWC	Soil Water Content
TR	Transpiration
TT	Tillage Treatment
USDA	United States Department of Agriculture
WP*	Normalized Water Productivity
WRMA	Water Resource Management Authority
WTSD	Water Treatment Sowing Date
Y	Yield (ton/ha)
Z	Rooting Depth
Z_n	Minimum Effective Rooting Depth
Z_x	Maximum Effective Rooting depth
ZT	Zero Tillage

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

ACKNOWLEDGEMENT

I would like to recognize and most sincerely thank my supervisors, Prof. Eng. E. C. Kipkorir and Prof. Wilson K. Ng’etich for their tireless and constant guidance, encouragement and support and always creating time despite their busy schedules throughout the entire study. I would also wish to highly recognize and appreciate the ministry of transport and public works Nyeri and University of Eldoret soil science Laboratory for the assistance received during data collection and analysis. My deepest gratitude also goes to the University of Eldoret, School of Engineering, lecturers and administration for according me support and guidance.

I am also greatly indebted to Mr. L. Sessions (Proprietor, Lengetia Farm Ltd) and the entire management and staff of Lengetia farm Ltd for giving me the opportunity to access and set up my field experiments in their Farm and continued support during the entire period of the study. Finally, I am grateful to Eng. W.W. Nyagah, P. Njue, P. Karanja, parents, brothers and sisters, for their constant encouragement and moral support. The help and support in different phases of the study by my friends are acknowledged.

God bless you all.

CHAPTER ONE

INTRODUCTION

1.1 Background Information

Over the past years the number of undernourished people has increased to over one billion people while over two billion suffer from micronutrient deficiencies worldwide (FAO, 2009; FAO, 2012). This is believed to result from population increase, climate change and decline in agricultural crop productivity among other factors. Climate change is a major threat to food and agriculture systems (FAO, 2015).

The situation in Kenya is no difference with an ever rising population. In 2009, the total population was 38 million people (KNBS, 2010) and this was expected to reach 45.56 million by 2015 with a growth rate of 2.11% per annum (KNBS, 2015). As evidenced by the frequent droughts and relief food programs in Kenya, hunger is still prevalent. The population increase points out increased demand for food despite the decline in crop productivity. This decline, and especially on the major food commodities is brought about by failure to use appropriate technology adequately leading to soil erosion and degradation, and erratic climate; high temperatures, variable rainfall onsets and extreme weather conditions (frequent floods and droughts). Nyangito *et al.,* (2002) indicate that low productivity, high capital costs, and inappropriate production technologies characterize wheat production in Kenya.

The growing population calls for an increase in crop production which will either come from increasing production per unit area on medium to high potential land, or, extension into areas not currently used for cultivation. However, only 17% of Kenya's land is productive (Onyari *et al.*, 2010) with over 80% land in Kenya in ASAL area, one of the regions which Vision 2030 singles out for special attention (Republic of Kenya, 2011). Additionally, most of the land in the fragile ASAL is under rain-fed farming system which is characterized by temporal and spatial variability of rainfall and therefore limited productivity. Zinyengere *et al.,* (2011) concurs that climate variability and unpredictability is expected to increase and exert more pressure on food production especially on rain-fed farming system. In Kenyan semi-arid areas, the rainfall is usually low and unreliable (Wamari *et al*., 2012).

In Kenya, wheat is the second most important cereal (Monroy *et al.*, 2013) in terms of quantity and calories consumed which is directly or indirectly affected by the limited productivity. And as Nyangito *et al.,* (2002) notes, domestic wheat production in Kenya has been erratic and declining. On the contrary, wheat products consumption in the urban is on the rise at 34 percent more than maize and more than twice as much on rice (Muyanga *et al*., 2003) with a growing annual consumption of 4% in contrast to -0.7% decline in production in Kenya (Muyanga *et al.*, 2003). With declining production Kenya meets most of its wheat demand through imports (Nyangito *et al.*, 2002) averaging about five times of its wheat production (Monroy *et al.*, 2013) as illustrated in Figure 1.1 (FAOSTAT, 2013).

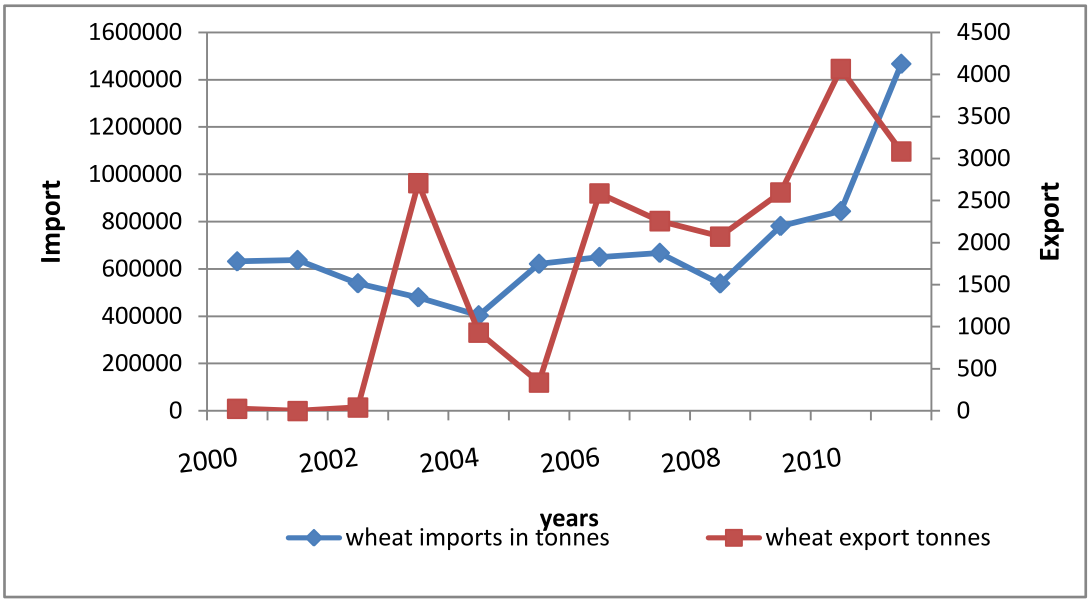

Figure 1.1: Relationship between wheat grain import and export in Kenya (2000-2011) (Source: FAOSTAT, 2013).

The reported challenges in wheat farming as noted earlier have been due to low technology adoption; soil degradation, inadequate capital, poor market structure, high production cost and climate hazard (Nyangito *et al.,* 2002). With the rain-fed systems, most farmers depend on rainfall onsets to do their sowing. This is difficult with the current change in climate and rainfall variability in space and time (hence unpredictable onsets). The timing and relative lengths of each growing period vary substantially with location (Mujdeci *et al*., 2010) and this leads to reductions in yields by up to 75% when they occur (Barron *et al*., 2003). This is as a result of delayed sowing and false starts of the sowing period which shorten the growing cycle seriously affecting yield. Further, most rain-fed farmers depend on hired agricultural machinery which also contributes to delay in land preparation, sowing and harvesting with associated high cost of land preparation and in turn high production cost. It was therefore apparent that sowing date, which is a technology problem, has received little attention.

Laikipia County is among the main wheat growing regions and falls under ASAL area of Kenya whose seasonal rainfall according to Huho *et al.*, (2012) has been marked by delayed onsets, declining number of rain days and increased intensities altering farming calendars with negative effects on the yields. To increase and sustain production in this area, improvement in farm management practices and soil and water conservation farming systems and timely sowing from weather prediction need to be encouraged.

In the past several methods for calculating and predicting the date of onset of the rains that is taken as the start of the growing season have been used with some level of accuracy (Ati *et al.*, 2002). For example the observation of some plants phenology e.g. flowering of the Acacia trees mark the end of dry period. The ability to estimate accurately the actual start of the growing season is crucial and the use of models has been emphasized as better and more accurate tools than traditional methods. AquaCrop model (Raes *et al.*, 2009; Steduto *et al.*, 2009) compared to the traditional weather indicators can be used to predict dependable levels of onset dates of the rainy season and the length of the growing season.

1.2 Problem Statement

In Kenya most farmers depend on rainfall onset to do their planting (wet sowing). However due to climate change and associated rainfall variability, it is very difficult for them to predict rainfall onset, intensity and reliability. This results in delayed sowing or false starts which shorten the growing season and seriously affects production leading to crop loss. According to Chandna *et al.*, (2004) and Sen *et al.,* (2014), delayed sowing accounts for a loss of approximately one tonne per hectare

(1ton/ha). This loss is critical bearing in mind the problem of declining productivity in Kenya and the increased demand for food.

Overdependence on contracted agricultural machinery by most farmers among other factors results in delayed sowing (Monroy *et al*., 2013), which delays land preparation, sowing, maturity and the subsequent harvesting of the crop. However, even when the machines are available, constraints such as land sizes, machine breakdowns among other factors exists which often hinder farmers from sowing their entire crop at the first onset of sowing period (Mhizha, 2010).

Conservation of soil water in semi-arid areas requires appropriate tillage practices which conserve adequate soil moisture for plant growth reducing the effect of moisture deficit on yield and or shortening the length of growing season (Karuma *et al.,* 2014). Therefore, there is need to determine suitable dates and alternative tillage practices to mitigate these risks associated with climate variability and various soil water regimes associated with tillage practices.

Climate prediction and modeling of onset date(s) has a high potential for improved production and management strategies, enabling producers to better adapt management decisions to the season (Hansen, 2002), therefore moderating sowing delays and stabilizing yields. With this understanding, this study intended to predict suitable starts of growing season using AquaCrop model in zero tillage and conventional tillage practices in Laikipia County.

1.3 Justification

This study focused on wheat production which is the second most important cereal grain in Kenya after maize. This means that wheat production is an important consideration to meet increased demand for food in Kenya (Monroy *et al.*, 2013) despite the problem of declining yields (Mahagayu, 2007), especially in ASAL areas. As a result Kenya is a net importer of wheat as seen from Figure 1.1 (FAOSTAT, 2013).

Laikipia is characterized by the ASAL climatic conditions despite being a major potential grain producer. Although the area receives mean annual rainfall of 650 mm per year, it can be very unreliable. Similarly the onset of the rains is highly variable and can be delayed by up to two months in some seasons (Ojwang' *et al.*, 2010). This, coupled with over-reliance on rain-fed agriculture (MAFAP, 2013), contributes to declining wheat production in the area. Evaluation of optimal sowing date(s) for dry and wet sowing of rain-fed wheat crop under varying tillage practices is therefore necessary to moderate delay in sowing and false starts.

Conservation tillage practices are being adopted in Laikipia and are known to conserve soil moisture for improved yield (Kaumbutho & Kienzle, 2007). Additionally, the timing of the sowing time is essentially determined by the soil moisture in the root zone which is being influenced by tillage practices. Onyari *et al.,* (2010), indicates the need for further research on interaction of tillage practices and sowing time and their effects on crop growth for improved yield production. No available study had been carried out to determine the optimal sowing date(s) for wheat under varying tillage practices in Laikipia. Therefore this study contribute to the much needed literature and if adopted would result to improved food production in ASAL areas where it is most needed.

AquaCrop a water productivity model was used for scenario analysis as it computes crop yield as a function of water availability to crop through a water balance in the root-zone while accounting for yield reduction as a result of water stress. It also balances output accuracy with simplicity and robustness and requires fewer parameters compared to other crop growth models.

1.4 Objective of the Study

1.4.1 Main Objective

The main objective of the study was to determine the optimal sowing dates for maximum yield of wheat crop under zero and conventional tillage.

1.4.2 Specific Objectives

The specific objectives of the study were;

i. To determine the moisture variations in zero and conventionally tilled fields.
ii. To determine and compare the impact of planting dates, conventional and zero tillage practices on wheat crop yield.
iii. To calibrate and validate AquaCrop model for simulating wheat crop yield under conventional and zero tillage practices.
iv. To determine the optimal sowing date(s) for rain-fed wheat in Laikipia County based on optimization analysis (using Microsoft Excel Solver Tool) of AquaCrop simulated grain yields.

1.5 Hypothesis

H_0-There is no significant difference between wheat crop yields from early onsets on zero tilled fields and conventionally tilled fields.

H_A-There is significant difference between wheat crop yields from early onsets on zero tilled fields and conventionally tilled fields.

1.6 Scope of the Study

The study focused on the measurement and analysis of soil moisture and wheat crop yield as affected by sowing dates and tillage practices through modeling of wheat crop yield under the field trials using AquaCrop model. The study area was Laikipia east sub-county characterized under ASAL region where awareness and practice of zero tillage is currently gaining interest due to low production under conventional practices and the increased climate variability.

The field for experiment was selected to be in Lengetia farm and not in different locations within the County with varying tillage practices due to the need for control of variables and soil heterogeneity. Additionally the study was carried out for one year due to the constraint of resources available and time available for the study.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Agricultural production takes place in an environment characterized by risks and uncertainty especially in arid and semi-arid zones where water supply to crops from rainfall is variable and unreliable (Fereres *et al.,* 2007). This rainfall variability has led to development and application of various practices for conserving soil water and increasing water productivity of the little available water. Example of such adaptation practices include conservation tillage, deficit irrigation and staggering of sowing dates within the growing season, use of high yielding and drought resistant crops among others.

In recent years, interest in conservation tillage systems has increased in response to the need to limit erosion and reduce soil degradation while promoting soil and water conservation (Karuma *et al.,* 2014; Schwartz, 2006). Soil and water conservation through tillage is one of the appropriate ways of addressing soil moisture deficit in rain-fed agriculture, however, the effectiveness of conservation agriculture requires to be evaluated further (Rockstrom *et al.,* 2009).

2.2 Stored Soil Water and Zero Tillage

Derpsch *et al.,* (2010) argues that intensive soil manipulation in conventional tillage leads to farm degradation while Wander and Yang (2000) concur that reduced soil manipulation through reduced tillage is required to solve farmland degradation and improve on yield production. All these are attributed to conservation of soil moisture and enhanced infiltration rates. Intensive tillage leads to soil pulverization which causes erosion of fine clays sealing the pores and thus affecting soil structure and its hydraulic properties.

Various studies have reported increased soil moisture content under zero tillage compared to conventional tillage (Cameron, 2003; Chaghazardi *et al.,* 2016). This variation is characteristic of reduced evaporation, improved soil structure with greater infiltration rates, and efficient storage of soil water due to presence of crop residue. Similarly, studies on different tillage practices with equal volume of residue on the soil surface indicate improved crop emergency and early growth in zero tillage (Schwartz, 2006). These points out that other beneficial factor in addition to residue cover are contributing towards improved soil water status (Schwartz, 2006).

According to a study on the effects of near surface soil water dynamics on four parallel strips with alternating tillage treatments, mean soil water contents of zero tilled plots were greater than tilled plots except during and immediately after precipitation events (Schwartz, 2006). Despite high initial rainfall infiltration under conventional tillage, higher water contents persisted throughout the season in untilled plots. Increased soil water status near the surface under zero tillage promote rapid crop establishment and root propagation early in the growing season and lead to increased water use efficiency (Moroke *et al*., 2005).

Sen *et al.,* (2014) indicated improvement in soil retention and increase in crop yield under zero tillage and respective early crop establishment. Opara-Nadi and Lal (1986) observed that total porosity, moisture retention, saturated and unsaturated hydraulic conductivity, and the maximum water-storage capacity increased under zero tillage with mulches. These were as a result of the change in soil hydraulic properties accompanied by enhanced vapor flow near the surface and greater absorption of radiation by a tilled surface with reduced albedo. In Pakistan, zero tillage is preferred because of reduced cost of water and land preparation by up to 30% while preventing late sowing of wheat, increasing water use efficiency, controlling erosion and increasing crop production (Imran *et al.,* 2013).

2.3 Wheat Crop

Wheat (*Triticum aestivum L.*) is an important cereal grain crop due to its contribution of a major portion of staple food for the world's population (Imran *et al.,* 2013). In Kenya, however, despite being the second most important cereal, its production has been declining (Monroy *et al*., 2013). The gap in production has been met through reduction in export and increase in import which dampen the domestic prices (Nyangito *et al.,* 2002*).* This poses serious challenges as it is a disincentive to domestic wheat farmers and can make them look for alternative crops thus abandoning wheat farming. The competition for export can lead to closure of the wheat products manufacturing industry in Kenya.

Wheat is usually sown at a depth of around 3-5 cm, although greater depths may be used under dry conditions to avoid seed damage by light showers or the need for moisture seeking therefore placing the seed in moist soil. However, it has the disadvantage of delaying emergence and growth and in extreme situations may reduce stand density. Mostly sowing is usually into moist soil (wet sowing) but in some dry environments 'dry sowing' is practiced shortly before the expected start of the rainy season. Plant densities range from 50 to over 500 plant/m^2 (Steduto *et al.,* 2012) and row spacing of 0.15 to 0.25 m depending on the production system. Sowing is by broadcasting in some cases especially for small holder farmers and by seed drill for mechanized medium and large-scale farms where tractor drawn drill is used for sowing.

Soil water stress is considered the most limiting factor in wheat crop growth and water stress affect the crop differently at different stages of its development (Steduto *et al.,* 2012). This forms a basis for measuring sensitivity to water stress at various stages of crop cycle (Mhizha, 2010). For wheat, the tillering to stem elongation, flowering period and early to mid-grain filling are the most sensitive growth stages to water stress, while water stress during ripening and vegetative phases has little impact provided the crop is able to recover from this stress in the subsequent stages (Steduto *et al.,* 2012).

Wheat development depends on weather conditions and planting date while management decisions in wheat production are growth stage dependent (HGCA, 2016). Therefore, by adjusting the sowing dates, drought stress can be avoided at the most sensitive growth stages and thus reducing water stress effect on yields. Other than water stress, temperature stress, salinity, water logging (aeration problem) and fertility stress are among other stress factors affecting the quantity and quality of wheat produced (Steduto *et al.,* 2012). The magnitude of their impacts and response varies with the wheat varieties.

Among the new developed drought and rust resistant wheat varieties by research institutions and plant breeders in Kenya is *Korongo*. This is a characteristic semi-dwarf late maturing variety (120-130 days) suitable for production in low rainfall areas. Therefore accurate timing of the sowing time is required to avoid shortening the length of growing period to optimize on water use. Other varieties with their characteristics and target yield are available at.

(http://www.wheatatlas.org/country/varieties/ken/0)

2.4 Crop Simulation Models

Crop simulation modeling involves the use of developed computer software to predict growth, development and yield of agricultural crops. Further, Water reports (FAO, 2002) indicated that models are powerful tools for extending findings and conclusions to conditions not tested in the field and are especially useful for predictions under various conditions of water supply, soil, and of crop management.

There are lots of models that simulate the growth and development of maize, wheat and other cereal crops most of which have been used by various researchers. Some of the frequently used agricultural models include CropWat, AquaCrop, CropSyst, WOFOST (van Ittersum *et al.,* 2003), CERES and DSSAT among others. Each of these models is able to simulate growth for a range of crops. However they vary in their presentation of physical processes and the type and number of input data parameters requirement. For example, WOFOST is strong in analyzing the impact of fertilizer use, CERES, CropSyst (Stockle *et al.,* 2003), DSSAT (Jones *et al.*, 2003), have the ability to simulate different crop varieties while CROPWAT is best considered in simulating farmer's practices etc.

Among them, the three models that are specifically strong on the relationship between water availability, crop growth and climate change are CROPWAT, AquaCrop and WOFOST. They have a user-friendly interface, but comparatively Aquacrop uses a relatively small number of parameters and tries to balance simplicity, accuracy and robustness (Steduto *et al*., 2009) and can therefore be used to develop scenarios.

Based on these qualities, AquaCrop model developed by the Land and Water Division of FAO (Raes *et al*., 2009; Steduto *et al*., 2009) was used in this study.

The AquaCrop model has been tested and is able to accurately simulate various crops responses under varying field management practices and climatic condition. It is recommended for use especially under conditions of limited input information and yield predictions under variable water supply situations and management practices. Other advantages of AquaCrop include; it's wide applicability with acceptable accuracy, requiring only commonly available input parameters (*i.e.* climate, soil, crop and field data) and allows easy verification of simulation results with simple field observations.

2.5 Applications of AquaCrop Model

The type of application depend on the objective, type of user, the sequential scale of analysis and the time steps, that is, daily, monthly or annually. In this respect, AquaCrop model has a variety of applications which include: the study of the effect of climate change on food production, assessment of water use efficiency/ evapotranspiration water productivity (WP_{ET}) (Geerts *et al*., 2009; Andarzian *et al.*, 2011), to understand crop response to environmental changes, carrying out yield gap analysis and can be used as a tool for decision making (Fereres *et al*., 2007; Raes *et al.*, 2012). These applications can spread from field to farm scale and beyond e.g. application to benchmark yield gaps in rain-fed and irrigated agriculture and the assessment of long-term productivity. Among AquaCrop model's applications the generation of sowing dates using the rainfall depth criterion (Raes *et al.,* 2004) and simulation of soil water content at the root zone was used for determination of optimal sowing date. Water productivity was used as a measure of water use efficiency in yield production.

2.6 Water Productivity and Irrigation Scheduling

Water productivity is the ratio of the mass of marketable yield to the volume of water consumed by the crop (Geerts & Raes, 2009; Andarzian *et al*., 2011). An increase in water productivity means an increase in crop yields per unit of water consumed. As a result, more water is available for other uses (Pereira *et al*., 2002). In order to achieve this, the crop yield response to water must be known and irrigation scheduling (Allen *et al.*, 1998; Steduto *et al.*, 2012) done to meet this need. That is, an understanding of the crop water requirements and how much water stress the crops can endure (allowable depletion) (Geerts & Raes, 2009) and still obtain reasonable yields (Steduto *et al.*, 2009; Steduto *et al.*, 2012).

2.7 Timing of Sowing Onset Date(s) and its Effects on Yield

Soil water condition at sowing is an important consideration for wheat production particularly in low rainfall regions (Heng *et al*., 2007 and Asseng *et al*., 2008). However other factors such as air temperature also influence timing of sowing date and their impact on yield. Optimal sowing time corresponds to adequate soil water content at the root zone to support crop growth. This is what is observed and or simulated to determine and generate the sowing dates with low risk of failure. Rahman *et al*., (2002) reported a significant yield reduction of 20.8% and 40.1% with successive delay in sowing at every 20 days interval. Similarly, Onyari *et al.*, (2010) indicated that the timing of sowing date has a significant impact on yield and reported a significant reduction in chickpea biomass yield from a delayed sowing date by two weeks from the onset of rain in the semi-arid area of Kenya irrespective of the varied tillage practices.

Various approaches have been used in the past to predict sowing onsets comprising both traditional methods and science-based prediction methods. They include Ramadan method (Ati *et al.,* 2002); the use of plant phenology e.g. Acacia trees (Sekhwela & Yates, 2007); use of accumulated rainfall totals (Walter's & Sivakumar's method) (Ati *et al.*, 2002; Sivakumar, 1988), use of rainfall evaporation method and historical analogues approach (Hansen & Indeje, 2013). Their use was not without challenges with the traditional methods reported to perform poorly. Walter's method predicts quite early onset while Sivakumar's predicts late onsets (Ati *et al.*, 2002). Similarly the use of plant phenology is threatened by the deforestation and depletion of this indigenous species like the acacia and thus limited use.

Various models e.g. AquaCrop model (Asseng *et al.*, 2008) has been developed for modeling sowing dates by either appraising the rain or air temperature data file in the model. Temperature is considered especially when studying the effect of climate changes and resultant increase in air temperature to predict sowing date for future years (Raes *et al.*, 2012). Similarly, rainfall data consideration is best suited for rain-fed cropping where sowing onset is determined by rainfall event(s).

Modeling of onset dates through simulation of root zone moisture content can be used to reduce uncertainty and thus managing risks e.g. of crop failure from a false start of the sowing period or delayed sowing which significantly shorten the growing period. If properly modeled, initial soil water (left over from the previous season) can influence early establishment of the crop and contribute to water use and yield later in the season, particularly in low rainfall seasons (Kipkorir *et al*, 2007). However, different yield results are obtained when different sowing dates are used (Chandna *et al*., 2004; Asseng *et al*., 2008, and Sen *et al.,* 2014). This indicates that some sowing onsets are more favorable than others and therefore the need to select the optimal (Mhizha, 2010).

2.8 Determination of the Optimal Sowing Date(s)

Early sowing has been emphasized by many authors; (Chandna *et al.*, 2004; Onyari *et al.,* 2010; Sen *et al.,* 2014) with reported decline in yield of up to one ton/ha when sowing is delayed after the first sowing opportunity within an optimum sowing window. However, although the early onset is reported to give the best mean yield, practical implementation is not possible. There are a number of constraints faced by farmers such as machine breakdown, labor availability and draught power which hinder them from sowing their entire fields at the first occurrence of the onset date. Mhizha, (2010) recommended staggering of the sowing date to accommodate the above challenge and other uncertainties (Raes *et al.*, 2004) which are difficult to predict or control. Therefore optimization analysis of simulated yields is carried out to determine the sowing dates which give optimum yields.

Probability analysis has been used with AquaCrop simulated yields by ranking yield results and issuing probability for each and those with the best yields selected as the optimum dates (Fereres *et al.,* 2009). However, this method does not take into account constraining factors such as the maximum acreage which can be sown in a day given the available resources.

Microsoft Excel Solver® tool has been used for optimization analysis of simulated yields. Optimization analysis is applied to obtain the algorithm that allocates the best acreage proportion to the generated sowing dates for maximum total yield taking care of the constraints over the simulation period. The objective is usually to maximize mean grain yield or minimize standard deviation of simulated yields (Mhizha, 2010). Then the best sowing strategies are selected as the optimum sowing dates.

CHAPTER THREE

MATERIALS AND METHOD

3.1 Introduction

For the purpose of this research, zero tillage was defined based on the number of soil manipulation operations. This concur with Tripathi *et al*., (2013) as the process of planting wheat seed after the previous crop, directly drilling on untilled soil which retains previous crop residue (Plate D.2 appended for reference), while conventional tillage is defined as the intensive tillage with multiple passes of a tractor (Plate D.1 appended) to accomplish land preparation for wheat sowing (Tripathi *et al*., 2013).

3.2 Experimental Site

The experiment was carried out at Lengetia a wheat farm planting approximately 4500 acres of wheat in Laikipia County every year. This specific farm was identified and selected because of its successful and consistent wheat farming and the practice of zero tillage for over ten years in this ASAL area. The County lies between latitudes 0°17'S and 0°45'N and longitudes 36°15'E and 37°20'E, with area that approximates 9,666 km^2 divided into three sub-counties: Laikipia East, Laikipia West and Laikipia North as illustrated in Figure 3.1.

Laikipia County is among the few remaining counties with vast lands which are ideal for conservation farming by way of their location in the ASAL and suitable soils which can hold and retain soil moisture if properly conserved. It experiences largely a bimodal rainfall pattern with the long rain season between March and May and the short rain season between October and November as presented in Figure 3.2.

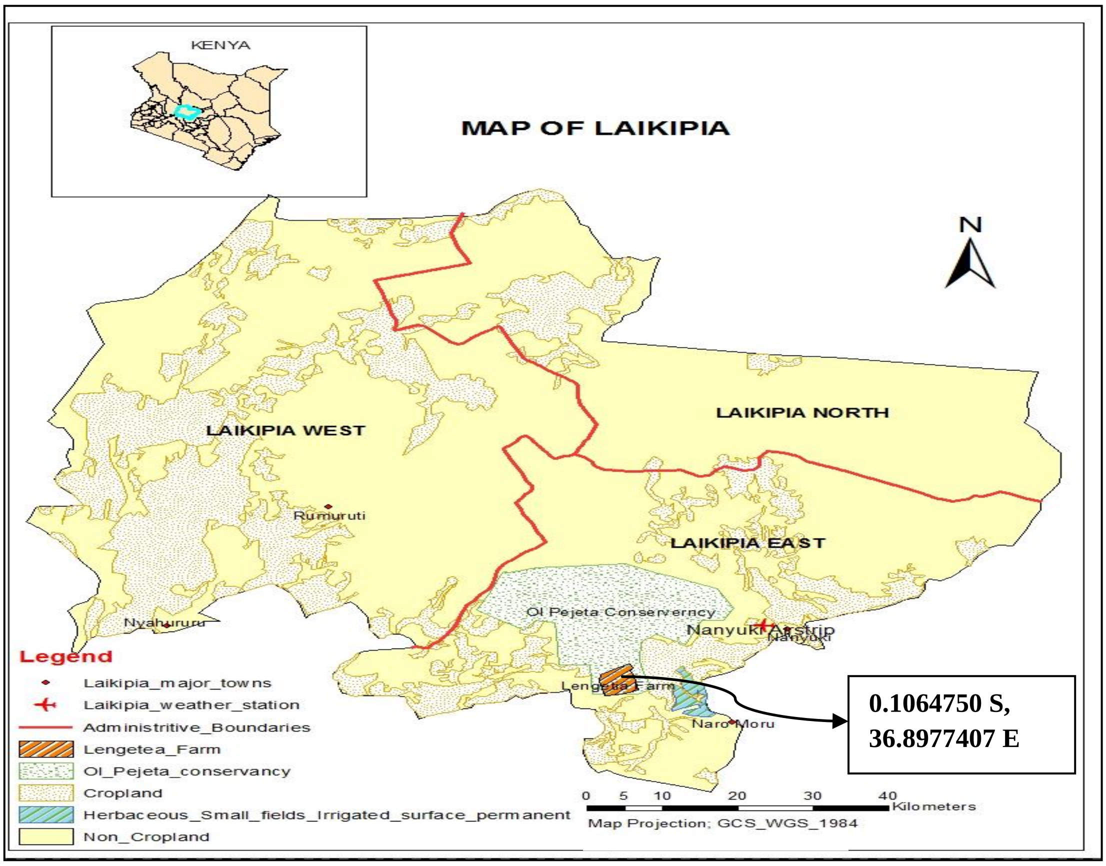

Figure 3.1: Laikipia County map indicating location of the study area and major land uses in the county. (Source: Author, 2016).

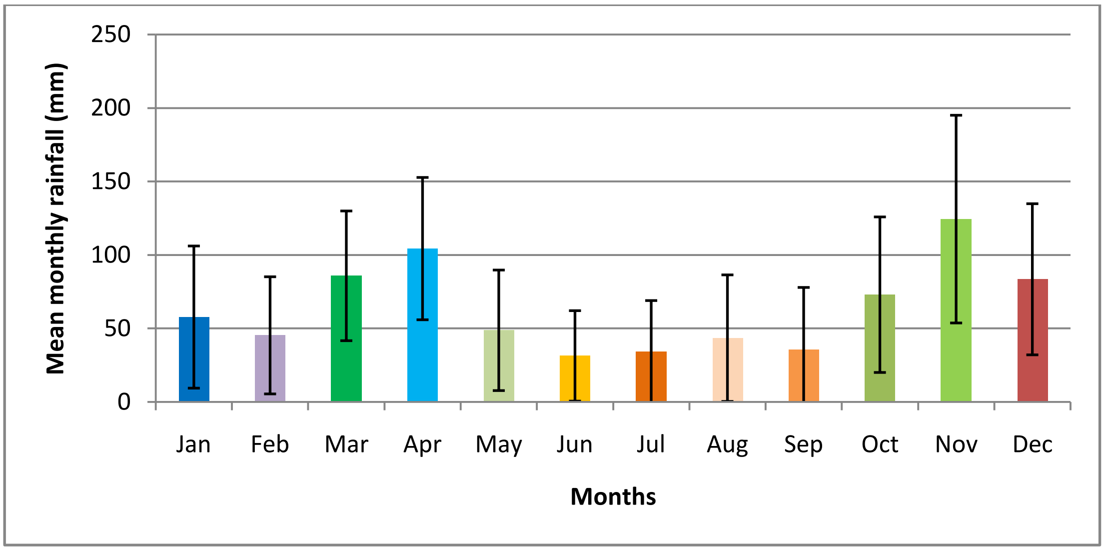

Figure 3.2: Mean monthly rainfall distribution for the period 1955-2015 indicating the two rainfall seasons (Source: Ewaso Nyiro South WRMA). The error bars indicate standard deviation.

Although annual rainfall average about 650 mm per year, it can be very unreliable, especially in areas which have two distinct rainy seasons (Ojwang' *et al*., 2010). Similarly the onset of the rains is highly variable and can be delayed by up to two months in some seasons. From field observation and experiment, the area receives few rain days of very high intensity (Huho *et al*., 2012) characteristic of such ASAL areas (Barron *et al*., 2003).

3.3 Experimental Treatments and Design

3.3.1 Experimental Details

The experiment was carried out over the short rain season starting September 2015 to February 2016. The rain-fed trials and the water regime trials were planted on a randomized complete block design in split plot arrangement. Two tillage treatments (zero tillage (ZT) and conventional tillage (CT)) formed the main plots factors, the four sowing dates as the sub-plots factors and three blocks formed the replicates. In the split-plot arrangement used (Mhizha, 2010); zero tilled field (ZT) and conventional tilled field (CT) were laid parallel to each other along the land slope to ensure that none was draining into the other. Four sowing onset dates; three rain-fed and a water regime control treatment (with supplemental irrigation) were randomized among the subplots as; one dry onset (sowing date one-SD1), one normal onset (sowing date two- SD2), one late onset (sowing date three-SD3) and one normal onset under supplemental irrigation (water regime treatment - WTSD2). Figure 3.3 illustrate the experimental layout while Table 3.1 shows the sowing dates used.

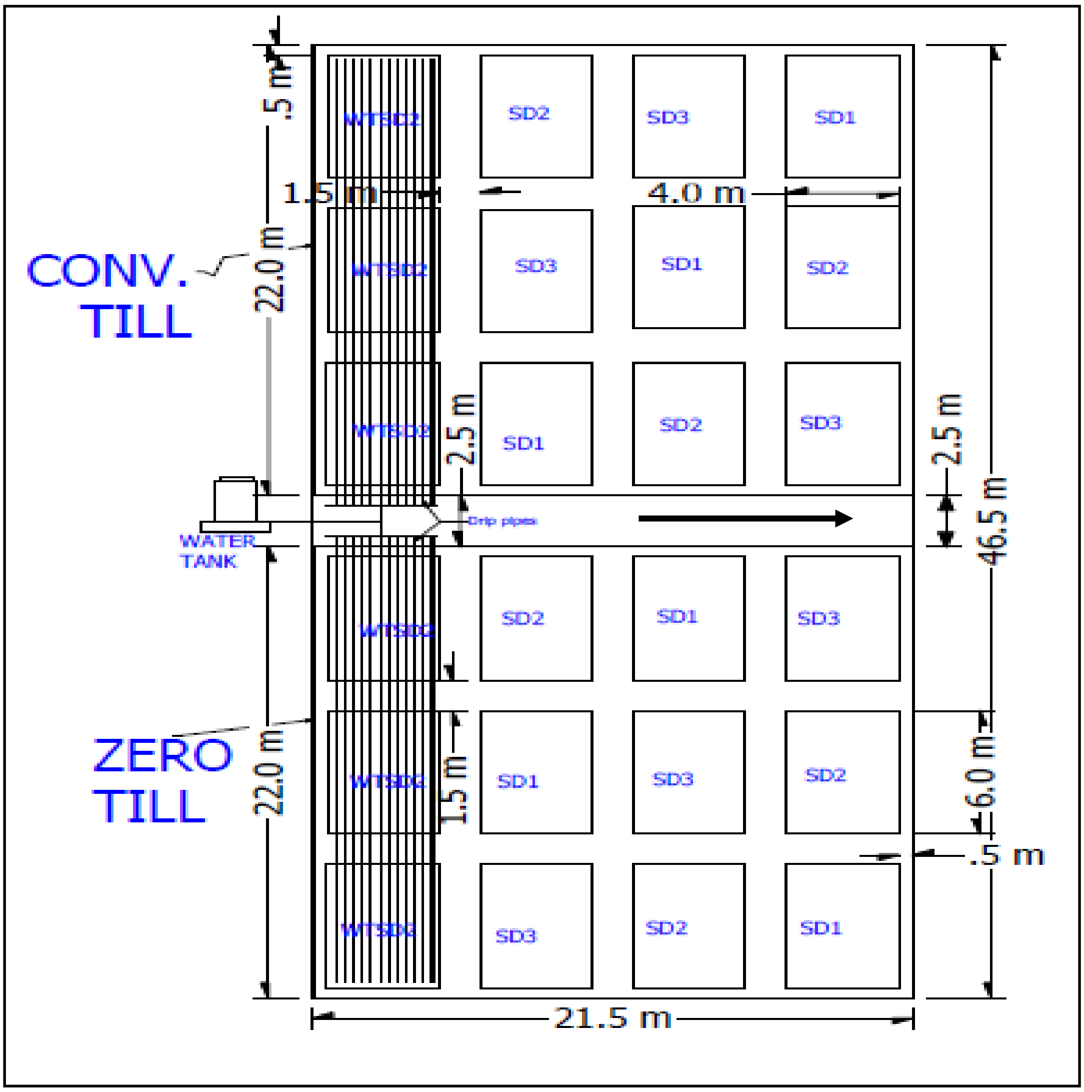

Figure 3.3: Field trial layout adopted at the site. (Source: Author 2016)

Table 3.1: Sowing dates representing the three sowing season characteristics determined by onset of rainfall an adjustment of rainfall criterion in AquaCrop (Raes, 2012)

Sowing Date	Occurrence	Symbol	Sowing time Characteristic	
			Onset time	Type of sowing
29th September	1st	SD1	Early	Dry
21st October	2nd	SD2	Normal	Wet
21st October	2nd	WTSD2	Normal (irrigated)	Wet
31st October	3rd	SD3	Late	Wet

The control plots were the treatments under normal onset both in zero and conventional tillage. Each of them received supplemental irrigation to limit water stress (i.e. WTSD2-ZT and WTSD2-CT) for use in calibration of AquaCrop model. Therefore the total treatments/subplots were, two tillage treatments (zero and conventional (2TT)), by four onset dates treatments (4TD) replicated thrice i.e. (2TT × 4TD × 3=24), as indicated in the layout of plots given in Figure 3.3.

The sub-plots were 24 m^2 (4 m × 6 m) each consisting of 12 rows, 6 m long and 0.3 m between rows (spacing recommended for dry areas) separated by 1.5 m to ensure that the treatments in plots were independent of each other. The two main blocks (ZT and CT) were separated by 2.5 m pathway on which the water tank on its stand was mounted to provide water for supplemental irrigation on control plots.

All the plots in the blocks received the same cultural practices of fertilizer application, control of pests, diseases but land preparation and sowing dates were varying (Fig: 3.3 and plate 3.1). Only the control treatments (water regime) received supplemental irrigation.

A split plot arrangement was selected because it was not possible to randomize tillage treatments as one among the important factors of the experiment but the sowing dates were easy to vary and randomize.

Plate 3.1: Trial field layout (7th Nov 2015, 40 days after first sowing onset). (Author, 2015)

3.3.2 Irrigation Scheduling

Supplemental irrigation was designed to ensure that wheat crop in the control treatment (WTSD2-ZT and WTSD2-CT) does not experience water stress throughout the growing period. The irrigation was scheduled based on FAO guidelines for crop water requirement (ETc) equation 3.1 (Steduto *et al.*, 2012).

$$ETc = K_c * ETo \qquad \text{Eqn. 3.1}$$

ETo was determined using historic climate data and ETo calculator with Penman – Monteith equation for ETo (Allen *et al.,* 1998) and a mean ETo value obtained. The crop coefficient (K_C) was dependent on the crop growth stages; initial, development, mid, and late stages as 0.4, 0.8, 1.2 and 0.7 respectively (Steduto *et al.,* 2009). Irrigation was scheduled to supplement rainfall such that, every time rainfall was received (less than irrigation depth); its equivalent depth was deducted from the scheduled irrigation event. If the rainfall received was greater or equal to scheduled irrigation depth, then, irrigation was skipped.

Using total available water (TAW) obtained from soil texture analysis (Section 4.1.2) and considering an effective rooting depth of 60 cm, the net application depth (I_{net}=RAW (mm)) determined at an allowable depletion, p=0.55 (Geerts & Raes, 2009) (Equation 3.2).

$$RAW = p * TAW * Z_r \qquad \text{Eqn. 3.2}$$

The gross irrigation depth (I_{gross}) was then determined (Equation 3.3) assuming an application efficiency of drip irrigation (Ea) of 85%.

$$I_{gross} = \frac{I_{net}}{Ea} \qquad \text{Eqn 3.3}$$

Considering an emitter discharge rate of 0.53 L/hr, and a wetted radius of 7.5 cm per emitter, and ETc (equation 3.1), the irrigation interval (*i*) (Equation 3.4) was computed.

$$i = \frac{I_{net}}{ETc} \qquad \text{Eqn. 3.4}$$

Water was supplied to the wheat using drip irrigation system from a raised tank installed on site. The drip lines (laterals) had built in emitters with a nominal discharge of 0.53 L/hr spaced at 15 cm apart.

The results of irrigation scheduling on the control treatments were thirteen irrigations of 43 mm each. However as a result of received rainfall, two irrigations were skipped during the mid-stage as presented in Table 3.2.

Table 3.2: Results of irrigation scheduling on the water regime control treatment plot

	Crop growth development stages			
	Initial	**Development**	**Mid**	**Late**
ETo (mm/day)	4.2	4.2	4.2	4.2
Kc	0.4	0.8	1.2	0.7
ETc (mm/day)	1.7	3.4	5.0	2.9
Length of growth stage	15	25	50	40
Irrigation interval (days)	25	12	8	14
Number of irrigations	1	2	5 (*2irrigations skipped*).	3
Total water irrigated				473mm
Net application depth (I_{net})				43mm

3.4 Description of AquaCrop Model

AquaCrop model is a water-driven crop growth model which simulates attainable yields as a function of water consumption by calculating the daily water balance in the soil. As illustrated in Figure 3.4, final yields are simulated in four steps; development of canopy cover, crop transpiration, above-ground biomass and final crop yield. These processes (respectively indicated by the bold arrows in Figure 3.4) are affected directly by either temperature or water stresses or both. In AquaCrop, the crop responds to four water stress thresholds, which trigger crop canopy reduction, stomata closure, acceleration of canopy senescence and change in harvest index (HI) (Raes *et al.*, 2012). These water stress responses at various stages of crop development are demonstrated by the dotted arrows; a, b, c, and d, respectively in Figure 3.4. Among the AquaCrop outputs are the final biomass, harvestable yield and evapotranspiration water productivity.

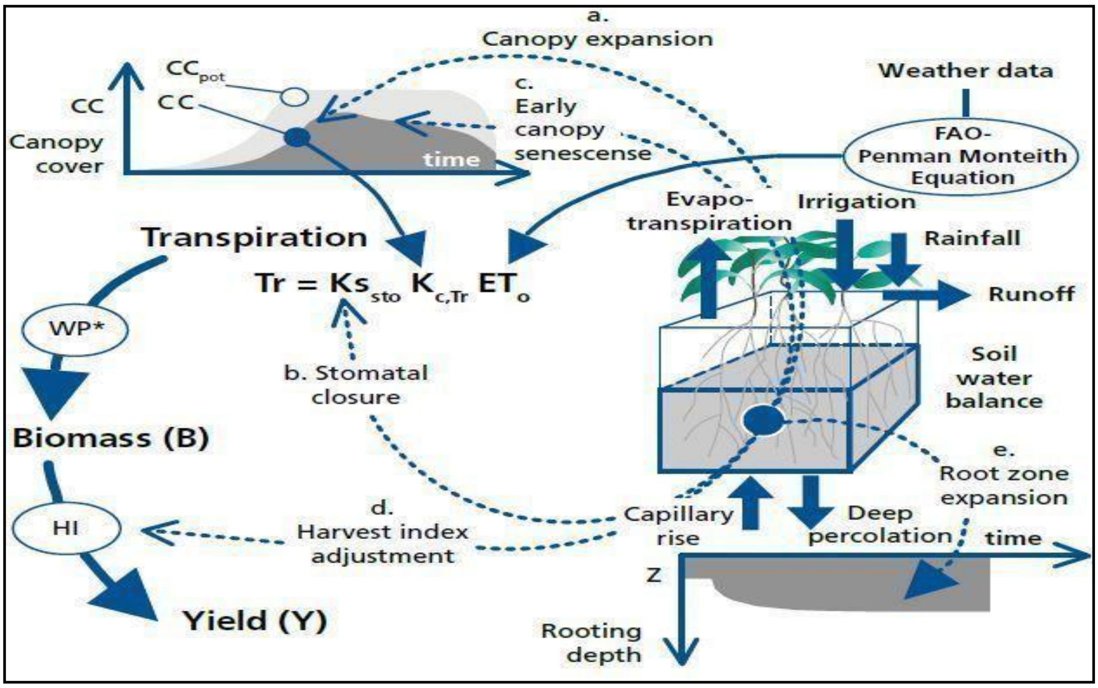

Figure 3.4: Flowchart of the calculation scheme of AquaCrop (bold lines). The dotted lines show the effect of water stress on canopy cover, root zone expansion, crop transpiration and yield (Source: Raes *et al*., 2009).

3.5 Generation of Onset Dates

Generation of the onset of growing period using AquaCrop Model was based on historical farmer's practice of sowing (to establish the normal (wet) planting date and sowing window), historical climatic data and criteria for selection of dry sowing date(s) by the AquaCrop Model based on 19 years historical rainfall. The onset dates are generated based on soil moisture at the root zone to match the requirement for wheat to germinate.

The Raes *et al.*, (2004) rainfall criterion was used with little adjustment due to the fact that accumulated rainfall of 40 mm was limited under ASAL climate. The adjustment was that germination was triggered by received rainfall of at least 10 mm for four consecutive days. This is the amount of rainfall required to raise the soil water content at wilting point to field capacity in a profile of 10 cm of the top soil (Section 3.9.2). Also considering that there was stored soil water from zero tillage practice over the years this rainfall was sufficient to trigger germination and the stored soil water would support crop growth until the next rainfall event was received.

A soil water balance analysis by the AquaCrop model and yield simulation was used to determine whether the generated date was a false start based on yield and risk of failure of the crop after germination. Other alternatives such as onset based on air temperature and CO_2 exist and may also be used but for this study, the soil moisture content was the limiting factor and therefore the rainfall criterion was preferred.

3.6 Soil Samples and Sampling Method

The field was traversed in a zigzag pattern and representative soil sample for physical and chemical properties determination collected from eight points on the field. Core sampler was used to collect sub-samples from a depth of 90 cm at 0-25 cm, 25-45 cm, 45-65 cm and 65-90 cm intervals (undisturbed core of soil of known volume). A composite sample was obtained from mixing and quarter method on the eight sub-samples for respective soil depth intervals. This method was used because it was convenient for a small field and fully represented the area.

The soil tests and analysis was carried out at; the University of Eldoret soil science laboratory (texture analysis), Crop Nutritional Laboratory (chemical classification and texture), KARLO-Kabete Laboratory and Ministry of Transport and Public Works Laboratory at Nyeri (aboveground biomass and soil water content).

3.7 AquaCrop Data Input and Parameters

The following parameters were determined and data collected and recorded for use as input to the AquaCrop model.

3.7.1 Climate Parameters

Daily weather data was measured from the experimental field before, during and at the end of the experimental period. The data was used to run AquaCrop simulation for each day of the simulation period and for computation of reference evapotranspiration (ETo) which was also an input to AquaCrop model. Historical climatic data for at least 30 years required to be collected from the nearest meteorological station to the experimental site. However, only 19 years of daily data was available from Lamuria meteorological station managed by Water Resource Management Authority (WRMA-Ewaso Nyiro South catchment) which lies on Latitude 0^{o} 08’ S and Longitude 36^{o} 56’ E about 2 km from project site.

The daily climate data measured included: Daily rainfall data in millimeters (mm) measured using a rain gauge. This was used in AquaCrop Model to update the soil water balance and to compute the effect of water limitation to the crop growth and production process. Daily minimum and maximum temperature in degrees Celsius (^{0}C) for determination of crop development and phenology and for adjustment of biomass production and the effect of temperature stresses. Wind speed measured at 2 m above the ground using anemometer was also recorded.

The reference evapotranspiration (ETo) was estimated using FAO Penman Monteith equation by means of ETo software using the above climate data except rainfall (Allen *et al*., 1998). This equation was maintained as the sole formula for computing

ETo (Allen *et al.*, 1998). Finally, mean annual atmospheric carbon dioxide (CO_2) concentration which is a default file in AquaCrop model was adopted.

3.7.2 Soil Parameters

The initial soil moisture content, soil textural class and the bulk density were necessary input parameters in the AquaCrop model. Similarly to carry out simulation runs, the soil moisture contents at wilting point, field capacity and at saturation were required. These parameters were measured and determined from representative soil samples (section 3.6 above). Soil moisture content was determined by gravimetric method from samples taken from a depth of 10 cm, 25 cm, 45 cm and 60 cm representing water content at 0-20 cm, 20-30 cm, 30-60 cm and 60 cm layers respectively taken every 10-14 days throughout the growing season.

Hydrometer method (Okalebo *et al.,* 2002) was carried out to determine the mineral percentage proportion of sand, silt and clay particles then used USDA textural triangle to derive the textural class of the soil. Pedo-transfer functions generated by soil texture (Saxton *et al.*, 1986) available in soil hydraulic properties calculator were used to determine the moisture content at wilting point (PWP), field capacity (FC) and at saturation (SAT) and the hydraulic conductivity (K_{sat}).

3.7.3 Crop Parameters

Aboveground dry biomass was measured every two weeks by sampling and weighing three plants from each sub-plot and weighing after oven drying to constant weight at 70^oC. Crop canopy cover (CC) was determined using digital photographs taken (in three replicates per sub-plot) by a Nikon CoolPix S2800 taken for analysis every two weeks across the crop growth stages. Plate: 3.1 show a sample nadir digital photo taken and used for canopy cover measurement. CC (%) was calculated by analyzing these digital images using the Sample-Point program (Booth *et al.*, 2006).

Plate 3.2: Sample nadir digital photo used for canopy cover measurement (Source: Author, 2015).

This software had been used by other researchers and recommended for its accuracy in measuring CC% from nadir digital photos (Zhang *et al.,* 2013).

The final grain yield was measured by harvesting three representative quadrants of one square meter (1 m^2) each, selected randomly from each treatment after maturity as illustrated in Plate: 3.3 (a-c). The samples were oven dried to constant weight at 70^oC and weighted for final biomass then grain threshed and weighed for final yield determination. The maximum rooting depth reached was measured at the end of the season by digging around 1.2 m deep to expose the roots at full maturity (Plate 3.3(d)) and rooting depth estimated with measuring tape.

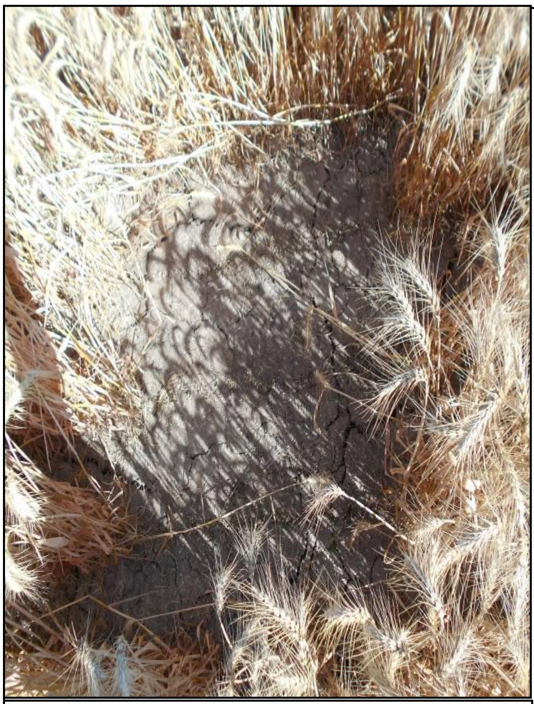

Plate 3.3(a): Quadrant sampled for measurement of final biomass and yield (Author, 2016)

Plate 3.3(b): Sampled crop from various quadrants for measurement of final biomass and yield (Author, 2016)

Plate 3.3(c): Quadrant sampled for measurement of final biomass and yield. (Author, 2016)

Plate 3.3(d): Estimation of maximum effective rooting depth by visual inspection of soil profile. (Author, 2016)

3.7.4 Field and Crop Management

Sowing was done at the respective SD1, SD2, SD3, WTSD2 onsets dates (Table 3.1, Section 3.3.1) generated through modeling with the criterion of accumulated rainfall enough to cause germination within the farmers sowing period. Certified seed of wheat (*Triticum aestivum*) of the Kenya *Korongo* (KSRR-VIII) variety was sown. This was a new rust resistant, commercial variety classified as semi-dwarf released in the year 2012 by KARI- National Plant Breeding Research Center. The criteria that were used to select it for this research were based on plant breeders information (KARLO-Njoro) and farmers experience recommending it as best compared with other varieties in terms of bearing up periods of high water stress and resistant to rust and other diseases. Also among the other new varieties it had a higher yield potential of 8.5 ton/ha reaching maturity at 120-130 days.

Seed drilling was done manually on drills of 3-5 cm and a seed rate of 25 Kg per acre (62.5 Kg/ha) based on farmers experience over the years in this dry area. At sowing, Di-Ammonium phosphate fertilizer (DAP) was applied at recommended rate of 40 Kg/acre (soil fertility analysis results carried out at Crop Nutrition Laboratory) with a yield target of 6 ton/ha. Further, Urea was used for top dressing at early tillering at a rate of 110 Kg/acre to supplement the low Nitrogen in the soil and later top dressing with Ammonium Sulphate at 30 Kg/acre to supplement for the low Sulphur in the soil. Fertilizer recommendation was also based on the results of fertility analysis and the FAO irrigation and drainage paper 66 (Steduto *et al.,* 2012) guideline, for each tonne of yield per hectare given as 25-40 Kg/ha N, 3-5 Kg/ha P and 15-30 Kg/ha K. The crop was then managed according to the guidelines in HGCA (2016) guidelines on spray timing in wheat crop.

3.8 AquaCrop Model Calibration and Validation

Calibration was done using the results of control treatment (WTSD2) and validation done using results of the remaining treatments for both conventional and zero tillage. Only the parameters that vary with cultivar and environment were adjusted depending on availability of data about the parameters.

Calibration of this model was necessary to fine tune it to the soil, crop and climate of the study area. This was done using the observations of water regime control field treatments (WTSD2) as the input and run simulations with the model to predict output whose measure was the root zone soil moisture, dry biomass (B), yield and canopy cover (CC). This output of the model was compared with the measured and observed yield from experimental field plots. Any variation of the simulated output from the observed output was adjusted by adjusting model parameters using trial and error for the cultivar specific parameters (each at a time) which are known to affect the output parameters.

To validate the model, the results of the other experimental plots (SD1, SD2 & SD3) were used to run the model whose output was compared with the observed results of the experimental plots. This demonstrated and determined the models ability to model and simulate yield for wheat crop under the given experimental field and management practices.

3.9 Determination of Optimal Sowing Date

Several dry and wet sowing dates (within the sowing window) from available 19 years of historical rainfall data were generated based on depth criterion (Raes *et al*.,

2004) modified for ASAL region. The generated dates were used to run several multiple simulation of yield using calibrated AquaCrop model.

3.9.1 Initial Conditions

The practice of the farmers is to leave the land in fallow during the long season (March, April, May) and sow during the short rain season (October, November, December). It was therefore assumed that this rainfall is stored in the soil for the short season and combined with received rainfall depth of at least 10 mm for four (4) consecutive days was enough to germinate the seed and support it till the next rainfall event was received. Therefore the initial soil water content was tuned to be at field capacity although this condition is always altered when the land is tilled in seed bed preparation. This exposes the soil to evaporation and contributes to a substantial loss in soil moisture. Therefore a confirmation of the viability of this assumption was made using the readily available water (RAW) at the top soil.

3.9.2 Rainfall Depth Onset Criterion

Adjustment on the Raes *et al.*, (2004) rainfall depth criterion was made. The wheat seed is sown at 5 cm depth for the dry onset (Early) and therefore this depth was doubled to give a root depth of 10 cm. The total available water for the top soil in the study area was used to determine the amount of rainfall required to raise the top soil water content at 10 cm to field capacity from wilting point. From soil physical analysis, the Total Available Water (TAW) at the top soil was 134 mm/m (section 4.1.2, Table 4.1) which translate to 13.4mm at 10cm depth. Also considering an allowable depletion (p) of 0.5 (Steduto *et al.*, 2012), the Readily Available Water (RAW) was 6.7 mm (Eqn. 3.5)

$$\boldsymbol{RAW} = \boldsymbol{p} * \boldsymbol{TAW} \qquad \text{(Eqn } \mathbf{3.5}\text{)}$$

$$= 0.5 * 13.4$$

$$= 6.7\ mm$$

The computed value 6.7 mm was scaled up to 10 mm to take care of losses of up to 3.3 mm due to evaporation since the study reference evapotranspiration is 4.2 mm/day (Table 3.2).

3.9.3 Generation of Onset Dates with Historic Data

From experience the farmers sowing window ranges from 15th September to 15th October of every year for the target short rain season sowing. This window was extended by two weeks on both ends with all simulations started on the 1st day of September of each year giving a sowing window of two months with the last search date at 31st October of each year. The extension by four weeks was considered and meant to simulate possible chances of a shift of the season either to an early onset or a late onset and therefore minimize possibility of missing potential early or late onsets.

The generated dates were grouped into the three seasons starts; early (1st-30th September), normal (1st-14th October) and late (15th -31st October). The selection criterion of generated dates was three dates every year representing the early, normal and late onset. That is, starting from the initial search date the onset was taken to be the date on which the criterion was first satisfied or exceeded (Kipkorir *et al.,* 2004). The first date within the range of early onset was selected to represent early onset and correspondingly for the normal and the late onset.

3.9.4 Optimization Analysis

Optimization analysis on the simulated yield results for every year and for different generated planting dates over the 19 years of available historic daily climate data was applied to obtain the optimal allocation of acreage proportion to the various sowing treatments with the best maximum yields every year. This was achieved using Microsoft Excel Solver Tool and simulated yields in AquaCrop model.

For purpose of developing the optimization objective function, a total yield term (Y_T) was defined as the weighed summation of the grain yield simulated for each of the three sowing options for each year and over 19 years of available historic data (Equation 3.6)

$$\boldsymbol{Y_T = \sum_{s=1}^{3} (A_i Y_{S_i})} \qquad \textbf{(Eqn 3.6)}$$

The aim was to maximize mean grain yield for all the 19 years. Therefore the objective function which formed the target cell was;

$$\mathbf{max} \sum_{\mathbf{j=1}}^{\mathbf{N}} (\mathbf{Y_T/n}) \qquad \textbf{(Eqn 3.7)}$$

$$for\ j = 1\ to\ N$$

Subject to constrain on area; $0 \le A_i \le A$ and

$$A_1 + A_2 + A_3 \le A$$

$$for\ i = 1,2,3$$

Constraints on the changing cell; $0 \le A_1 \le 0.4\mathrm{A}$

$$0 \le A_2 \le 0.6A$$

$$0 \le A_3 \le 0.6A$$

The values, 0.4, 0.6 and 0.6 are the weight factors corresponds to 25%, 37.5% and 37.5% proportional area allocation recommended for the early, normal and late sowing dates respectively. This was obtained from expected target yields and frequency of failure at 50% probability of exceedance (Section 4.5.3 and 4.5.4).

Where,

$S_{i,}$ is the respective simulated onset date (i.e. SD1, SD2 and SD3 representing the early, normal and late season onset), for i=1, 2, 3.

Y_s , is the simulated grain yield of the s^{th} sowing date (ton/ha)

$A_{i,}$ is a weighted factor, a proportion of area (acreage) allocated through optimization to sowing date $S_{i.}$

A, is the total area (unit or 100%) to be considered and allocated to the three sowing seasons based on the proportions obtained in the frequency analysis.

N, is the total number of years of simulated yield considered in the optimization (based on available historic climate data, 19 years).

The A_i weighted factor given to each yield term in the summation was aimed at allocating more land to desirable treatments and less (or even none) to undesirable treatments not likely to contribute positively to average yield.

Therefore the weighting factor formed the changing cells of the optimization procedure while the target cell was the mean of total yield (Y_T/n) over the 19 years. The target cell was maximized for highest stable yields. By means of constraints; the number of options selected in the optimization was restricted.

3.10 Data Analysis

Data analysis was done with regard to the objectives. Frequency analysis and homogeneity test using RAINBOW was applied to secondary climate data and simulated yield data to check and ensure that they belonged to the same statistical population (Raes *et al.*, 1996*;* Raes *et al.*, 2006). Additionally, the Excel spreadsheet (windows 2007) and SPSS statistical software (Version 20) were used for tabulation, descriptive statistics and graphical representations.

Measured soil moisture content for the entire growing period (130 days) was tabulated; variations and means presented graphically. Observed yields from zero and conventional tillage treatments were used to compare the effects of each on yield by comparing their means, variance and standard deviation. Similarly the effect of various onset dates on yield was calculated by comparing the means, variance and standard deviations for yield results under early, normal and late onset within conventional tillage independently and a similar analysis under zero tillage. Then, the statistic test was calculated and Hypothesis tested at 5% level of significance. Microsoft excel solver tool was used for optimization analysis of the yield simulated by AquaCrop model (from multiple projects) to obtain the algorithms that allocate best acreage proportion to the varying sowing dates (section 3.9.4).

The following statistical indicators namely, Coefficient of determination (R^2), root mean square error (RMSE), Nash-Sutdiffe model efficiency coefficient (EF) (McCuen *et al*., 2006) and Willmott's index of agreement (d) were performed to evaluate AquaCrop models performance in simulating canopy cover (CC %), biomass (B in ton/ha), soil water content (SWC, mm) and the harvestable yield (Y ton/Ha).

CHAPTER FOUR

RESULTS

4.1 Introduction

An experimental study was conducted to determine the effect of sowing dates on crop grain yield as a result of soil water availability to crop at planting on one hand and the impact of tillage practices on soil moisture and crop grain yield on the other hand. The results of the study are presented in this chapter as follows; weather data, soil physical and chemical parameters, effect of available soil water at sowing on crop yield and tillage effect on soil moisture and crop yield, AquaCrop model calibration and validation and finally the yield optimization analysis.

The soil of the study area was analyzed for physical and chemical classification which was characterized with high clay content and low Nitrogen levels. Wheat crop grain yield under zero tillage, conventional tillage and the sowing date treatments was subjected to various statistical tests and measure for any significant variation. Both sowing onset and tillage practices affected the crop yield. The measured soil moisture content every ten days indicated significant variation in soil moisture between the two tillage treatments which had a significant effect on the canopy development, biomass and final grain yield.

4.1.1 Climate Characteristic

The climate characteristic was summarized in Figure 4.1 as effective decadal rainfall during the season and the computed decadal ETo using ETo calculator (Allen *et al.*, 1998) from observed weather data on site during the experiment. From the figure, apart from the two distinct peaks, only three decades received rainfall in excess of

ETo. Daily rainfall distribution and ETo data was plotted and presented in Appendix C, Figure C.1 for reference. The effective rainfall (rainfall received during the growing period) was 483 mm while the total irrigation water applied to the water regime control treatment (WTSD2) was 473 mm totaling to 956 mm. This amount is higher than the crop water need of wheat which ranges 450-650 mm (Steduto *et al.*, 2012). This is because, the value is the recorded rainfall and not all received rainfall was infiltrated (lost in run-off) while some percolated (drainage to ground water). Also, in some observed situations, rainfall was received after irrigation had been applied and therefore not useful to the crop.

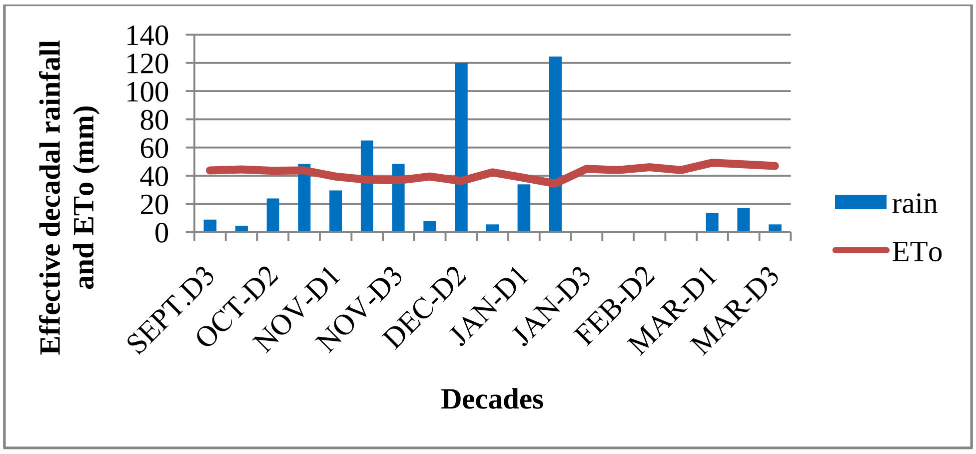

Figure 4.1: Effective Decadal Rainfall and ETo between September 2015 to March 2016

4.1.2 Soil Physical and Chemical Properties

The soil profile as determined both by visual inspection of the soil from excavated pits and from sampled soil samples in the trial site comprise of two horizons. These are classified into textural classes (USDA) as clay soil at the top 0-25 cm and middle 25-65 cm but with varying proportion and the clay loam soil from 65-90 cm. Other physical properties are as summarized in Table: 4.1.Similarly, from chemical analysis of sampled 25 cm of top soil, the soil had low Nitrogen and high Potassium on the top soil. Additional results of the soil chemical characteristic are summarized in Table 4.2.

Table 4.1: Major physical soil characteristics of the soil of the trial site (0-90 cm)

Profile Depth	**Soil Texture**				**Moisture Content**					
(cm)	**Clay (%)**	**Silt (%)**	**Sand (%)**	**Textural class**	**FC (%)**	**PWP (%)**	**SAT (%)**	**TAW (%)**	**Bulk Density (g/cm3)**	**K_{sat} mm/hr**
0-25	56	23	21	Clay	45.8	32.4	54	13.4	1.22	1.784
25-45	45	21	34	Clay	37.3	25.0	51.8	12.4	1.28	1.624
45-65	47	23	30	Clay	39.2	26.3	52.4	12.9	1.26	1.66
65-90	23	29	36	clay loam	32	19	50	13	1.32	2.5

FC- Field capacity , PWP- permanent wilting point, SAT-saturation, TAW-total available water, K_{sat}-saturated hydraulic conductivity

(Source: Author, 2016)

Table 4.2: Major chemical characteristics of the topsoil (0-25cm deep) from the trial site soil

PARAMETERS	SYMBOL	RESULT	UNIT	GUIDE		REMARK
				LOW	HIGH	
pH(H_20)	pH	6.32		6.00	6.80	Optimum
EC (salts)	EC(S)	162	µS/cm		<800	Optimum
Phosphorus	P	49.8	Ppm	30.00	100.00	Optimum
Potassium	K	1220	Ppm	229.00	918.00	Very High
Magnesium	Mg	699	Ppm	353.00	706.00	Optimum
Sulphur	S	9.61	Ppm	20.00	200.00	Very Low
C.E.C	C.E.C	29.4	meq/100g	15.00	30.00	Optimum
Nitrogen	N	0.11	%	0.20	0.50	Low
Organic Matter	OM	3.16	%	3.00	8.00	Optimum
C/N ratio	C:N	16.7		10.00	25.00	Optimum
Calcium	Ca%	53.5	%	60.00	72.00	Low
Magnesium	Mg%	19.8	%	10.00	20.00	Optimum
Potassium	K%	10.6	%	2.00	8.00	Very High
Sodium (ESP)	Na%	0.76	%	0.00	5.00	Optimum
Ca:Mg Ratio	Ca:Mg	2.7	%	4.00	7.00	Low

(Source: Author, 2016)

The bulk density and saturated hydraulic conductivity in Table 4.1 were input data in AquaCrop soil file during calibration. The chemical properties of the soil in Table 4.2 were used to determine the type and rate of fertilizer application suitable for wheat crop.

4.2 Soil Moisture Variations in Zero and Conventionally Tilled Fields

Farming and soil management practices affect the amount of water infiltrating into the soil as well as the rate of evaporation from the soil. Practices retaining crop residue on the ground influence soil moisture by reducing evaporation and enhancing infiltration through reduction in runoff when it rains. Similarly, reduced operations on soil through zero tillage improve on soil water retention through improved soil structure and drainage. This is according to results of field soil moisture measurement as presented in Table 4.3 and Table 4.4 for brevity.

Table 4.3: Descriptive statistics on Soil Water Content (0- 60 cm depth)

	Min. (mm)	Max. (mm)	Mean (mm)	Std. Error	Std. Deviation (mm)
SD1-ZT	215.1	290.2	252.14	6.10	19.30
SD1-CT	184.8	253.1	213.82	6.33	20.03
SD2-ZT	230.0	297.2	269.47	6.55	20.73
SD2-CT	186.2	245.5	219.76	6.09	19.24
SD3-ZT	233.5	287.6	258.89	7.23	20.45
SD3-CT	189.5	245.6	215.41	7.37	20.84
WTSD2-ZT	259.3	287.4	276.02	3.03	9.08
WTSD2-CT	220.9	277.5	250.20	6.07	18.21

CT-Conventional tillage ZT-Zero tillage WTSD2- Water regime treatment
SD1,2,3- Sowing dates one, two & three respectively

Table 4.4: Soil moisture variation as influenced by tillage treatments (0-60cm)

Independent variables (field plots)		**Test for equality of variances**		**T-test for equality of means**		
Zero tilled	Conventionally tilled	F	Sig.	Sig. (2-tailed)	Mean difference	Std. error Difference
SD1	SD1	.126	.727	.000	38.32	8.80
				.000	38.32	8.80
SD2	SD2	.086	.772	.000	49.71	8.94
				.000	49.71	8.94
SD3	SD3	.001	.977	.001	43.48	10.32
				.001	43.48	10.32
WTSD2	WTSD2	2.453	.137	.002	25.82	6.78
				.003	25.82	6.78

Zero tillage split plot maintained higher moisture contents at all times compared to conventionally tilled plots with the tested variation significant at $P<0.05$ as presented in Figure 4.2 for SD1 while additional results for SD2, SD3, WTSD2 are appended for reference (Appendix A; Fig A.1-A.6). The data also indicate a higher standard deviation for the conventionally tilled fields as compared to zero tillage fields as indicated by the error bars in the figures. A test of significance at 95% confidence interval performed in the respective sowing dates between the two tillage treatments indicated significant difference between the soil moisture content of the two tillage plots. The difference in soil moisture was especially strong for the early onset (dry sowing date one-SD1) while the variation was high among the conventional tillage plots.

Even after a rainfall event as seen in Figure 4.2, zero tillage maintained higher surface soil moisture as well as soil water content at the root zone (60 cm profile). From field observation, zero tillage fields experienced reduced runoff because of increased surface roughness due to presence of crop residue on the ground.

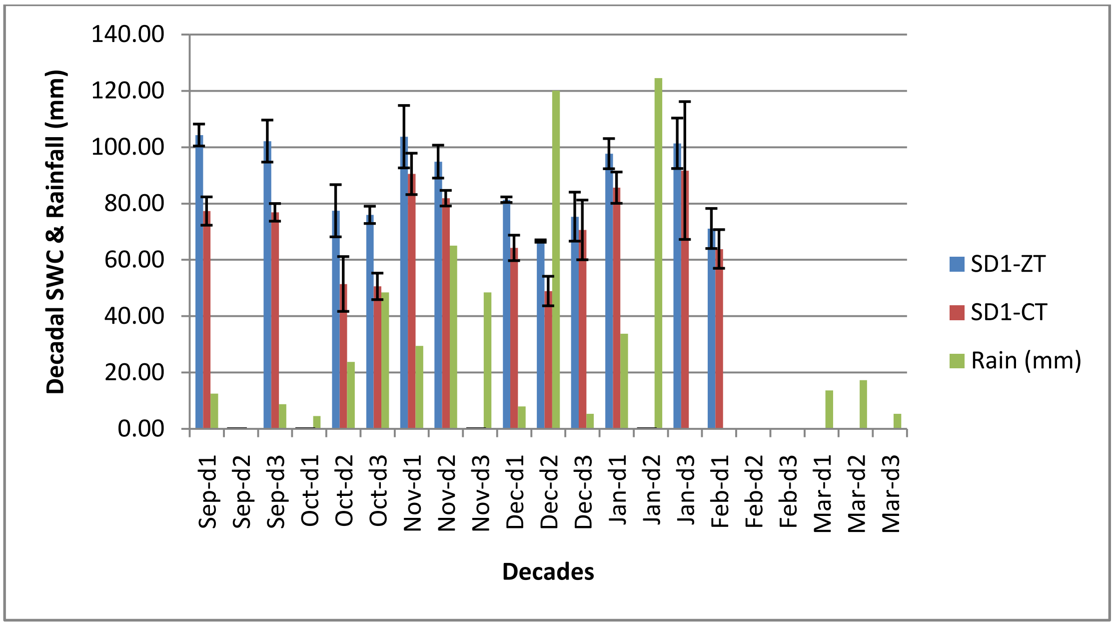

Figure 4.2: Bar graph showing the variation in top soil moisture content (0-25cm) and the effective decadal rainfall within the growing period (SD1 Plot). The error bars indicate standard deviation.

This could have enhanced infiltration rates in zero tilled fields and thus the high moisture content. On the contrary, conventionally tilled fields were observed to experience high runoff and erosion of the loose fine soil particles which seal the surface hindering infiltration. This had the effect of reduced soil moisture content and hindered crop establishment as seen in Plate 4.1 section 4.3.

T-test computation (Table 4.4, column 5) indicated a significant difference ($P<0.05$) in mean soil moisture content between tillage practices. The zero tillage practice had higher soil water content than conventional tillage.

Further analysis on soil moisture was carried out on the top 0-25 cm and results are as appended in Appendix A (Table A.1 & A.2) for reference and graphically (Appendix-

A: Fig A.5 & A.6) showing the difference and the variations throughout the growing period. There was significant difference (P<0.05) in top soil moisture content for the early onset (SD1). However the difference was not significant under SD2, SD3 and WTSD2 treatments.

4.3 Crop Yield Response to Sowing Onset and Tillage Practices

Early sowing for this experiment was termed as the dry onset (SD1) just before the onset of the rainfall but within the farmers sowing window. Early sowing can result to false starts (Sen *et al*., 2014) and requires that the seed be placed at deeper depths compared to wet sowing to avoid damage of seed by light showers. On the other hand, delayed sowing can shorten the growing period resulting to yield losses which for this study was represented by SD3.

Additionally, as much as timely sowing is recommended, it is almost always delayed by land preparation and farming practices (Chandna *et al.,* 2004). This combined with the need for soil conservation and soil moisture conservation practices introduce zero tillage one among the conservation agriculture practices. Zero tillage ensures that there is improved water retention and infiltration, reduced runoff and reduced time of land preparation and soil degradation. Therefore, tillage treatment’s effect on yield was determined in this study.

Wheat crop sown under zero tillage had an early establishment by two days in the dry onset (SD1). The start of emergence was on day eight (8) after sowing for zero tillage, two days earlier than the crop under conventional tillage. Similarly the crop was more uniform in establishment attaining 90% emergence at sixteen (16) days after sowing and also uniform in development at all growth stages. Contrary to zero tillage, under the dry onset, conventional tillage had a low stand density and took longer to attain standard establishment and this non-uniformity persisted throughout the growing period. This complicates the management decisions guided by the development growth stage of the crop and affects crop yield (HGCA, 2016). Under conventional tillage and upon receipt of a significant rainfall event, soil surface sealing occurred resulting to soil capping and resultant effect of hindering seed emergence (Plate 4.1(a)) contrast zero tillage (Plate 4.1(b)).

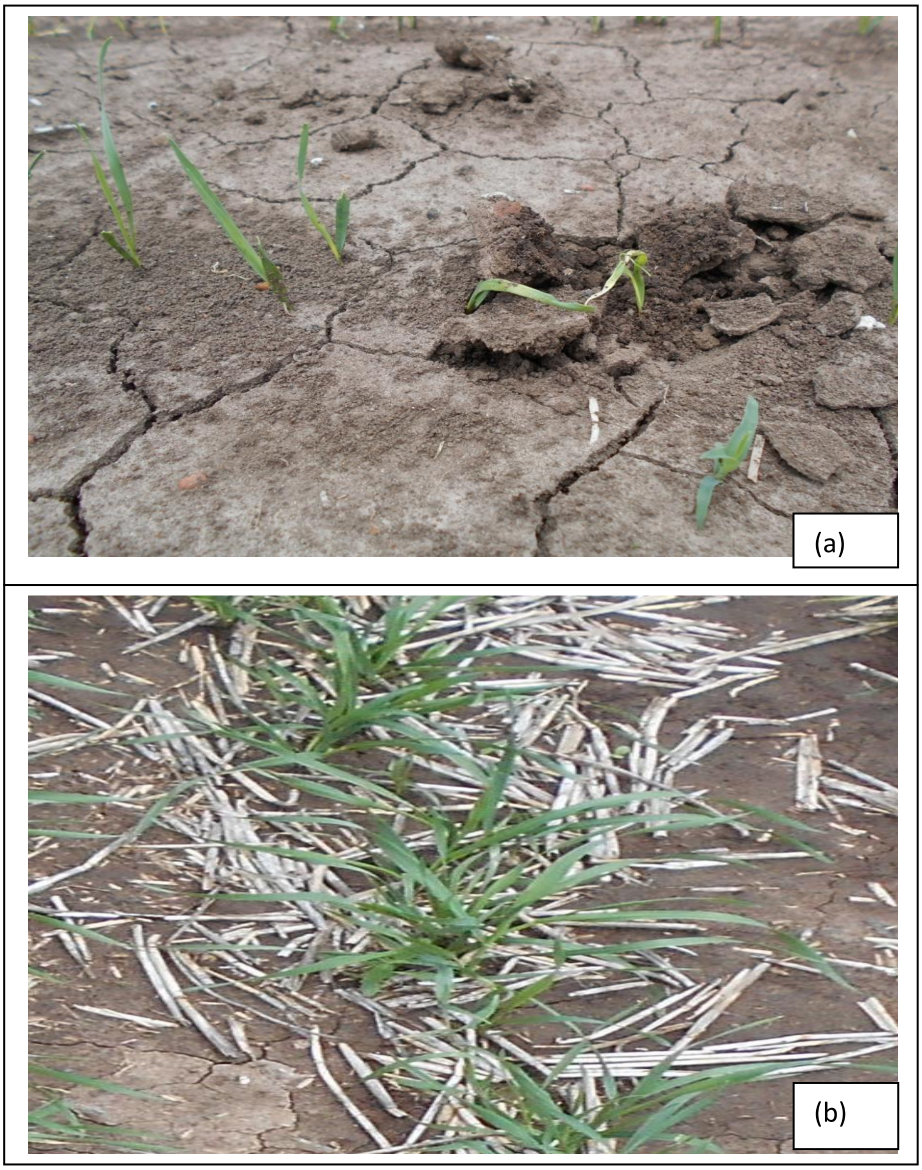

Plate 4.1: Effects of soil surface sealing (capping) hindering seed emergence in SD1 conventional tilled field (a) as compared to SD1 zero tillage (b), (Photo taken on 2nd Nov 2015) (Author, 2015).

The result of field trials indicated a significant influence on yield by tillage practice as presented in Figure 4.3, Section 4.3.1. The rain-fed wheat yield ranged between 4.20 ton/ha (under dry onset on conventional tillage) to 9.45 ton/ha (under the late onset on zero tillage).The yield results in trials under supplemental irrigation ranged between 12.92 and 13.61 ton/ha respectively for zero and conventional tillage. This variation was very significant and indicated that water is a major limiting factor in crop production considering that the crops received similar application of fertilizer. These results therefore suggest the influence of both sowing onsets and tillage practice on soil water availability to crop and subsequent effect on wheat crop yield.

For purposes of ANOVA, the results were grouped according to experimental design used (split plot design). The main block trials had one tillage practice on each split plot (zero tillage or conventional tillage) and three sowing dates, so their analysis allows for investigation of sowing dates effects only (Table 4.5 & 4.6) using ANOVA. While the two split plots had both tillage and sowing dates treatment and so their analysis allowed for both sowing dates and tillage effects to be studied (Table 4.7, Section 4.3.2) using the student T-test.

4.3.1 Crop Yield Response to Sowing Date Occurrence

Undertaking ANOVA on the difference between and within means in zero tillage under varying sowing dates indicated significant difference ($P<0.05$) only when compared with irrigated trials. Under rain-fed trials the variation is not significant (Table 4.5). A similar analysis on the conventional tillage indicated a strong variation between means and thus very significant effect of sowing dates on grain yield (Table 4.6). The data was summarized and presented as a box plot (Figure 4.3).

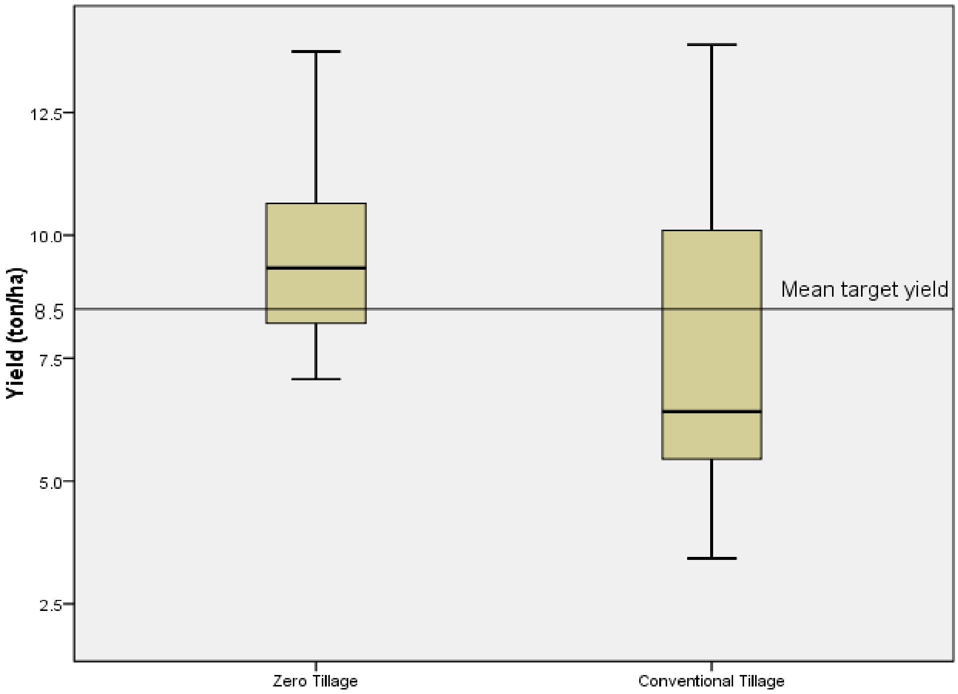

Figure 4.3: Effect of sowing date on wheat crop grain yield for zero tillage and conventional tillage practices.

The zero tillage box-plot was comparatively short. The minimum and maximum observed grain yield in zero tillage was 7.07 ton/ha and 13.74 ton/ha respectively. This indicates that the grain yield from zero tillage had high level of agreement with each other irrespective of the different sowing dates. On the other hand, the conventional tillage box-plot was comparatively long. The minimum and maximum observed grain yield in conventional tillage was 3.42 ton/ha and 13.88 ton/ha respectively. This indicates that the grain yield from conventional tillage had quite varied results subject to the different sowing dates which is essentially related to soil water content.

The zero tillage box-plot was higher with the median at 9.34 ton/ha as compared to 6.41 ton/ha in conventional tillage box-plot. This suggests variation between the two tillage practices. The first three sections of the zero tillage box-plot (reading from the bottom) are relatively even in size while the fourth is widely uneven. This shows that yield from the three sections was almost the same while those in the last section (top of the box-plot) were highly varied. The difference is attributed to the results of irrigated treatments (WTSD2-ZT) as is also the case in (WTSD2-CT). From the same plot, under zero tillage, the grain yield was evenly distributed about the median value, while in conventional tillage; the degree of spread was high and skewed to the upper quartile above the median value. Overall, the mean yields of zero tillage (9.75 ton/ha) were higher than those of conventional tillage (7.68 ton/ha). In conventional tillage, the sowing dates had significant effect on yield ($p<0.05$) and thus the observed high spread of the data with a relatively low median.

To get the proportional increase or decrease in yield as affected by sowing onsets, it was assumed that the observed results under the normal onset (SD2) were the attainable yield under rain-fed condition for zero tillage and conventional tillage. These are 8.41 ton/ha and 6.68 ton/ha respectively which was different by 20.6%. For zero tillage SD1 yielded lower grain yield by 2.4% while SD3 was higher by 12.4% from the normal onset SD2. For conventional tillage any shift from the normal onset resulted in a decrease in yield of 37.1% and 6.7% for SD1 and SD3 respectively (Figure 4.4, Section 4.3.3).

Further analysis of the sowing dates effect within tillage treatments are presented in Table 4.5 for zero tillage split plot and Table 4.6 for conventional tillage split plot.

Table 4.5: Onset dates effects on yield under zero tillage

(I) SOWING ZERO	(J) SOWING ZERO	Mean Difference (I-J)	Std. Error	Sig.
SD1-ZERO-1	2	-.203	.83	1.000
	3	-1.24	.83	.611
	4	-4.71*	.83	.003
SD2-ZERO-2	1	.203	.83	1.000
	3	-1.04	.83	.757
	4	-4.50*	.83	.003
SD3-ZERO-3	1	1.24	.83	.611
	2	1.04	.83	.757
	4	-3.47*	.83	.017
WTSD2-ZERO-4	1	4.71*	.83	.003
	2	4.50*	.83	.003
	3	3.47*	.83	.017

*. The mean difference is significant at the 0.05 level.

Table 4.6: Onset dates effects on yield under conventional tillage

(I) SOWING CONV	(J) SOWING CONV	Mean Difference (I-J)	Std. Error	Sig.
SD1-CONV-5	6	-2.48*	.40	.001
	7	-2.03*	.40	.005
	8	-9.41*	.40	.000
SD2-CONV-6	5	2.48*	.40	.001
	7	.46	.40	.821
	8	-6.93*	.40	.000
SD3-CONV-7	5	2.03*	.40	.005
	6	-.46	.40	.821
	8	-7.38*	.40	.000
WTSD2-CONV-8	5	9.41*	.40	.000
	6	6.93*	.40	.000
	7	7.38*	.40	.000

*. The mean difference is significant at the 0.05 level.

The sowing dates onsets had more significant effect and variation on wheat crop grain yield under conventional tillage as compared to zero tillage. The total mean yield for rain-fed wheat crop was 5.70±1.08 ton/ha and 8.69±0.54 ton/ha for conventional tillage and zero tillage respectively for the three sowing dates selected (Table 4.7, Section 4.3.2).

4.3.2 Crop Yield Response to Tillage Practices

Since only two tillage treatments were used, independent T-test analysis for equality of means was carried out for the same sowing date occurrence but under different tillage practice and results presented in Table 4.7. These results indicated that at $p<0.05$, tillage practices affected wheat crop grain yield. The effect was strong for both the early-dry (SD1) and late-wet (SD3) season. However, for the normal (SD2) and the water treatment (WTSD2) under normal season onset the difference was not significant.

The result showed a decreasing yield in conventional tillage towards the dry season, while yield increase for all sowing dates under zero tillage was noted. As was noted in analysis of soil water content (section 4.2) which was statistically significant at $p<0.05$, similarly the yield was affected. This significant variation indicates that in conventional tillage under the early and late onset, the soil water was not sufficient for crop production. During the late onset, the growing season was shortened while in the early onset, the crop establishment and stand density was reduced and thus the low yields.

A similar analysis as in section 4.3.1 was performed to estimate the percent increase or decrease in yield due to tillage effect. SD1, SD2 and SD3 produced higher yields in zero tillage by 48.9%, 20.6% and 34.1% respectively compared to conventional tillage, while in water regime treatments under normal onset date (WTSD2) conventional tillage yielded higher by 5.4%. This indicate that, zero tillage is able to conserve soil water to support crop growth and reduce the effect of shortening the growing period due to water stress late in the growing season. This confirms the potential of zero tillage in soil water conservation compared to conventional tillage.

Table 4.7: Effect of tillage practice on wheat crop grain yield

	Independent variables Mean Yield ton/ha		Levene's Test for Equality of Variance		T-Test for Equality of means		
Onset date	ZT	CT	F	Sig.	T	$LSD_{0.05}$	St.dev
SD1	8.21	4.196	1.30	0.32	8.50	0.001	2.84
SD2	8.41	6.681	3.08	0.15	1.98	0.118	1.23
SD3	9.45	6.226	0.12	0.75	18.62	0.000	2.28
WTSD2	12.92	13.607	6.35	0.07	-0.83	0.453	2.12
Mean	9.75 (8.69)	7.68 (5.70)	**KEY** CT-conventional tillage				
St.dev	1.95 (0.54)	3.66 (1.08)	ZT-zero tillage SD1,2,3-Sowing dates one, two & three respectively WTSD2 –water regime treatment ( )-mean yield and standard deviation under rain-fed condition				

The tillage effect had strong significant effect and variation on wheat crop grain yield under the SD1 and SD3 for rain-fed wheat crop indicating a high standard deviation of 2.84 and 2.28 respectively compared to 1.23 under the normal onset SD2 (Table 4.7).

4.3.3 Crop Response to Combined Effect of Sowing Dates and Tillage Practices

It was observed that significant interaction between sowing time and tillage resulted in greater grain yield obtained from zero tillage than in conventional tillage. The observed wheat crop grain yield was between 4 ton/ha and 13 ton/ha depending on the treatment. Conventional tillage gave the least yield of 4 ton/ha for the dry onsets (SD1) under rain-fed condition while the late onset in zero tillage gave the highest yields of 9.45 ton/ha under rain-fed condition. This value is higher than the National plant breeders rated yield target 8.5 ton/ha for this variety. However, under conventional tillage, irrespective of sowing dates used the yield was within the rated target yield of the variety. Thus the high yield under zero tillage above the target yield was attributed to the effect of tillage practice on yield and accounts to 11.2% increase in wheat crop yield. Figure 4.4 present the summary of mean wheat grain yield response to sowing dates and tillage practices for all the trials.

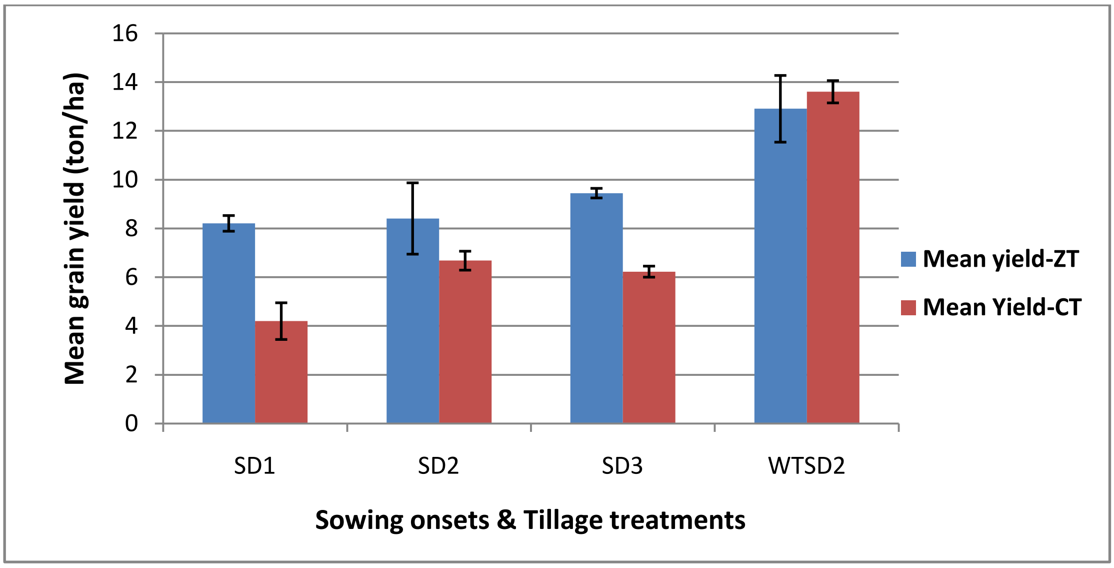

Figure 4.4: Observed mean wheat grain yield response to sowing dates and tillage practices. The error bars shows standard deviation.

Considering that the target yield for this variety is 8.5 ton/ha and assuming that it is attainable under optimal non-limiting conditions of soil quality, fertility, crop management and climatic condition, it was used as the base for computing the percentage difference in wheat crop grain yield in this area under early sowing, normal sowing or late sowing. This variation is representative of the soil water availability to the crop at planting to germinate the seeds and to meet the crop water requirement during the entire length of the growing season.

Under zero tillage the early onset synonymous to dry sowing resulted to a loss of 3.41% in grain yield, 1.01% for the normal onset and an increase in yield of 11.17% for the delayed or late onset. Comparatively under conventional tillage the losses were 50.64% for SD1, 21.4% for normal SD2 and a loss of 26.75% for the late SD3. Assuming all the other factors of production constant and optimal apart from soil water, under conventional tillage, in all the sowing dates, the soil moisture did not meet the crop water requirements thus suffered water stress which resulted to the respective crop yield losses relative to the target yield. However, in zero tillage the losses were lower because zero tillage enhances soil water conservation thus increasing the soil water availability to crop reducing water stress in the crop.

Under rain-fed condition, the late onset (SD3) in zero tillage had the best yield of 9.45 ton/ha. However, there were several observed challenges associated with this sowing timing in both tillage treatments. These include; increased pests and diseases incidences which required frequent spraying to control. The need to spray frequently was made difficult due to the stickiness of the clay soil when wet and the washing away of sprayed chemicals by rain.

The overall observation was that SD3 produced more because the trial plots were manageable and micro-managed. This results to increased cost of production or otherwise negative effect (reduction) on crop yield for an average farmer. Management and control of pests and diseases in the SD1 and SD2 was not significantly affected by weather while the incidences of such attacks were fewer compared to SD3.

4.4 Local Calibration of AquaCrop model

AquaCrop is a canopy-level and engineering type of model, mainly focused on simulating the attainable crop biomass and harvestable yield in response to the water available (Steduto *et al.,* 2009*).* Data for calibration was obtained from the field experimental plots under supplemental irrigation and normal season onset (WTSD2). The variables that were tuned and the resultant parameters after calibration are presented in Table 4.8.

The calibration and validation was first done on the conventional tillage section 4.4.1 and 4.4.2 and the obtained crop parameters in section 4.4.1 adopted for calibration and validation in the zero tillage (Section 4.4.3 and 4.4.4). Only the crop management file was adjusted to depict zero tillage.

Table 4.8: The crop parameters for wheat obtained after calibration

Description	Value	Unit
Initial canopy cover	1.86	%
Canopy growth coefficient (CGC)	13.7	%/day
Canopy decline coefficient (CDC)	9.5	%/day
Initial plant density	124	Plants per square meter
Canopy development		
Time from sowing to emergence	6	Days
Maximum canopy cover (CC_X)	94%	Function of plant density and variety ability to tiller
Time from sowing to start of flowering	68	Days
Time from sowing to canopy senescence	110	Days
Time from sowing to maturity	130	Days
Length of flowering stage	14	Days
Root deepening		
Maximum effective rooting depth, Z_x	1.00	Meters
Time from sowing to maximum rooting depth	75	Days
Minimum effective rooting depth, Z_n	0.30	Meters
Water stress response factor		
Crop water productivity normalized for climate and C02 (WP*)	17	g/m^2
Soil water depletion threshold for canopy expansion- Upper threshold	0.00	Fraction of TAW
Soil water depletion threshold for canopy expansion- Lower threshold	0.35	Fraction of TAW
Soil water depletion threshold for stomatal closure- Upper threshold	0.25	Fraction of TAW
Soil water depletion threshold for canopy senescence- Upper threshold	0.45	Fraction of TAW
Reference harvest index, HI_O	49%	Assumed for the hybrid variety
Building up of HI	52	Days
Crop transpiration coefficient (Kc_{Tr})	1.40	

4.4.1 AquaCrop Model Calibration in Conventional tillage

i. Green Canopy cover

Canopy cover (CC) affects the rate of transpiration and consequently biomass accumulation and therefore accurate calibration is necessary. The observed and simulated CC development fitted well with adequate statistical values (Table 4.9). However at the early stage, the model underestimated the canopy development (Figure 4.5) but overall it followed the standard logistic growth curve for AquaCrop for optimal conditions (Raes *et al.,* 2010).

In the study the observed maximum canopy cover was 94% which was attained after 51 days after sowing. The simulated canopy cover did not differ significantly from the observed (Figure 4.5). The efficiency of the model in simulating canopy cover was good at 0.92 while an R^2 of 0.95 was found to be a good correlation between the simulated and observed parameters (Figure 4.5). This shows that the performance of the model in simulating canopy cover was good. Similarly, the high value of index of agreement (d=0.98) indicated that there was good agreement between the simulated and measured canopy cover. The root mean square error (RMSE) was slightly higher at 10.4% but within acceptable limits in the model (Table 4.9).

Table 4.9: Goodness-of-fit analysis for the simulated canopy cover (CC), Soil water content (SWC), biomass (B, both final and intermediate biomass)

Crop Parameter	Statistical Indices			
	R^2	RMSE	d.	EF
Optimal Value	1.0	0.0	1.0	1.0
Canopy cover	0.95	10.4	0.98	0.92
Biomass	0.80	9.33	0.82	0.43
Soil water content	0.51	14.8	0.67	0.24

R^2: coefficient of determination; EF: Nash-Sutcliffe efficiency; d: index of agreement; RMSE: root mean square error.

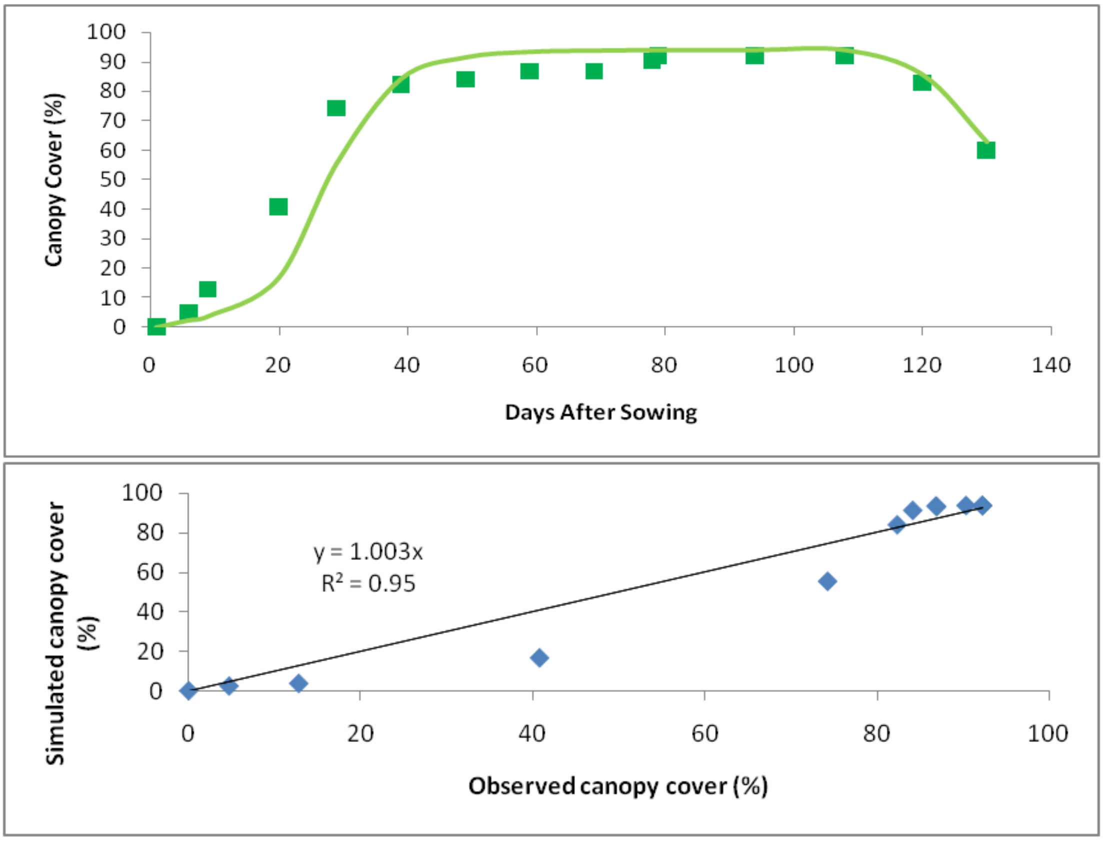

Figure 4.5: WTSD2-CT- Observed (dots) and simulated (continuous line) CC for the rain-fed wheat after calibration.

ii. Soil Water Content

Accurate simulation of soil water balance is very important, as all stress thresholds in AquaCrop are a direct function of soil water. The soil water content in the root zone was expressed as an equivalent depth (mm) throughout the growing season to a measured depth of 60 cm (Figure 4.6).

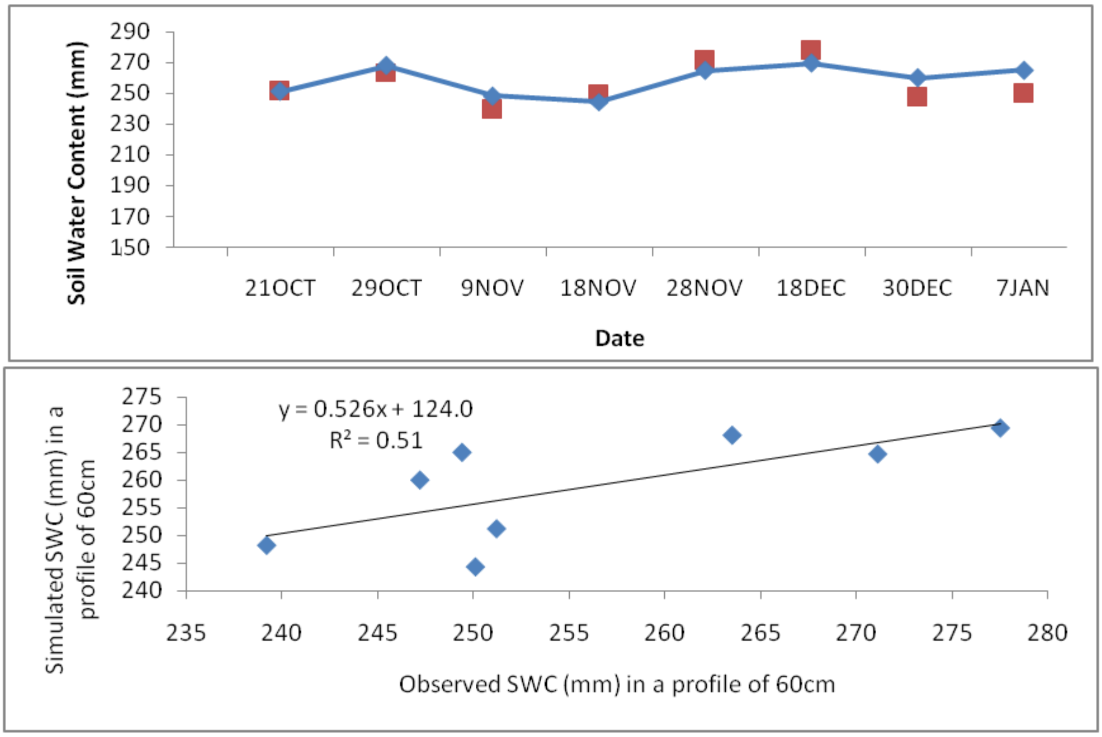

Figure 4.6: Observed (dots) and simulated (continuous line) soil water content (SWC) depth for supplemental irrigation (Control treatment-WTSD2-CT) in a profile of 60 cm.

There was an acceptable agreement between the simulated and observed moisture content as indicated by the index of agreement, d, of 0.67 although lower than that of canopy cover. The model had low efficiency simulating soil water content (EF=0.24) as is similarly indicated by a high value of RMSE of 14.3 mm. A low R^2 of 0.51 (Figure 4.6) indicated little correlation of the measured and simulated moisture content.

iii. Biomass and Yields

There was acceptable correlation between the simulated and observed biomass (R^2=0.80) although the efficiency was low (EF=0.43) with a RMSE of 9.33 ton/ha (Table 4.9). The index d of 0.82 was satisfactory and indicated acceptable agreement of simulated and observed compared to the optimal value of 1(Figure 4.7).

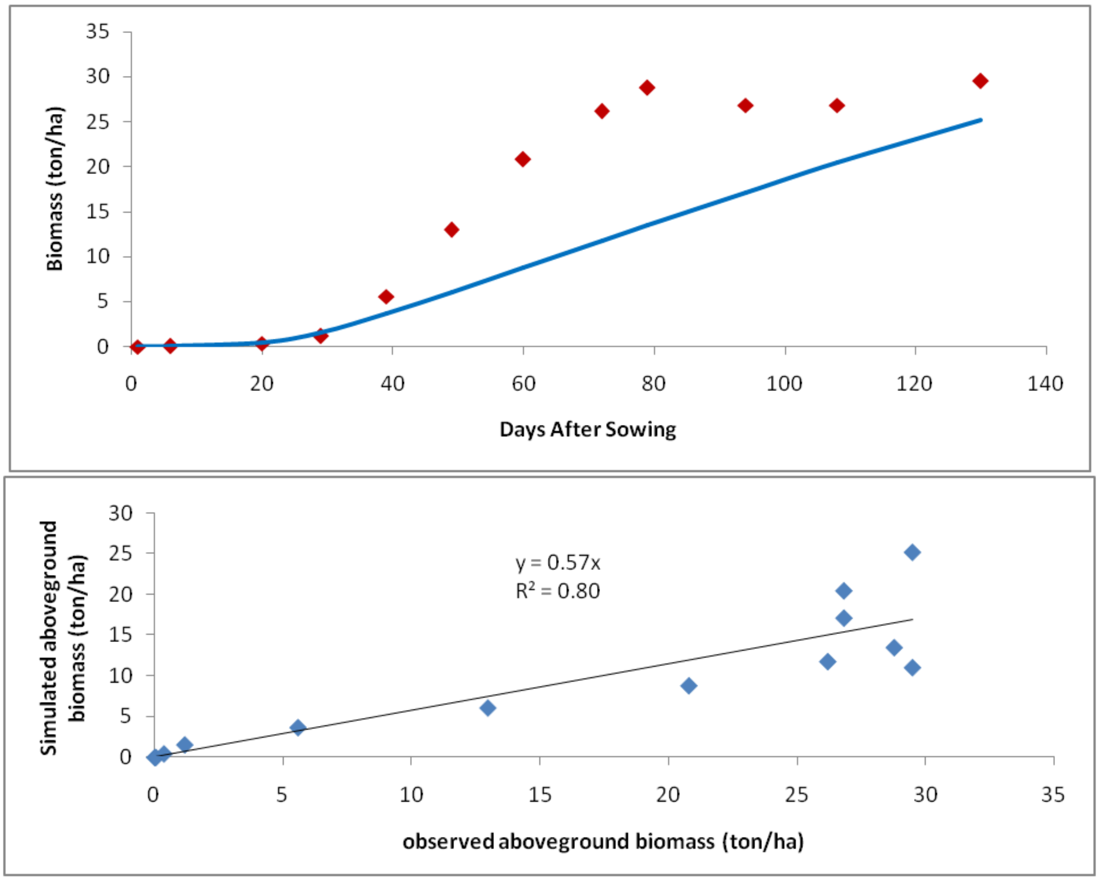

Figure 4.7: Observed (dots) and simulated (continuous line) aboveground biomass for the supplemental irrigation (control treatment-WTSD2-CT)

From the statistical analysis of the simulation results (Table 4.9), it was concluded that the main features of wheat, as affected by water stress, were well modeled by AquaCrop. R^2 for canopy and biomass was ≥ 0.80 and $d \geq 0.67$ for all the variables and the EF of 0.92 for canopy cover was significant. The relatively small RMSE confirmed the goodness of fit between the observed and simulated canopy cover results. Although the efficiency of simulation of biomass and soil moisture content was relatively low, the satisfactory simulation of canopy cover indicated that the calibration process was satisfactory, and the resulting crop model parameters were adapted. As will be seen in the discussion, the model could not simulate biomass and soil moisture accurately because of the tillering characteristic of the crop variety as illustrated in Plate 4.2 and the tillage impact on soil moisture.

Plate 4.2: Photo indicating the heavy tillering indicative of high biomass (SD2 field on 20th February 2016), (Source: Author, 2016)

The result of simulation indicated an underestimation of both the final yield and biomass of 1.27 ton/ha and 4.31 ton/ha respectively. As seen in Table 4.11; the difference in simulated biomass is high (14.6%) but the model was able to simulate yield with a variation of less than 10 percent (9.3%).

4.4.2 Validation of AquaCrop Model in Conventional Tillage

The AquaCrop model validation was done based on the comparison between simulated and observed data for all treatments in conventional tillage other than the water regime treatments that were used in model calibration (Section 4.4.1). These are calibrated crop parameters (Table 4.8, Section 4.4) and data results of the SD1-CT, SD2-CT and SD3-CT Treatments. The validation results indicated that the model simulated the crop parameters; CC, B and yield reasonably well (Figures 4.8, 4.9 & 4.10 (1(a) - 3(b)) and Table 4.10).

i. Evaluation of canopy cover in conventional tillage

The model was able to simulate CC adequately in the rain-fed conditions experiencing water stress at various stages of crop growth and development. Figure 4.8 (1(a)-3(b)) presents the validation results for CC. It was observed that with water stress the canopy cover declined. The attained maximum CC% was 80.4% (SD1), 88.9% (SD2) and 85.5% (SD3). These represent a decline of 14.4%, 5.4% and 8.7% respectively compared to that attained (94%) under conditions of no water stress (WTSD2).

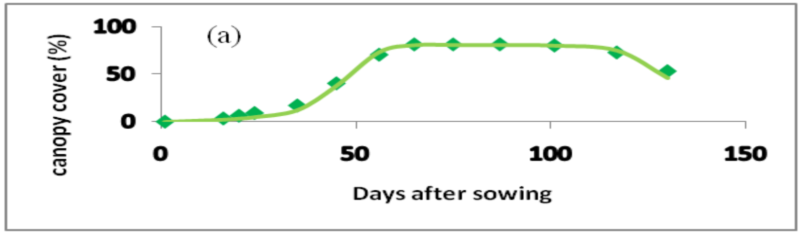

Figure 4.8 (1a): SD1-CT- Observed (dots) and simulated (continuous line) canopy cover (CC) for the rain-fed wheat after calibration.

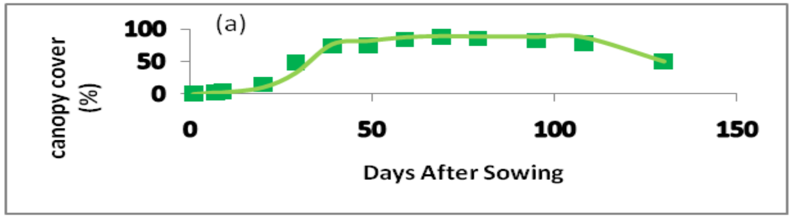

Figure 4.8 (2a): SD2-CT- Observed (dots) and simulated (continuous line) canopy cover (CC) for the rain-fed wheat after calibration.

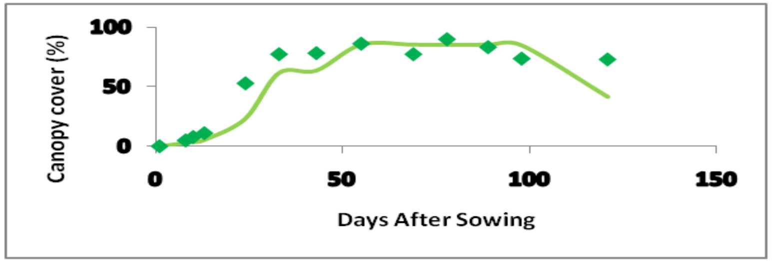

Figure 4.8 (3a): SD3-CT- Observed (dots) and simulated (continuous line) canopy cover (CC) for the rain-fed wheat after calibration.

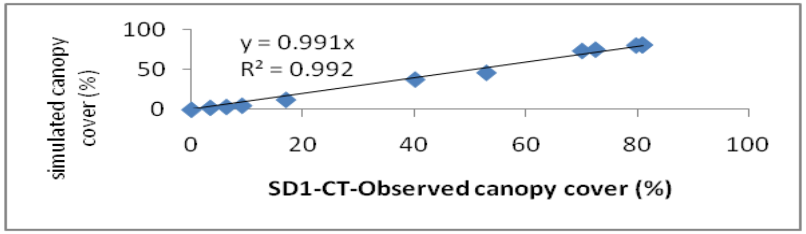

Figure 4.8 (1b): SD1-CT- Simulated versus Observed canopy cover (CC) for the rain-fed wheat after calibration.

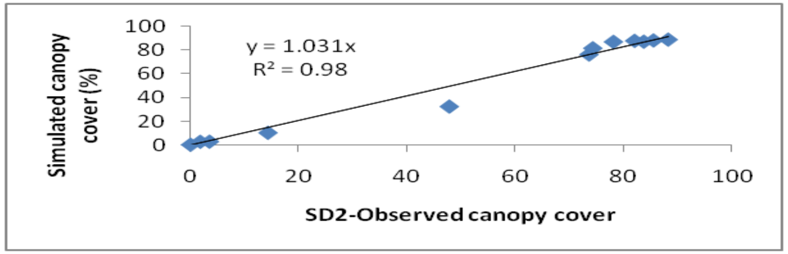

Figure 4.8 (2b): SD2-CT- Simulated versus Observed canopy cover (CC) for the rain-fed wheat after calibration.

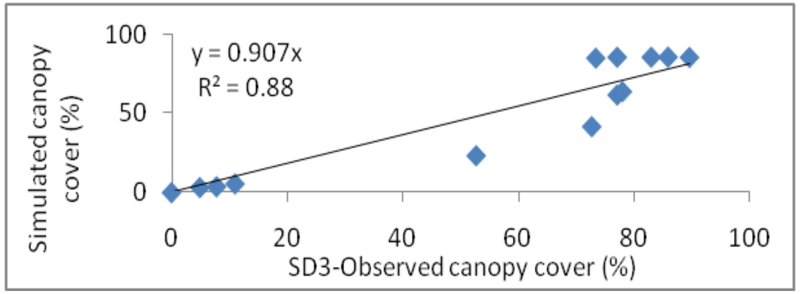

Figure 4.8 (3b): SD3-CT- Simulated versus Observed canopy cover (CC) for the rain-fed wheat after calibration.

ii. Evaluation of soil water content in conventional tillage

The results of validation are presented in Figure 4.9 (1(a)-3(b) and Table 4.10. The comparison between the observed and simulated soil water content in a profile of 60 cm was satisfactory for SD3 the efficiency was low for SD2 and SD1. Basing the assessment on the index of agreement (d) which was 0.77, 0.72 and 0.92 respectively for SD1, SD2, and SD3, the simulation was acceptable. Similarly the RMSE was 18.7 mm, 23.3 and 12.7 respectively which was within reasonable range considering that the field management file in AquaCrop could not sufficiently represent the management practices affecting soil water movement and retention fully e.g. surface crusting which affect the amount of water infiltrating. Overall the water stress affecting yield was satisfactory simulated.

iii. Evaluation of biomass in conventional tillage

An overview of the validation results of biomass for the rain-fed condition is given in Figure 4.10 (1(a)-(3(b)). Although the model underestimated B for the water regime treatment (section 4.5) the simulation under rain-fed condition (SD1, SD2 and SD3) was satisfactory (R^2 of 0.87, 0.92 & 0.96 respectively and EF$\geq$0.82). Under water stress, biomass decline and tillering is also affected negatively and therefore this is a possible explanation to better simulation under rain-fed condition.

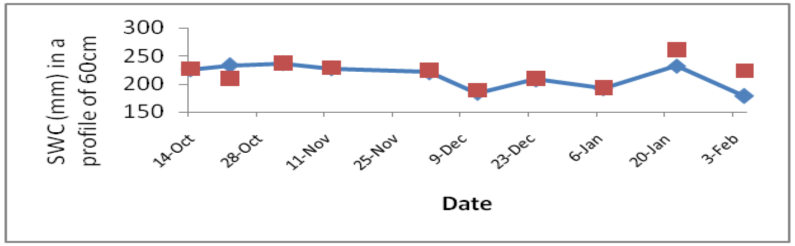

Figure 4.9 (1a): SD1-CT- Observed (dots) and simulated (continuous line) soil water content (mm) depth in a profile of 60cm for rain-fed wheat.

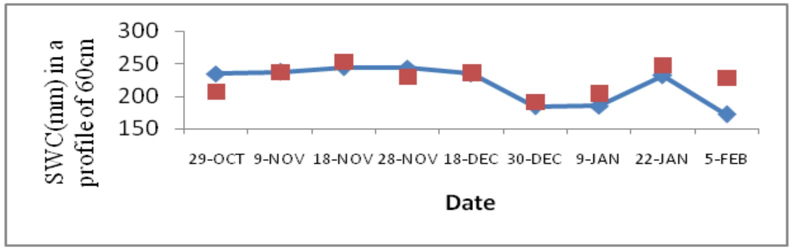

Figure 4.9 (2a): SD2-CT- Observed (dots) and simulated (continuous line) soil water content (mm) depth in a profile of 60cmfor rain-fed wheat.

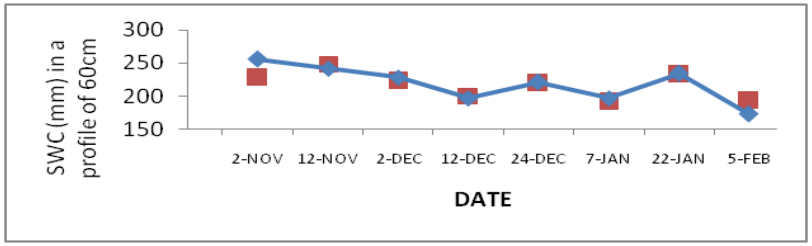

Figure 4.9 (3a): SD3-CT- Observed (dots) and simulated (continuous line) soil water content (mm) depth in a profile of 60cm rain-fed wheat.

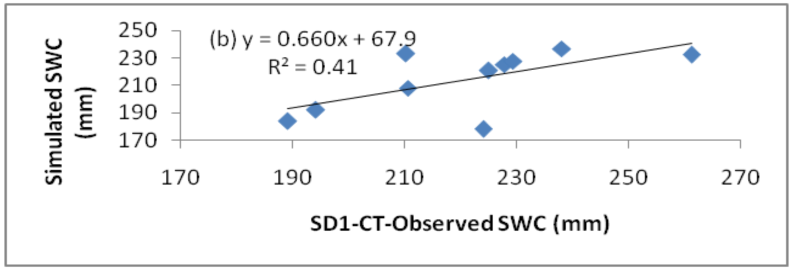

Figure 4.9 (1b): SD1-CT- Simulated versus Observed soil water content (SWC) in (mm) for the rain-fed wheat after calibration.

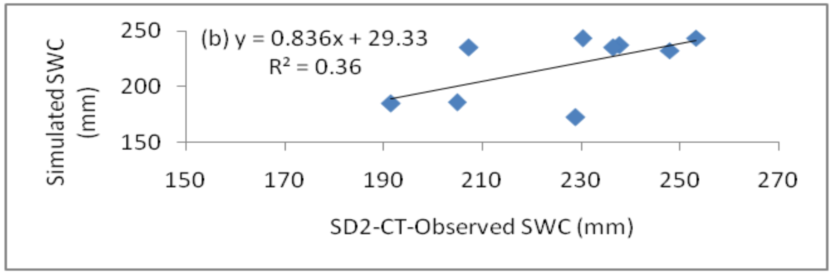

Figure 4.9 (2b): SD2-CT- Simulated versus Observed soil water content (SWC) in (mm) for the rain-fed wheat after calibration.

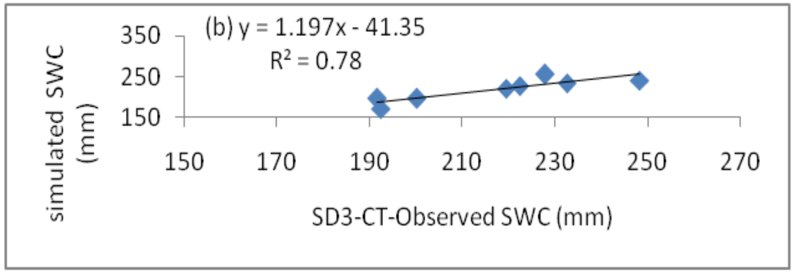

Figure 4.9 (3b): SD3-CT- Simulated versus Observed soil water content (SWC) in (mm) for the rain-fed wheat after calibration.

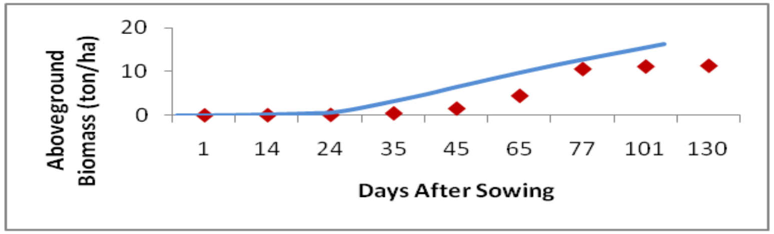

Figure 4.10 (1a): SD1-CT- Observed (dots) and simulated (continuous line) aboveground biomass (ton/ha) for rain-fed wheat after calibration.

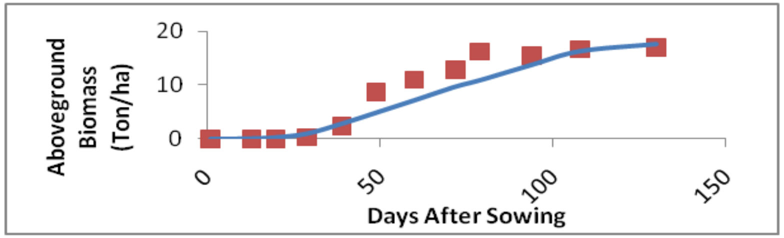

Figure 4.10 (2a): SD2-CT- Observed (dots) and simulated (continuous line) aboveground biomass (ton/ha) for rain-fed wheat after calibration.

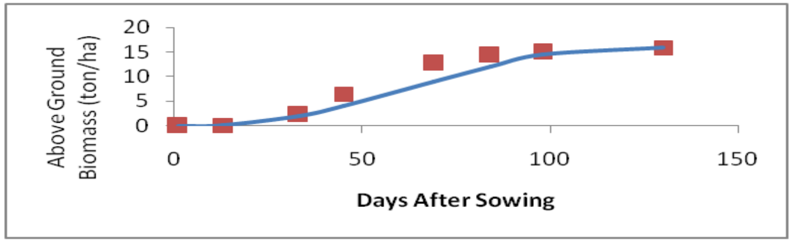

Figure 4.10 (3a): SD3-CT- Observed (dots) and simulated (continuous line) aboveground biomass (ton/ha) for rain-fed wheat after calibration.

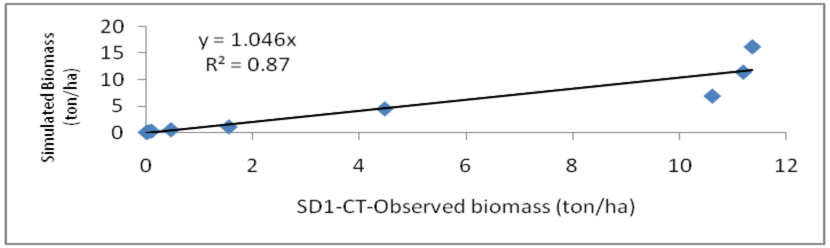

Figure 4.10 (1b): SD1-CT- Simulated versus Observed biomass (B) in ton/ha for rain-fed wheat after calibration.

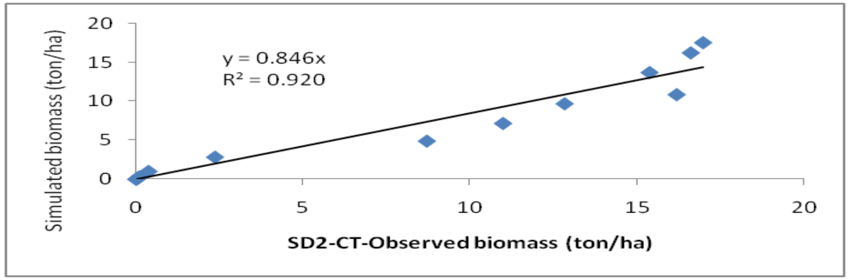

Figure 4.10 (2b): SD2-CT- Simulated versus Observed biomass (B) in ton/ha for the rain-fed wheat after calibration.

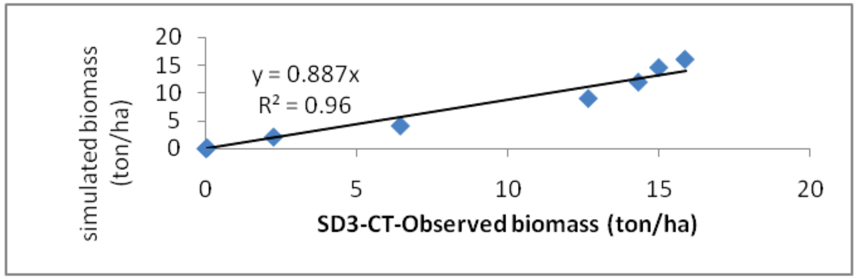

Figure 4.10 (3b): SD3-CT- Simulated versus Observed biomass (B) in ton/ha for the rain-fed wheat after calibration.

iv. Evaluation of final yield and final biomass in conventional tillage

Figure 4.11 indicate satisfactory simulation of grain yield using the calibrated AquaCrop model with a good correlation coefficient of 0.83.

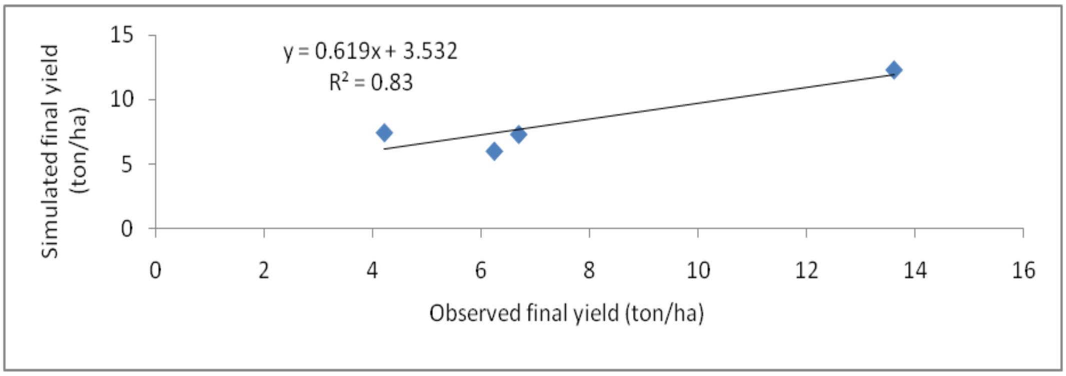

Figure 4.11: Simulated versus Observed final grain yield after calibration

Table 4.10: Summary of the Goodness-of-fit analysis for the simulated soil water content (SWC), canopy cover (CC), biomass (B, both final and intermediate biomass) in conventional tillage

Sowing treatment	Parameter	R^2	EF	d	RMSE
	Optimum value	1.0	1.0	1.0	0
SD1-CT	CC	0.995	0.91	0.98	9.0%
	SWC	0.41	0.12	0.77	18.7 mm
	B	0.87	0.82	0.96	2.06 ton/ha
SD2-CT	CC	0.98	0.97	0.99	6.0%
	SWC	0.36	-0.40	0.72	23.3 mm
	B	0.92	0.87	0.96	2.47 ton/ha
SD3-CT	CC	0.88	0.83	0.96	14.0%
	SWC	0.79	0.56	0.92	12.7 mm
	B	0.96	0.93	0.98	1.76 ton/ha
Grain Yield-CT	Y	0.83	0.78	-0.08	1.22 ton/ha

The results of final biomass and yield simulation (Table 4.11) indicated models ability to simulated wheat crop yield under rain-fed conditions and varied sowing treatment in conventionally tilled field.

Table 4.11: Final yield and final aboveground biomass (ton/ha) both observed and simulated using the calibrated model (Section 4.4) under conventional tillage and also showing the percent difference.

Sowing treatment	Simulated Yield (ton/ha)	Observed yield (ton/ha)	Percent difference (%)	Simulated Final Biomass (ton/ha)	Observed Final Biomass (to/ha)	Percent difference (%)	WP($_{ET}$) Kg/m^3
WTSD2	12.34	13.61	<9.3	25.18	29.49	<14.6	1.94
SD1	7.46	4.20	>77.5	16.25	11.36	<43.0	1.53
SD2	7.33	6.68	>7.7	17.57	15.98	<10.0	1.54
SD3	6.02	6.23	<3.4	16.02	15.87	<0.97	1.36

Further, Table 4.11 represents ET water productivity both for water regime control treatment and rain-fed trials. In rain-fed trials under conventional tillage, the normal onset (SD2) had the best ET water productivity (1.54). Any shift from the normal onset resulted to a decrease in water productivity, i.e. 1.53 and 1.36 for SD1 and SD3 respectively. However, under the WTSD2 the value is slightly higher (1.94). This is consistent with the observed yields under water regime trials in conventional tillage.

4.4.3 AquaCrop Model Calibration in Zero Tillage

As earlier mentioned in section 4.4.1, the crop characteristic file obtained after the calibration in conventional tillage (Table 4.8) was adopted for zero tillage. This is taking into consideration that the control treatments had no water stress and therefore crop growth and development had no significant difference. Additionally, a similar wheat variety was used and therefore the cultivar specific parameters were not affected by tillage in a no water stress condition. The crop management file was adjusted by turning off runoff, including 30% mulch from organic plant materials (reduced evaporation by 15%) and soil bunds of 0.10 m. These parameters were tuned through trial and error until a representative result of the condition in the zero tillage was obtained.

Soil bunds were considered to represent the improved soil water retention under zero tillage which was not experimented in the study. Similarly, during rainfall there was little runoff as compared to the observed high runoff on the conventional tillage. With this adjustment the model was calibrated adequately for canopy cover, biomass and final grain yield. However, the soil water content was poorly simulated with no correlation between the simulated and the observed.

i. Canopy cover

Figure 4.12 below represents the simulation of CC under optimal condition (WTSD2-ZT) after calibration. The observed and simulated CC development fitted well with adequate statistical values (Table 4.12). The curves also followed the logistic growth curve of AquaCrop. As seen in Figure 4.12, the observed canopy cover had a very fast increase then stabilizing immediately after. However from the simulated CC, the canopy development is distributed but agreeing well with observed at mid and late stage. Irrespective of this missed fast growth by the model in the initial and development stage, the simulated and observed CC values did not differ significantly ($d=0.92$, $R^2=0.74$).

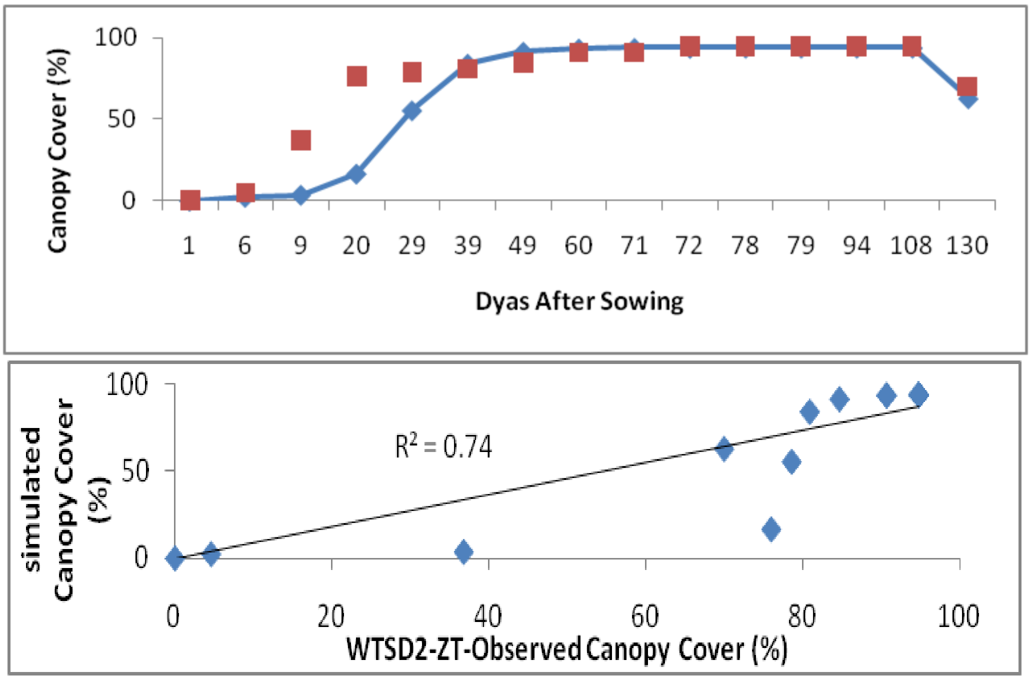

Figure 4.12: WTSD2-ZT- Observed (dots) and simulated (continuous line) canopy cover (CC) for the rain-fed wheat after calibration

ii. Soil water content

The soil water content at the root zone was expressed in equivalent depth in a profile of 60cm throughout the growing season (Figure 4.13). The model failed in simulating soil water content in zero tillage underestimating the soil water content in most cases. As indicated by the statistical performance indices, the simulated SWC neither agree nor correlated (Figure 4.13) with observed values (Table 4.12). Although the R^2 (0.13) and d (-1.76) were very low, the efficiency was above average indicating the models consistency in simulating SWC. Similarly the RMSE (14.2 mm) is low and indicate the little variation between respective data points of both observed and simulated but consistent in all measurements (Figure 4.13).

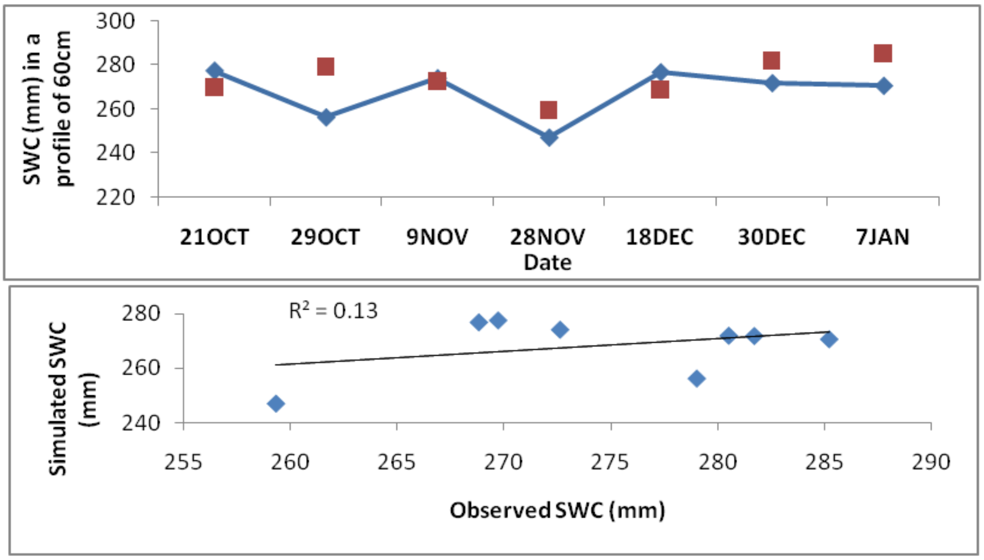

Figure 4.13: Observed (dots) and simulated (continuous line) soil water content (SWC) depth for supplemental irrigation (Control treatment-WTSD2-ZT) in a profile of 60cm.

iii. Aboveground biomass

In the simulation of biomass, the scenario was similar to that of CC with the model failing to simulate the rapid increase in B at the early stage (during tillering and elongation) but rather distributed over the growth season (Figure 4.14). Although there is rapid growth during tillering and development which the model missed, the overall result of B simulation was adequate (R^2=0.81, d=0.83) but with below average efficiency (EF=0.41), (Table.4.12). This wheat variety had a propensity to be vegetative at the initial and development stage which is characteristic of the optimal conditions of SWC, fertilizer and adequate spacing (30 cm between rows) used for dry area.

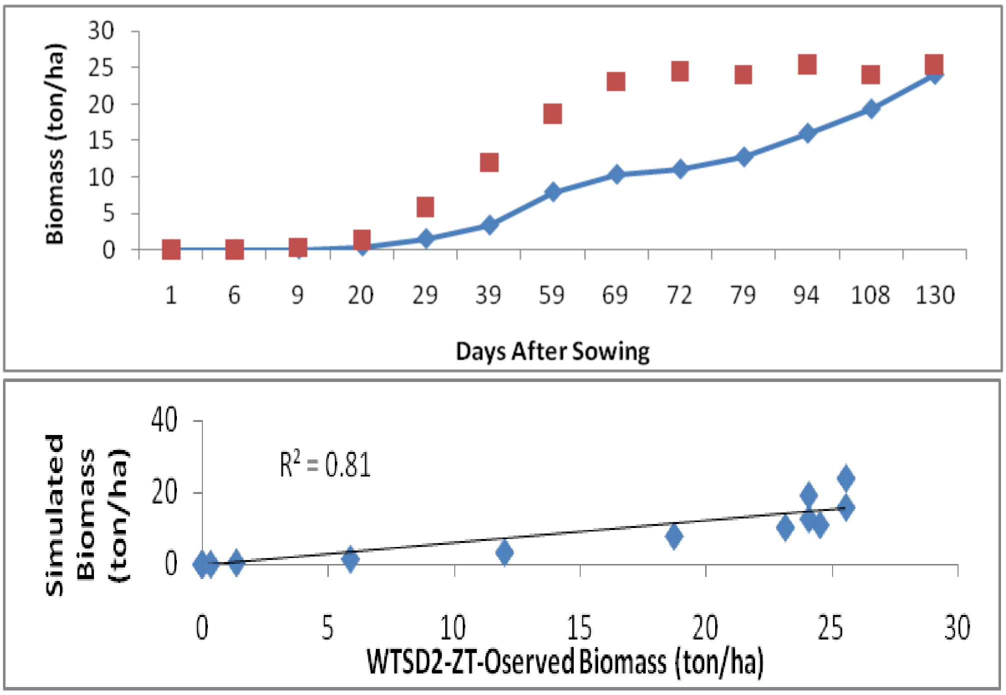

Figure 4.14: Observed (dots) and simulated (continuous line) aboveground biomass for the supplemental irrigation (control treatment-WTSD2-ZT)

Table 4.12: Summary of Goodness-of-fit analysis for the simulated canopy cover (CC), Soil water content (SWC), biomass (B, both final and intermediate biomass) after calibration in zero tillage

Crop Parameter	**Statistical Indices**			
	R^2	**RMSE**	**d**	**EF**
Optimal Value	1.0	0.0	1.0	1.0
Canopy cover	0.74	18.8%	0.92	0.64
Biomass	0.81	8.13 ton/ha	0.83	0.41
Soil water content	0.13	14.2mm	-1.76	0.52

R^2: coefficient of determination; EF: Nash-Sutcliffe efficiency; d: index of agreement; RMSE: root mean square error.

4.4.4 Validation of AquaCrop Model in Zero Tillage

The calibrated model was assessed for its performance in simulating CC, B and SWC under rain-fed condition and the various sowing dates representative of the early, normal and the late. Despite the poor performance and calibration of SWC, better model performance results were obtained than those of calibration (Table 4.13). This indicates that in zero tillage the model did not adequately simulate conditions with high soil moisture.

i. Evaluation of canopy cover in zero tillage

The results of validation of CC in zero tillage are presented in Table 4.13 and Figure 4.15. The model was able to simulate CC adequately in the rain-fed conditions experiencing water stress at various stages of crop growth and development. Figure 4.15 (1(a))-4.15 (3(b)) presents the validation results for CC which indicate a decline in CC when faced with water stresses. The attained maximum CC% was 88.7% (SD1), 92.1% (SD2) and 92.1% (SD3). These values were higher by 8.3%, 3.2% and 6.6% respectively from those observed in conventional tillage. These represent a decline of 5.6%, 2.02% and 2.02% respectively compared to that attained (94%) under optimal condition (WTSD2). These values are closer to the optimal and therefore indicate the reduced water stress in zero tillage.

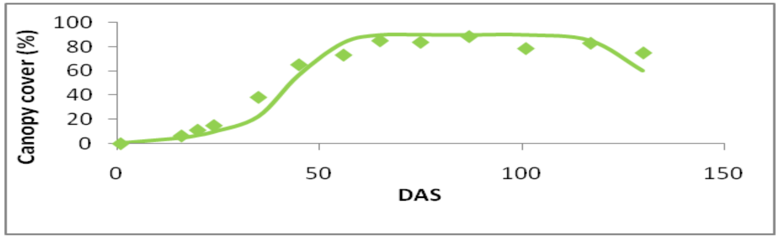

Figure 4.15 (1a): SD1-ZT- Observed (dots) and simulated (continuous line) canopy cover (CC) for the rain-fed wheat after calibration

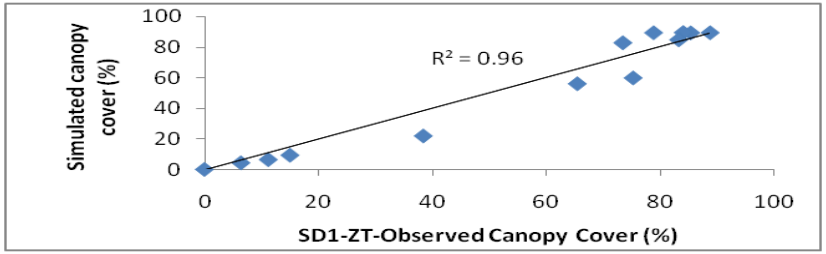

Figure 4.15 (1b): SD1-ZT- Simulated versus Observed canopy cover (CC) for the rain-fed wheat after calibration

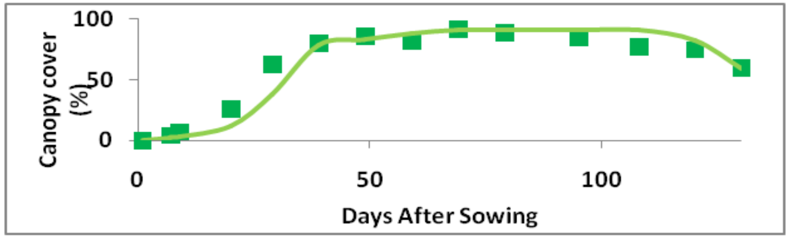

Figure 4.15 (2a): SD2-ZT- Observed (dots) and simulated (continuous line) canopy cover (CC) for the rain-fed wheat after calibration

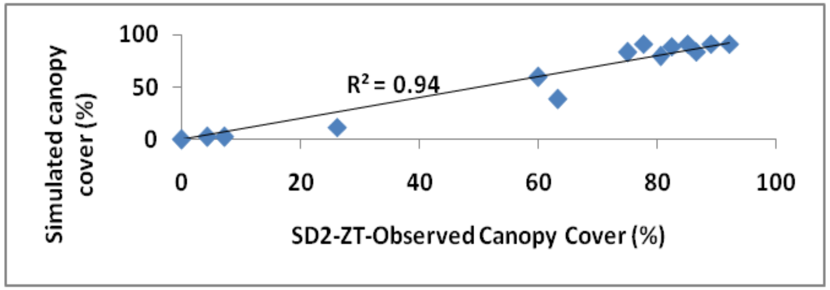

Figure 4.15 (2b): SD2-ZT- Simulated versus Observed canopy cover (CC) for the rain-fed wheat after calibration

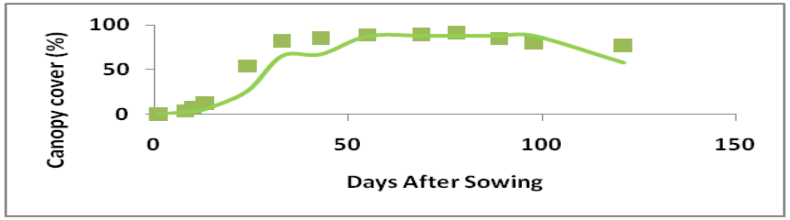

Figure 4.15 (3a): SD3-ZT- Observed (dots) and simulated (continuous line) canopy cover (CC) for the rain-fed wheat after calibration

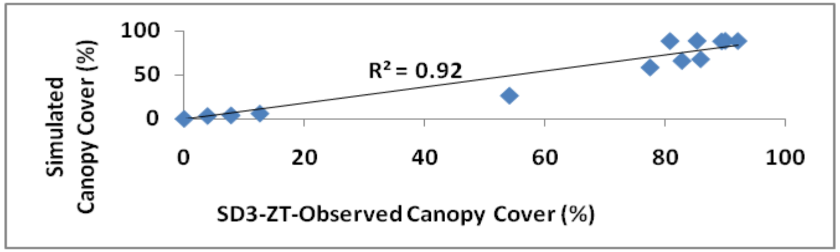

Figure 4.15 (3b): SD3-ZT- Simulated versus Observed canopy cover (CC) for the rain-fed wheat after calibration

ii. Evaluation of soil water content in zero tillage

The results of validation are presented in Table 4.13 and illustrated graphically in Figures 4.16 (1(a))-4.16(3(b)). The comparison between the observed and simulated soil water content in a profile of 60cm was not satisfactory although better than those obtained during calibration in zero tillage. The efficiency of simulating SWC was low (<0) for all sowing treatments with very high RMSE (>40 mm). This indicate that the observed soil water content better describe the soil water condition in the field as compared to simulated soil water content. Although the index of agreement (d) and R^2 were at or above average, overall the model failed in simulating soil water content in zero tillage. A similar scenario was experienced while simulating soil water content in conventional tillage affected by surface sealing (crusting).

iii. Evaluation of aboveground biomass in zero tillage

The result of validation of B was satisfactory as presented in Figures 4.17 and Table 4.13. A similar scenario (underestimation of biomass at the development stage) as that experienced in calibration (under optimal conditions Section 4.4.3, Figure 4.14) was observed although not as pronounced as was in calibration. At the mid and late stage the model recover this problem and overall adequate simulation in rain-fed condition (R2>0.85and d>0.88) Table 4.13.

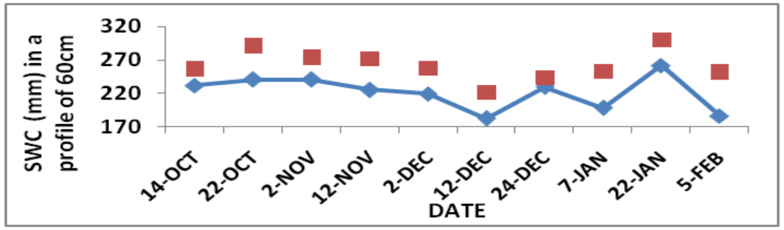

Figure 4.16 (1a): SD1-ZT- Observed (dots) and simulated (continuous line) soil water content (mm) depth in a profile of 60cm for rain-fed wheat.

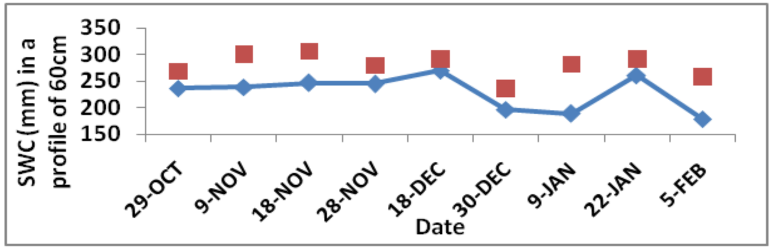

Figure 4.16 (2a): SD2-ZT- Observed (dots) and simulated (continuous line) soil water content (mm) depth in a profile of 60cm for rain-fed wheat

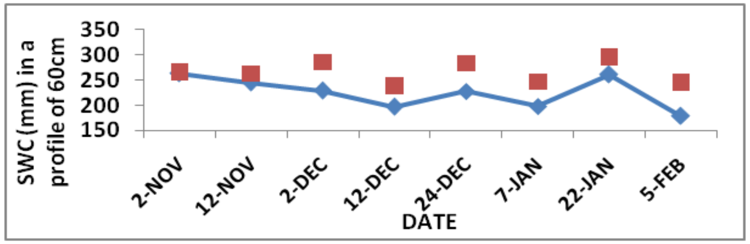

Figure 4.16 (3a): SD3-ZT-Observed (dots) and simulated (continuous line) soil water content (mm) depth in a profile of 60cm rain-fed wheat.

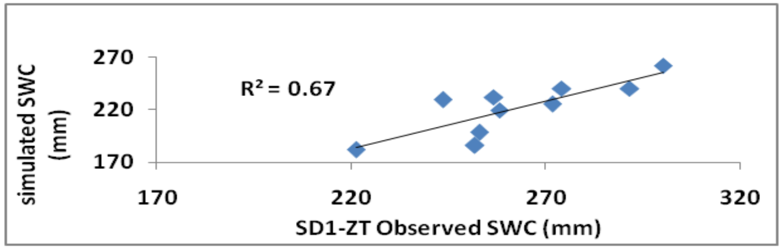

Figure 4.16 (1b): SD1-ZT- Simulated versus Observed soil water content (SWC) in (mm) for the rain-fed wheat after calibration

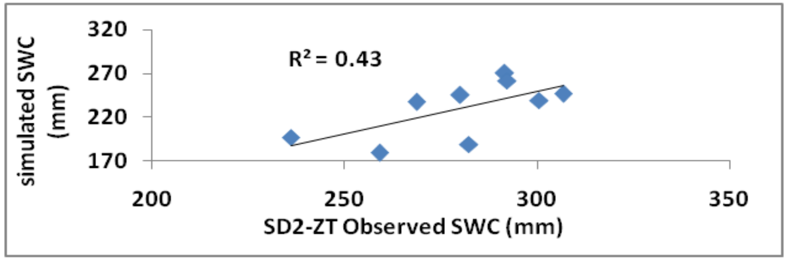

Figure 4.16 (2b): SD2-ZT- Simulated versus Observed soil water content (SWC) in (mm) for the rain-fed wheat after calibration.

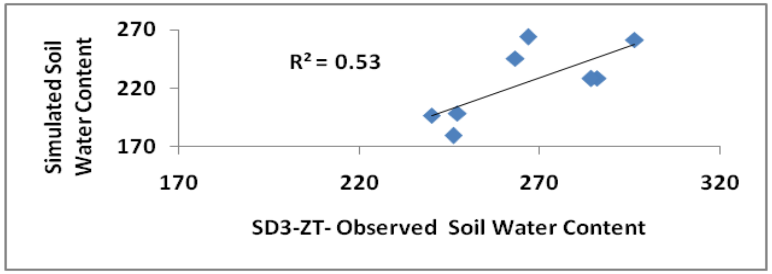

Figure 4.16 (3b): SD3-ZT- Simulated versus Observed soil water content (SWC) in (mm) for the rain-fed wheat after calibration.

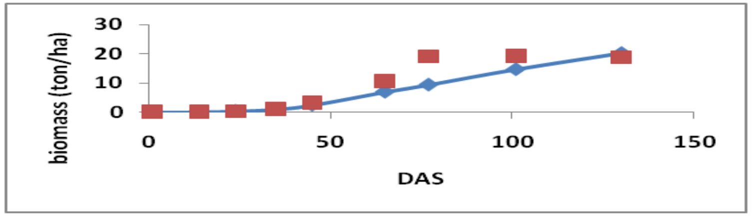

Figure 4.17 (1a): SD1-ZT- Observed (dots) and simulated (continuous line) aboveground biomass (ton/ha) for rain-fed wheat after calibration

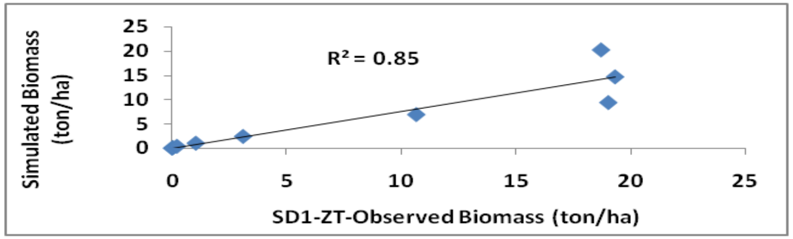

Figure 4.17 (1b): SD1-ZT- Simulated versus Observed biomass (B) in ton/ha for rain-fed wheat after calibration

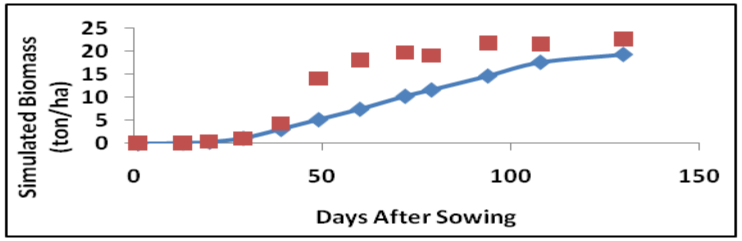

Figure 4.17 (2a): SD2-ZT- Observed (dots) and simulated (continuous line) aboveground biomass (ton/ha) for rain-fed wheat after calibration

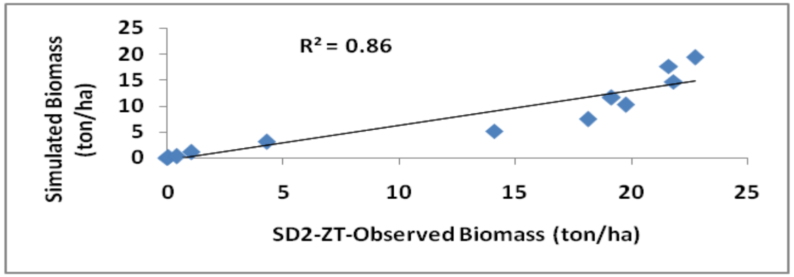

Figure 4.17 (2b): SD2-ZT- Simulated versus Observed biomass (B) in ton/ha for the rain-fed wheat after calibration

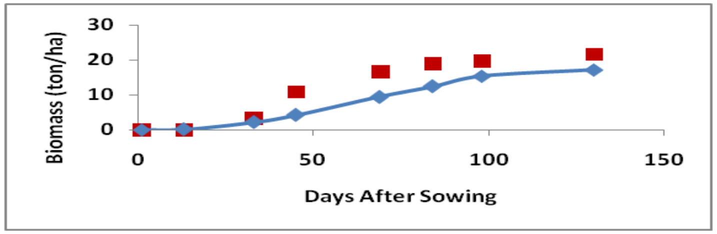

Figure 4.17 (3a): SD3-ZT- Observed (dots) and simulated (continuous line) aboveground biomass (ton/ha) for rain-fed wheat after calibration.

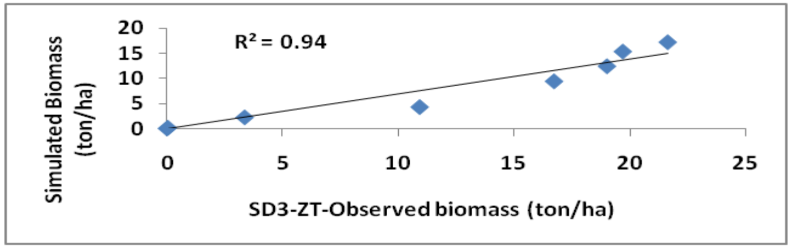

Figure 4.17 (3b): SD3-ZT- Simulated versus Observed biomass (B) in ton/ha for the rain-fed wheat after calibration

iv. Evaluation of final yield and final biomass in zero tillage

As seen from Figure 4.18, despite the low performance in soil water content simulation, average performance in simulation of yield was observed.

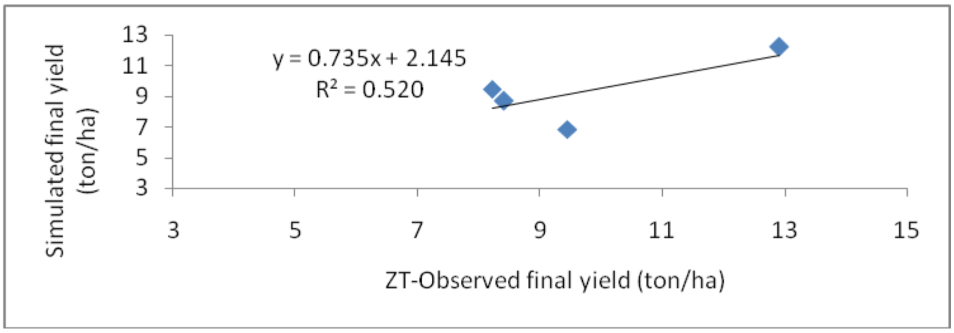

Figure 4.18: Simulated versus Observed final grain yield in zero tillage after calibration

Table 4.13: Goodness-of-fit analysis for the simulated soil water content (SWC), canopy cover (CC), biomass (B, both final and intermediate biomass)

Sowing treatment	Parameter	R^2	EF	d	RMSE
	Optimum value	1.0	1.0	1.0	0
SD1	CC	0.96	0.94	0.99	8.40%
	SWC	0.67	-2.87	0.55	43.1 mm
	B	0.85	0.79	0.94	3.83 ton/ha
SD2	CC	O.94	0.92	0.98	9.70%
	SWC	0.43	-6.05	0.47	55.4 mm
	B	0.86	0.6	0.88	5.92 ton/ha
SD3	CC	0.92	0.89	0.97	12.2%
	SWC	0.53	-4.39	0.54	45.9 mm
	B	0.94	0.69	0.91	4.76 ton/ha
Grain Yield	Y	0.52	0.38	0.04	0.86 ton/ha

A summary of the difference between simulated and observed yield in all the treatments in zero tillage were presented in Table 4.14. The variation between simulated and observed yield in SD3 was particularly high at 27.2% while that of SD1 was 15.6% and 3.3% for normal onset SD2.

Table 4.14: Final yield and final aboveground biomass (ton/ha) both observed and simulated using the calibrated model (Section 4.5.3) under zero tillage. The percent difference and water productivity (simulated WP_{ET}) are also presented.

Sowing treatment	Simulated Yield (ton/ha)	Observed yield (ton/ha)	Percent difference (%)	Simulated Final Biomass (ton/ha)	Observed Final Biomass (to/ha)	Percent difference (%)	$WP(_{ET})$ Kg/m^3
WTSD2	12.22	12.92	<5.4%	24.04	25.58	<6.0%	2.05
SD1	9.49	8.21	>15.6%	20.16	18.71	>7.7%	1.92
SD2	8.69	8.41	>3.3%	19.32	22.76	<15.1%	1.82
SD3	6.87	9.45	<27.3	17.21	21.63	<20.4	1.57

Further Table 4.14 presents ET water productivity both for water regime control treatment and rain-fed trials. Among the rain-fed trials under zero tillage, the early onset (SD1) had the highest ET water productivity (1.92 Kg/m^3). SD2 had slightly lower value (1.82 Kg/m^3) and then the value dropped to 1.57 Kg/m^3 for SD3. However, under the WTSD2 the value was high compared to rain-fed trials (2.05 Kg/m^3). All this values are higher than those obtained under rain-fed trials in conventional tillage (Table 4.11). Similarly, the WTSD2-ZT had a higher value than WRSD2-CT (1.94 Kg/m^3), which is almost equal to that of SD1-ZT (1.92 Kg/m^3). Comparatively, between sowing dates treatments under zero and conventional tillage, zero tillage had higher WP_{ET} (last columns, Table 4.11 and Table 4.14).

4.5 Assessment of Sowing Dates for Optimal Yields

This section applied calibrated and validated AquaCrop model and the 19yearshistoric climate data for the region to determine the optimal sowing dates under conventional tillage. Simulation in zero tillage was not considered for two reasons. One, from field observation under rain-fed condition, zero tillage was found to optimize the effect of sowing date with no significant variation in yield between rain-fed sowing treatments (Table 4.5). Two, the challenge of unsatisfactory calibration of soil water content (R^2=0.13 & d= -1.76) restricted its application in yield simulations with historic climate data. Taking into consideration that AquaCrop is water driven growth model, if water stresses resulting from low soil water content are not sufficiently modeled, the results would not be reliable and therefore misleading.

4.5.1 Generated Onset Dates

The 40 mm in 4 successive days criterion (Raes *et al.,* 2004) was very severe generating only one sowing date in some years while in some no onset within the sowing window. An attempt to use the less strict AREX criterion (25 mm in 7 days but with longer period of 10 days instead) (Raes *et al.,* 2004), was not successful because it also generated very few days (at most two and in some years none) occurring either too early or too late in the season. The two conditions could not be met for this region and therefore relaxed to 10mm in 4 successive days. This was based on the calculation of RAW (6.7 mm up scaled to 10 mm to cater for any losses) at 10 cm soil depth and through the observation during the experiment (the received rainfall which germinated the seed for SD1 was 8.8 mm less by 1.2 mm). The generated onsets were selected based on their occurrence as SD1, SD2 and SD3 representing the early, normal and late season as presented in Table 4.15.

Table 4.15: Average sowing date occurrence determined by the relaxed depth criterion

	Characterized season onset dates		
Number of onsets	Early Onset	Normal Onset	Late Onset
1	6-Sep	4-Oct	15-Oct
2	8-Sep	5-Oct	17-Oct
3	10-Sep	6-Oct	19-Oct
4	14-Sep	8-Oct	20-Oct
5	20-sep	10-Oct	26-Oct
6	30-Sep	14-Oct	31-Oct

The result of multiple yield simulation with the generated dates was then subjected to frequency analysis.

4.5.2 Frequency Analysis of Simulated Yield

Frequency analysis was performed to give an insight on how often the simulated yield was below the threshold yield (frequency of failure). Considering the model parameters specified for each season, 3 sowing onsets; early onset, normal onset and late onset for the 19 years of historic climate data, a total of 57 simulations was run. A frequency analysis using Microsoft Solver tool was applied to the simulated data to determine the yield levels expected at varying levels of probability of exceedance and with a set threshold incremental at 0.5 ton/ha level from 0 yield to maximum 12 ton/ha presented in Figure 4.19.

Beyond a threshold mean yield of 5.5 ton/ha, the probability of exceedance is zero percent for SD1, zero percent for threshold mean yield of 11 ton/ha for SD3 and zero% for mean yield greater or equal to 11.5 ton/ha (Figure 4.19).

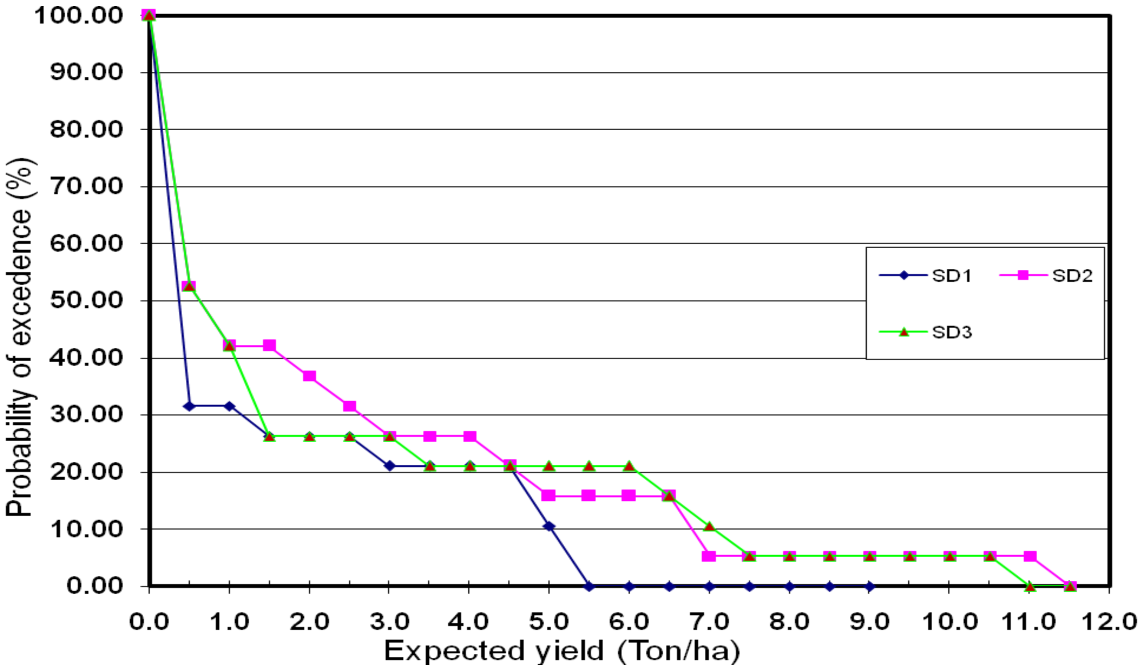

Figure 4.19: Probability of exceedance of wheat specified by planting dates (SD1, SD3 & SD3) obtained using AquaCrop model.

Further analysis of failure rate results indicated that the early onset had the highest failure rate followed by the late and finally the normal. The early onset has a high yield advantage for the viable early onset as compared to both the normal and the late only that the risk of failure of such onsets is high.

Similarly, in years without an early onset, the normal onsets had higher yield advantage than the late. The results also indicate a high failure rate for the early onset and late onsets as compared to normal onset depending on the characteristic of the rainfall in the season and not the occurrence, that is, neither too early nor too late into the season but the general wetness of the season.

At 20%, 50% and 80% probability of exceedance, the average expected yield is less or equal to 4.5, 0.5 and 0.38 ton/ha for the early onset (SD1), 4.5, 0.75 and 0.38 ton/ha for the normal (SD2) and 6,0.75, 0.38 ton/ha (SD3) respectively (Figure 4.19 and Table 4.16).

Table 4.16: Expected yields (ton/ha) for specified probability of exceedance

Probability of exceedance (%)	Expected yield (ton/ha) Early Onset	 Normal onset	 Late onset
20	4.5	4.5	6
50	0.5	0.75	0.75
80	0.38	0.38	0.38

4.5.3 Optimization Analysis

Due to the available constraints in wheat production and the need to stagger the sowing dates to minimize on the constraints (e.g. labor resource availability and land size), an optimization analysis was carried out. It was aimed at allocating the maximum possible acreage proportion to the dates with the best yields. The idea of failure rate was applied at 50% probability of exceedance (considered as the normal or average) such that the normal onset and the late onsets were set to receive 37.5% of the acreage each with the early set to receive 25% due to the high risk of failure associated with it.

The maximized mean yield results of optimization allocated 12.63% to the early, 34.74% to the normal and 30.53% to the late onset. This accounted to 77.89% of the total area to be sown with the remaining 22.11% not allocated due to the nature of the season with only two or one onset and the constraint on land size. Therefore the farmers should aim at doing most of their sowing during the 1st -14th of October under the normal season proportional to 34.74% of their total land area, 12.63% of the land area between 1st-30th September and 30.53% between 15th- 31st October.

CHAPTER FIVE

DISCUSSIONS

5.1 Introduction

The common approach to determine effect of tillage on soil has been to evaluate tillage using crop yields and or moisture content http://www.agriculture.alberta.ca, (De Vita *et al.*, 2007) and (Chaghazardi *et al.*, 2016). A similar approach was adopted where a field experiment was conducted to compare the effect of zero tillage versus conventional tillage on soil moisture and grain yield in wheat production. In addition to tillage, the sowing date's effect on wheat crop grain yield was also studied. The study was carried out in a majorly clay soil field which had been under zero tillage for over ten years (Kaumbutho & Kienzle, 2007).

The results of soil chemical analysis indicated low Nitrogen levels in the top soil which is characteristic for most fields under zero tillage (Alvarez & Steinbach, 2009) due to long exposure of the residue to the atmosphere. With no Nitrogen fertilization application to the crop under zero tillage to correct the deficiency, low yields have been reported despite the improvement in soil moisture content (Alvarez & Steinbach, 2009).

Additionally, the Potassium (K) levels were very high although this does not have any detrimental effect on crop. K is responsible for regulation of stomata closing and opening and thus a high level would mean an enhanced transpiration. Considering that this is a highly reactive element, it is tightly bound to the soil particles. It is not easily leached especially in clayey and silty soils but mainly removed from the soil through runoff and carried away with the eroded soil particles. This could be used as a confirmation of reduced runoff and reduced erosion under zero tillage. Another possible explanation of the high K levels in the top soil would be the presence of decomposing crop residue under zero tillage with wheat residue decomposition reported to release up to 20-32 Kg/ha (Lupwayi *et al.,* 2006). Therefore crop residues recycle substantial amounts of K for use in the subsequent crop.

5.2 Influence of Tillage Practices on Soil Moisture

The study established that there was significant variation in soil moisture between the two tillage practices. The variation observed was on both the top soil and the entire rooting depth throughout the season. Despite the fact that the field had been under zero tillage for several years, one season ploughing and harrowing (conventional field) resulted in significant soil moisture difference as seen in Table 4.3 and Table 4.4 (Section 4.2). Zero tillage treatments had higher moisture content to a depth of 60 cm considered throughout the growing season. This is consistent with the findings of other researchers (De Vita *et al.,* 2007; Chaghazardi *et al.,* 2016).

There are several possible explanations to this all pointing to improvement in certain soil properties (Potter *et al.,* 1995, Araya *et al.,* 2012 and Araya *et al.,* 2011). For instance, due to the undisturbed nature of the soil and continued use of chemical to weed in zero tillage, the plant roots remain in the soil and the plant’s residue remain on top of the soil. This residue on top of the soil and the dead root systems left within the soil in many cases enhance the soil structure formation (Cameron, 2003). This together with the increase in organic matter in the soil have been found to create larger pores in the soil causing it to hold moisture better when saturated with water especially in darker, heavier soils. Higher moisture content has been observed in zero tillage than conventionally tilled soils (Cameron, 2003). This is because of better water infiltration and reduced evaporation (Araya *et al*., 2012 and Potter *et al.,* 1995).

Although one year ploughing of what was formerly zero tillage could not fully reverse the effect of improved hydraulic conductivity and associated infiltration. The results however served as an indicator of the negative trend in soil moisture retention with immediate shift from zero tillage to conventional tillage. The immediate effect observed in soil moisture variation is attributed to increased evaporation arising from the removal of mulch and pulverized soil surface.

The decrease in evaporation and the greater ability to store moisture under zero tillage produces greater water reserves which can often support the crop during periods of drought stress in the plant. The more efficient use of soil moisture by zero tillage is reflected in the crop vigor (Plate B.1 appended for reference) and higher wheat grain yields (Section 4.3.1, Figure 4.3).

On the contrary, the intensive operation and disturbance of the soil under conventional tillage results in soil pulverization and increased wind erosion during operations in the dry season and water erosion when rainfall occurs (Appendix D: Plate D.1 appended for reference, Plate D.2 appended is a contrast in zero tillage). The observed low soil moisture in conventional tillage can be attributed to this reduced surface roughness and pulverization, which in turn result in high run-off and erosion. There is also increased evaporation and illuviation of fine soil particles which clog the pores reducing the infiltration and water holding capacity of the soil (due to surface sealing and crusting) an observation that was also noted by Rockstrom *et al*., (2003). The detrimental effect on soil affect crop establishment, development and final grain yield are evident in Plate 4.1(a) and Plate B.1 (appended for reference). Deficit of soil water in these areas is also attributed to low infiltration rates (due to surface sealing and crusting and low organic matter content) and subsequent high runoff rates (Rockstrom *et al.*, 2003).

The variation in soil moisture under tillage treatment was not sufficiently captured to display the impact immediately after rainfall of different intensities. This was because the field was not accessible immediately after rainfall due to the sticky nature of the soil when wet, otherwise possible compromise on accuracy of the measurement. Therefore gravimetric samples could not be taken immediately after rainfall and thus the intervals of 10-14 days used between measurements. In addition, the entire procedure of moisture determination was physical (gravimetric) and labor-intensive and could not allow shorter intervals less than ten (10) days.

5.3 Combined Effect of Tillage and Sowing Onset on Yield

These effects are discussed under two sections; one on tillage and the other on sowing although their interactions are highlighted.

5.3.1 Influence of Tillage Practices on Grain Yield

It was established that the wheat crop grain yield was responsive to tillage practice irrespective of the sowing dates for the rain-fed trial plots. However these findings contrast with those of Chaghazardi *et al.*, (2016) in wheat and chickpea. Although he reported a significant increase in soil moisture over three years of zero tillage, the effect on yield was not significant. Zero tillage has been reported to perform better in warm and dry environment as compared to cold seasons (Chaghazardi *et al.*, 2016), and therefore it is a possible explanation to better results in conventional tillage under supplemental irrigation (WTSD2-CT).

This field study indicated better results under rain-fed zero tillage as compared to conventional tillage. However, some studies reported no improvement while some indicated negative effects on crop yield by adopting such techniques (Baudron *et al.*, 2012; Van den Putte *et al.*, 2010). This means that in addition to tillage practice, appropriate farming practices such as timely planting, balanced nutrient management, crop protection and weed management are necessary to improve crop productivity.

5.3.2 Influence of Sowing Dates on Rain-fed Grain Yield

Despite the high temperatures in ASAL areas, sowing date influences the yield of rain-fed crops like wheat due to erratic and unreliable rainfall especially at the onset of the rainy season. This is because rainfall directly influences soil moisture which should be maintained at near field capacity in conventional tillage. This is however not possible under conditions of erratic and unreliable rainfall. Based on the observed significant difference in yields under conventional tillage, proper timing of the onset of the growing season has to be made.

Delay in sowing by ten days result to a loss of 6.7% while an early onset leads to a loss of 37.1% under conventional tillage. This is attributed to the high evaporation and associated water stress. However under zero tillage, an early onset results in a loss of 2.4% which is not very significant and a positive variation under delayed onset resulting in an increase of 12.4%. As was the observation from the field on late planting (Chandna *et al.*, 2004) similar observation of yield reduction and reduced input use efficiency of the wheat crop.

The results indicate that under zero tillage, optimization of yields is possible through staggering of sowing dates. On the other hand, under conventional tillage in the study area, early onsets have high risks of crop failure or significant reduction in yield.

Similarly, waiting for the wet season would complicate operations under this heavy clay soil and lead to soil degradation, (erosion, compaction and formation of hard surface hindering infiltration).

5.4 Calibration and Validation

The simulation of crop canopy cover was satisfactory although the model was not well able to simulate biomass especially at the development stage. This is as a result of low sowing density and the observed heavy tillering by this wheat variety (Plate 4.2, Section 4.4.1). The tillering and high biomass was associated with the significant reduction in crop density, improved seed variety, and sowing with wider spacing between and within the row giving each plant more room both above and below the ground. This is a scenario similar to that observed in system of crop intensification (Abraham *et al.*, 2014) or a similar practice in rice (system of rice intensification) (Styger *et al.*, 2011).

In their study Zhang *et al.*, (2013), was not able to simulate biomass accurately and they argued that the AquaCrop model cannot simulate wheat tillering well owing to the positive effects of winter wheat tillering. The high biomass meant increased transpiration rate which necessitated the need to increase the transpiration coefficient (Kc_{TR}) to 1.4 which was found to be responsive and improved the model performance in simulating biomass. The same coefficient was also seen to highly affect yield which within the model is proportionally derived from biomass through the Harvest index as illustrated in Figure 3.4, Section 3.4 (Raes *et al.*, 2009). The new high yielding variety necessitated the tuning of water productivity to 17 Kg/m^3 and consequently the Harvest index to 49% to depict the field observation. Despite the lower d values for biomass during calibration, the model simulated yield was better than the simulated biomass (Table 4.11, Section 4.4.2). A possible explanation was that the HI may have offset the shortcoming for the simulated biomass.

5.4.1 Calibration and Validation in Conventional Tillage

A particular case of interest in calibration of conventional tillage is the dry onset which the model was not sufficiently able to simulate accurately with a percent difference of 77.5% for yield and 43% for biomass. The major reason for this was the observed negative effect of soil pulverization increasing soil erodibility. This in turn contributed to soil crusting after a heavy rainfall and thus inhibiting emergence as illustrated (Plate 4.1(a) & (b)) a scenario which the model could not simulate. A soil crust is hard and relatively difficult to break, restricts emergence and in severe cases calls for replanting.

Therefore these indicate that as many researchers have reported, dry sowing is beneficial if a good establishment is attained (Sen *et al*., 2014).It also indicates that apart from sufficient rainfall which is a known limiting factor; good soil condition is also necessary for uniform and maximum establishment of the seedling. Zero tillage is among the recommended practices reducing or eliminating surface sealing as confirmed through field observation on the zero tillage sowing treatments during the experiment.

5.4.2 Calibration and Validation in Zero tillage

Calibration in zero tillage was not satisfactory especially for soil water content (R^2=0.13). The explanation lies in the effect of zero tillage on soil hydraulic properties which were not evaluated because they were not within the scope of the study and therefore not determined. Only moisture variation was evaluated. However, the calibration of CC and B as well as validation test with the poorly calibrated model produced representative results as compared to SWC. This was due to the high SWC observed meaning the crop did not experience significant water stresses which needed to be simulated by the model. Similarly, the model although underestimated SWC, it was within reasonable limits (RMSE=14.2 mm) but the effect was pronounced in the performance indices due to the consistency in measurement and simulation (underestimation all through for almost all data points). And since the crop file was adequately calibrated under conventional tillage, then the effect of soil file could not affect their results significantly.

5.4.3 Underestimation of Canopy Cover and Biomass Simulation during Development Stage.

The results of water regime treatments (WTSD2) confirm that the soil of the area was productive and can support wheat crop production if proper farming and management practices are adopted. The no significant variation in yields between the two control tillage treatments (P-value =0.45 at 5% level of significance-Table 4.7) confirms that soil water availability was the main limiting factor to crop production in this area.

With sufficient water and fertilizer, the crop tended to be vegetative as captured in the field observation and measurement of CC and B (Figures, 4.5, 4.7, 4.12 and 4.14) especially at development stage. The vegetative nature was also as a result of heavy tillering at this condition of no water stress as explained in section 5.2 and Plate 4.2. This indicated the need to recognize tillers as functional entities in crop simulation models like AquaCrop due to reported increase in grains and straws (biomass) in varieties and farming systems enhancing this characteristic (Abraham *et al*., 2014).

5.4.4 Water Productivity between Tillage Treatments

The simulated WP_{ET} for wheat (Table 4.11, Section 4.4.2 and Table 4.14, Section 4.4.4) for rain-fed trials in conventional tillage and zero tillage was within the reported values of water productivity of 0.6-1.9 Kg/m^3 at varying level of water application (Andarzian *et al.,* 2011). The high value of WP_{ET} in SD1-ZT almost equal to that of WTSD2-CT, indicated that early sowing with zero tillage optimizes both crop yield and water productivity under rain-fed conditions to equivalent levels in conventional tillage under irrigation. Even in dry areas reasonable yields can be obtained provided moisture conservation in the root zone is guaranteed (Temesgen *et al.,* 2012).Since water for irrigation is limited in the ASAL areas, moisture conservation through zero tillage is an alternative for sustainable crop production by solving the problem of land degradation and declining water productivity (Temesgen, 2007).

5.5 Optimization of Sowing Date(s)

Zero tillage optimize the sowing dates through retention of soil water (Buffer) from the long rains and advancement of sowing time through reduced time for land preparation (by 20-30 days (Chandna *et al.,* 2004)). Therefore it only requires a rainfall event or an irrigation event enough to trigger germination and the stored soil water will support crop growth until the next rain event. This is unlike in conventional tillage where the crop fully depends on received rainfall for germination, growth and development of the crop. This means that incase the received rainfall results in seed germination and then a dry spell occurs for longer period than the crop can withstand water stress (moisture depletion to permanent wilting point), it eventually dies and this is regarded as a false start (Sen *et al.,* 2014).

According to Tripathi *et al.,* (2013) research in India, a delay of every successive day in planting from the optimal sowing window decreased wheat grain yield progressively. Ali *et al.,* (2010) findings also concur with this study. As a result, in India, farmers started practicing conservation technologies such as zero tillage to cut down on their production costs and avoid planting delays (Tripathi *et al.,* 2013).

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

The following are the conclusions and recommendations of the study as well as areas which need further research.

6.2 Conclusions

The following are the conclusions from the study with regard to the study objectives. There is potential for improving soil moisture conservation for crop production through zero tillage. Zero tillage promoted soil moisture conservation.

Improvement in soil moisture through zero tillage can guarantee the farmer higher crop yields as compared to conventional tillage. From the study, the observed significantly high soil water content under zero tillage significantly contributed to the high grain yield. This means that by practicing zero tillage, the wheat production can increase to 8.21, 8.41 and 9.45 ton/ha respectively for the early, normal and late sowing. However, in conventional tillage, the risk of crop failure is high especially for the early onset from the challenge of soil degradation affecting germination (soil capping) and low soil moisture. This means that farmers practicing conventional tillage are likely to produce less than the target yield of 8.5 ton/ha by 50.64%, 21.4% and 26.75% respectively for early, normal and late sowing.

Sowing dates significantly affect grain yield in conventional tillage but in zero tillage all the sowing dates are optimal without significant difference in grain yield. This means that for farmers to attain a good crop establishment and harvest, in conventional tillage, they must align their sowing to the normal onset otherwise face the risk of false start in early sowing or water stress late in the season for late sowing combined with other challenges such as carrying out farm operations under wrong soil moisture. In this ASAL area, farmers can practice zero tillage and apply the sowing strategy of staggering sowing dates to reduce on constraints such as land size and labor resource and still optimize on their grain yield without high risk of crop failure.

The calibration of AquaCrop model in conventional tillage was satisfactory (R^2 of 0.95, 0.80 and 0.5respectively for CC, B and SWC) unlike in zero tillage where the soil water content calibration failed (R^2=0.133).This means that in this ASAL area AquaCrop model can be applied for scenario analysis with acceptable level of accuracy in conventional tillage. However its application in zero tillage is limited and it restricted its use in generation of sowing dates and subsequent simulation of yields for optimization analysis.

Finally, the results of optimization analysis of yield from sowing dates established that October 1st to October 14th classified as the normal onset was the most appropriate sowing period for wheat in conventional tillage in the short rain season studied. However with stored soil water from zero tillage practice, early onset has an added advantage of working under optimal soil moisture and early maturity of the crop.

In summary, zero tillage optimize the effect of sowing time allowing for staggering of dates as a sowing strategy without a compromise on yield or acreage under crop (supported by the observed high grain yield and water productivity).

6.3 Recommendations

From the results of the field experiment in Laikipia East Sub-county the following recommendations were made;

1. Zero tillage is recommended for use by farmers as a strategy to optimize soil moisture conservation and thus maximize crop yield.
2. AquaCrop model is recommended as a useful tool for use with acceptable level of accuracy for scenario analysis in ASAL areas to optimize wheat crop yield production especially under rain-fed condition.
3. It is recommended that zero tillage be used by farmers in the County to optimize their sowing dates without significant effect on yield or compromise on land size. Otherwise, under conventional tillage, the dates in the range 1st - 14th October are recommended as optimal during the short rain season. However, under conventional tillage harvest is not always guaranteed in dry years due to the high failure rate observed.

6.4 Recommendation for Further Research

The following recommendations for further research were made;

1. Further research is recommended on soil moisture variation between zero tillage and conventional tillage with shorter time steps of daily or weekly as well as reduced depth intervals of at most 10 cm each. Recommended soil moisture probes can be used for increased frequency and accuracy in the measurement and especially to indicate the immediate effect after a rainfall event.

ii. The findings of this study recommends improvement in the AquaCrop model to simulate tillering effect on biomass (possible coefficient for rate of tillering) and the challenge of soil crusting and surface sealing on crop emergence (both in time taken to germinate and uniformity of the establishment). This would enhance better simulations under scenarios similar to SD1-CT.

REFERENCES

Abraham, B., Araya, H., Berhe, T. *et al.*, (2014). The system of crop intensification reports from the field on improving agricultural production, food security, and resilience to climate change for multiple crops. *Agriculture & Food Security,* 3(4) p.12. doi:10.1186/2048-7010-3-4

Ali, M.A., Ali, M., & Sattar, M. (2010). Sowing date effects on yield of different wheat varieties. *Journal of Agriculture Research,* 48 (2), 157-162.

Allen, R., Pereira, L.S., Raes, D., & Smith, M. (1998). Crop evapotranspiration guidelines for computing crop water requirements. *FAO Irrigation and Drainage Paper No. 56.* Rome: FAO.

Alvarez A., & Steinbach.H.S. (2009).A review of the effects of tillage systems on some soil physical properties, water content, nitrate availability and crops yield in the Argentine Pampas.*Soil and Tillage Research,* 104(1), 1-15. doi:10.1016/j.still.2009.02.005

Andarzian, B., Bannayan, M., Steduto, P., Mazraeh, H., Barati, M.E., Barati, M.A., Rahnama, A., (2011). Validation and testing of the AquaCrop model under full and deficit irrigated wheat production in Iran. *Agricultural Water Management Journal,* 100, 1–8. doi:10.1016/j.agwat.2011.08.023

Araya, T., *et al.* (2011). Effects of conservation agriculture on runoff, soil loss and crop yield under rain-fed conditions in Tigray, northern Ethiopia. *Soil Use Management,* 27, 404–414.

Araya, T., *et al.,* (2012). Medium-term effects of conservation agriculture based cropping systems for sustainable soil and water management and crop productivity in the Ethiopian highlands. *Field Crops Research*, 132, 53–62.

Asseng, S., Milroy, S.P. & Poole, M.L. (2008). Systems analysis of wheat production on low water-holding soils in a Mediterranean-type environment: Yield potential and quality. *Field Crops Research,* 105, 97-106.

Ati, F., Stigter, J., & Oladipo, E. (2002). A comparison of methods to determine the onset of the growing season in Northern Nigeria. *International Journal of Climatology,* 22, 731-742. doi: 10.1002/joc.712

Barron, J., Rockstrom, J., Gichuki, F. & Hatibu, N., (2003).Dry spell analysis and maize yields for two semi-arid locations in East Africa. *Agricultural and Forest Meteorology,* 117, 23–37.

Baudron, F. D. R., Tittonell, P., Corbeels, M., Letourmy, P. and Giller, K. E., (2012).Comparative performance of conservation agriculture and current smallholder farming practices in semi-arid Zimbabwe. *Field Crops Research,* 132, 117–128.

Booth, D. T., Cox S. E. & Berryman, R. D. (2006). Point sampling digital imagery using SamplePoint. *Environmental Monitoring and Assessment*, 123, 97–108

Cameron, C., (2003). What are the effects of no-till farming on soil moisture and soil temperature compared to conventional tillage in rice County Kansas? *Cantaurus,* 11, 2-4.

Chaghazardi H. R., *et al.* (2016). Effects of tillage management on productivity of wheat and chickpea under cold, rain-fed conditions in Western Iran. *Journal of Soil and tillage research*, 162, 26-33.doi:10.1016/j.still.2016.04.010Elsevier B.V

Chandna, P. *et al*., (2004). *Increasing the Productivity of Underutilized Lands by Targeting Resource Conserving Technologies-A GIS/Remote Sensing Approach: A Case Study of Ballia District, Uttar Pradesh, in the Eastern Gangetic Plains.* Mexico. D.F: CIMMYT

De Vita *et al*., (2007). Breeding progress in morpho-physiological, agronomical and qualitative traits of durum wheat cultivars released in Italy during the 20th century. *European Journal of Agronomy*, *2*(1)*, 39-53.*

Derpsch, R., Friedrich, T., Kassam, A., & Hongwen, L., (2010).Current status of adoption of no-till farming in the world and some of its main benefits. *International Journal of Agriculture and Biological Engineering*, 3(1), 1-26. Doi:10.3965/j.issn.19346344. 2010.01.0-0.

FAO (2009). Declaration of the World summit on food security. *World Summit on Food Security 16-18th* November 2009, 1-7. Rome, FAO

FAO (2012).The state of food insecurity in the world 2012.*World Summit on Food Security*, Rome, FAO

FAO, (2002).*Deficit irrigation practices;* Organization Land and Water Development Division. Rome: FAO

FAO, (2015). *Post- 2015 development agenda and the millennium development goals,* Rome: FAO

Fereres, E., & Soriano, M.A., (2007). Deficit irrigation for reducing Agricultural water use. *Journal of Experimental Botany,* 58(2), 147–159.

Food and Agricultural Organization of the United Nations Statistics division, (FAOSTAT), (2013). Rome: FAO

Geerts, S., & Raes, D. (2009). Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agriculture Water Management*, *96* (9), 1275–1284.

Geerts, S., Raes, D., Garcia, M., Miranda, R., *et al.* (2009). Simulating Yield Response of Quinoa to Water Availability with AquaCrop. *Agronomy Journal101* (3): 499–508.

Hansen J., (2002). Realizing the potential benefits of climate prediction to agriculture: issues, approaches, challenges. Agric. *Syst*. 74, 309–330.

Hansen, J.W., & Indeje, M., (2013).Linking Dynamic Seasonal Climate Forecasts with Crop Simulation for Maize Yield Prediction in Semi-arid Kenya. *Agricultural and Forest Meteorology*, 125, 143-157. DOI: 10.1016/j.agrformet.2004.02.006

Heng L., *et al*., (2007). Optimizing wheat productivity in two rain-fed environments of the West Asia-North Africa region using a simulation model. *European Journal of Agronomy*, 26, 121-129

Home Grown Cereal Authority, (HGCA), (2016).*Wheat disease management guide*.Agriculture and Horticulture Development Board 2016 (AHDB) and (HGCA). Retrieved on 8th August, 2016 from https://cereals.ahdb.org.uk/publications/2016/february/23/wheat-disease-management-guide.aspx

Huho, J., Ngaira, J., Ogindo, H., & Masayi, N., (2012). The changing rainfall pattern and the associated impacts on subsistence agriculture in Laikipia east district in Kenya.*Journal of Geography and Regional Planning,* 5(7), 198-206.doi: 10.5897/JGRP12.018.

Imran, A., *et al.,* (2013).Response of wheat (*Triticum Aestivum*) cultivars to different tillage practices grown under rice-wheat cropping system. *Universal Journal of plant science,* 1(4), 125-131.doi: 10.13189/ujps.2013.010403.

Jones J., *et al* (2003). The DSSAT cropping system model. *Europe Journal of Agronony,* 18, 235–265.

Karuma, A., Mtakwa, P., Amuri, N., Gachene, K., Gicheru, P. (2014). Enhancing soil water content for increased food production in semi-arid areas of Kenya: Results from an On-Farm Trial in Mwala Districtin Kenya. *Journal of Agricultural Science,* 6(4), 125-134. doi:10.5539/jas.v6n4p125

Kaumbutho P. & Kienzle J, eds. (2007).*Conservation agriculture as practiced in Kenya: two case studies*. Nairobi: African Conservation Tillage Network, Centre de Coopération Internationale de Recherche Agronomique pour le Développement (CIRAD), Food and Agriculture Organization of the United Nations.

Kenya National Bureau of Statistics (KNBS) (2015).*Kenya population.* Retrieved 20th July, 2015, from http://www.tradingeconomics.

Kipkorir, E.C., Gachuir, J.S., Mukabana, M., Raes, D., (2004) Evaluation of the onset of the growing season for various climatic zones in Kenya by means of soil water balance method for different soil types. In: *Demare´ e, G., De Dapper, M., Alexandre, J. (Eds.), Tropical Climatology, Meteorology and Hydrology*. pp. 137–150.

Kipkorir, E.C., Raes, D., Bargerei, J., Mugalavai, E.M., (2007). Evaluation of two risk assessment methods for sowing maize in Kenya. *Journal of Agricultural and Forest Meteorology,* 144(3-4), 193-199. Elsevier B.V. doi:10.1016/j.agrformet.2007.02.008.

KNBS (2010).*The 2009 Kenya Population and Housing Census: Counting our people for the Implementation of Vision 2030*. Nairobi: Ministry of State for Planning, National Development and Vision 2030, Vol.1c.

Lupwayi N.Z *et al.*, (2006). Potassium release during decomposition of crop residues under conventional and zero tillage. *Canadian Journal of Soil Science*, 86(3), 473-481. 10.4141/sos-049.

MAFAP, (2013). Review of food and agricultural policies in Kenya. *MAFAP Country Report Series.* Rome: FAO.

Mahagayu, M.C., Kamwaga, J., Ndiema, A.C., Kamundia, J., & Gamba, P. (2007). Wheat productivity, constraints associated in the eastern parts of Kenya Timau division. *African Crop Science Conference Proceedings,* 8, 1211-1214. El-minia, Egypt: Africa Crop Science Society.

McCuen, R., Knight, Z., & Cutter, A., (2006). Evaluation of the Nash--Sutcliffe Efficiency Index.*J. Hydrol. Eng, 11,* 597–602.

Mhizha, T., (2010). *Increase of yield stability by staggering the sowing dates of different varieties of rain-fed maize in Zimbabwe*. D.Phil Thesis. Catholic University, Leuven,

Monroy, L., Mulinge, W., & Witwer, M., (2013). Analysis of incentives and disincentives for wheat in Kenya. *Technical notes series*. Rome: MAFAP, FAO.

Moroke T.S., *et al.*, (2005). Soil water depletion and root distribution of three dry-land crops. *Soil Science Society of America Journal,* 69,197-205.

Mujdeci, M., Kara, B., & Isildar, A. A. (2010). The effects of different soil tillage methods on water dynamics. *Scientific Research and Essays, 5*(21), 3345-3350.

Muyanga, M., Jayne, T.S., Argwings-Kodhek,G., & Ariga, J., (2003). Staple food consumption patterns in urban Kenya: trends and policy implications. *Tegemeo Working Paper No. 16*.

Nyangito, H., Ikiara, M., &Ronge, E., (2002).Performance of Kenya’s wheat industry and prospects for regional trade in wheat products. *Discussion Paper No. 17.* Nairobi:KIPPRA.

Ojwang’, O., Agatsiva, J., & Situma, C., (2010). *Analysis of climate change and variability risks in the smallholder sector: Case studies of the Laikipia and Narok Districts representing major Agro-ecological zones in Kenya*, Rome: FAO.

Okalebo, J., Gathua, W., & Woomer P., (2002). Laboratory methods of soil analysis and plant analysis: *A Working Manual*. TBSF UNESCO. Nairobi: EPZ Publishers.

Onyari, C., Ouma, J., & Kibe, A., (2010). Effect of tillage method and sowing time on phenology, yield and yield components of chickpea (*Cicer arietinum L.*) under semi-arid conditions in Kenya. *Journal of Applied Biosciences,* 34, 2156-2165: ISSN 1997-5902.

Pereira, L., Oweis, T., & Zairi, A. (2002).Irrigation management under water scarcity. *Agriculture Water Management*, *57,* 175–2006.

Potter, K. N., Torbert, H. A. and Morrison, J. E. ., (1995) Tillage and residue effect on infiltration and sediment losses on Vertisols. *American Society of Agricultural Engineers*, 38, 1413–1419.

Raes, D., Mallants, D., and Song, Z. (1996). RAINBOW - a software package for analyzing hydrologic data. In Blain, W.R. (ed.) Hydraulic Engineering Software VI. *Computational Mechanics Publications,* 525 – 534. Southampton.

Raes, D., Sithole, A., Makaru, A., & Millford, J., (2004). Evaluation of first planting dates recommended by criteria currently used in Zimbabwe. *Journal of Agricultural and Forest Meteorology,* 125, 177–185.

Raes, D., Steduto, P., Hsiao, T., & Fereres, E. (2010).*AquaCrop Reference Manual: Users Guide*. Rome: FAO.

Raes, D., Steduto, P., Hsiao, T.C., & Fereres, E., (2012). AquaCrop Reference manual (Version 4.0). Retrieved 2nd February, 2015 from http://www.fao.org/nr/water/aquacrop.html

Raes, D., Steduto, P., Hsiao, T.E., Fereres, E., (2009). AquaCrop—the FAO crop model to simulate yield response to water: Main algorithms and software description. *Agronomy Journal*, 101, 438-447. doi:10.2134/agronj2008.0140s

Raes, D., Willems, P. and GBaguidi, F. (2006). RAINBOW - a software package for analyzing data and testing the homogeneity of historical data sets. *Proceedings of the 4th International Workshop on 'Sustainable management of marginal dry-lands*. Islamabad, Pakistan, 27-31 January 2006.

Rahman, A., Tawaha, M., & Munir, A.T., (2002).Effects of dates and rates of sowing on yield and yield components of lentil (*lens culinaris medic.)* under semi arid conditions.*Pakistan Journal of Biological Sciences*, 5, 531-532.

Republic of Kenya (2011).*Vision 2030 Development Strategy for Northern Kenya and Other Arid Lands*. Nairobi: Ministry of State Development of Northern Kenya and Other Arid Lands and Ministry of Planning, National Development & Vision 2030.

Rockstrom, J., Barron, J., & Fox, P. (2003).*Water productivity in rain-fed agriculture: Challenges and opportunities for smallholder farmers in drought prone tropical agroecosystem*. CABI, IWMI, Wallingford, UK, Colombo, Sri Lanka. PMid:14728794, PMCid:PMC1693286.

Rockstrom, J., Kaumbutho, P., Mwalley, J., Nzabi, A.W., *et al* (2009). Conservation farming strategies in East and Southern Africa: yields and rain water productivity from on-farm action research. *Soil and Tillage Research*, 103, 23-32.

Saxton K.E et al., (1986) Estimating generalized soil-water characteristics from texture. *Soil Science Society of America Journal*, 50(4), 1031-1036.

Schwartz R., *et al.*, (Eds.), (2006). Proceedings of the 28th Southern Conservation Systems Conference, June 26-28, 2006, Amarillo, Texas, USDA-ARS *Conservation and Production Research Laboratory Report* No. 06-1, p. 286, Bushland, Texas.

Sekhwela, B.M., &Yates, D.J., (2007). Phenological study of dominant Acacia tree species in areas with different rainfall regimes in the Kalahari of Botswana. *Journal of Arid Environments,* 70(1), 1-17.

Sen A. *et al.*, (2014), Zero *Tillage, a Boon for Wheat in Rice, Wheat Cropping System,* accessed from www.bhu.ac.in/agriculture/zero_tillage.html on 9th December, 2015.

Sivakumar MVK. 1988. Predicting rainy season potential from the onset of rains in southern sahelian and sudanian climatic zones of West Africa. *Agricultural and Forest Meteorology* **42**, 295–305.

Steduto, P., Hsiao, T.C., Fereres, E., and Raes, D. (2012).Crop yield response to water.*FAO Irrigation and Drainage Paper No. 66*. Rome: FAO.

Steduto, P., Hsiao, T.C., Raes, D., Fereres, D. (2009). AquaCrop—the FAO Crop Model to Simulate Yield Response to Water: Concepts and Underlying Principles. *Agronomy Journal*, 101, 426-437. doi:10.2134/agronj2008.0139s

Stockle C.O., *et al.*, (2003). CropSyst, a cropping systems simulation model. *European Journal of Agronomy*, 18, 289-307.

Styger, E., Aboubacrine, G., Attaher, M. A., & Uphoff, N. (2011). The system of rice intensification as a sustainable agricultural innovation: Introducing, adapting and scaling up a system of rice intensification practices in the Timbuktu region of Mali. *International Journal of Agricultural Sustainability,9*(1), 67-75. doi:10.3763/ijas.2010.0549

Temesgen, M., (2007). Conservation tillage systems and water productivity implications for smallholder farmers in semi-arid Ethiopia.Ph.D. Thesis,Cergy-Pontoise University, France.

Temesgen, M., Savenije H. Rockström, J., Hoogmoed W., (2012). Assessment of strip tillage systems for maize production in semi-arid Ethiopia: Effects on grain yield, water balance and water productivity. *Physics and Chemistry of the Earth Parts A/B/C,* 47–48, 156-165.

Tripathi, R., Raju, R., & Thimmappa, K., (2013). Impact of zero tillage on economics of wheat production in Haryana. *Journal of Agricultural Economics Research Review,*26 (1), 101-108.

Van den Putte, A., Govers, G., Diels, J., Gillijns, K. and Demuzere, M., (2010) Assessing the effect of soil tillage on crop growth: A meta-regression analysis on European crop yields under conservation agriculture. *European. Journal of Agronomy*, 33, 231–241.

Van Ittersum M.K., (2003). Approaches and applications of the Wageningen crop models. *European Journal of Agronomy*, 18, 201–234.

Wamari, J. O., Sijali, V. I., Kheng, L. H., Miriti, J. M., & Esilaba, A. O. (2012). Use of Aquacrop model to predict maize yields under varying rainfall and temperature in a semi-arid environment in Kenya. *Journal of Meteorology and Related Sciences*, *6*, 23-32.

Wander, M., & Yang, X., (2000). Influence of tillage on the dynamics of losses and acclude particulate and humified organic matter fractions. *Journal of Soil Biology and Biochemistry,* 32, 1151-1160.

Zhang, W., Liu, W., Xue, Q.W., Chen, J., Han, X. (2013) Evaluation of the AquaCrop model for simulating yield response of winter wheat to water on the southern Loess Plateau of China. *Water Science and Technology Journal, 68* (4) Pg.823. doi: 10.2166/wst.2013.305

Zinyengere, N., Mhizha, T., Mashonjowa, E., Chipindu, B., Geerts, S., & Raes, D., (2011). Using seasonal climate forecast to improve maize production decision support in Zimbambwe. *Agricultural and Forest Meteorology,* 151(12), 1792-1799. doi:10.1016/j.agrformet.2011.07.015.

APPENDICES

Appendix A- Soil Moisture

Table A.1: Descriptive statistic on the top soil moisture (0-25cm)

Treatments	Min. (mm)	Max. (mm)	Mean (mm)	Mean Std. Error	Std. Deviation (mm)
SD1-ZT	66.65	104.28	87.64	4.11	14.25
SD1-CT	48.91	91.69	71.11	4.44	15.37
SD2-ZT	70.52	111.66	89.21	4.56	14.43
SD2-CT	47.78	100.37	76.19	5.15	16.28
SD3-ZT	67.23	100.74	83.61	4.16	11.77
SD3-CT	57.79	90.93	74.19	4.01	11.34
WTSD2-ZT	79.73	115.84	98.63	3.41	10.23
WTSD2-CT	73.75	117.73	97.64	4.74	14.21

Table A.2: Difference in top soil moisture content (0-25)

	Levene's Test for Equality of Variances		t-test for Equality of Means				
Treatments	F	Sig.	T	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference
SD1	.004	.947	2.733	22	.012*	16.533	6.050
			2.733	21.874	.012*	16.533	6.050
SD2	.230	.637	1.893	18	.075	13.022	6.880
			1.893	17.743	.075	13.022	6.880
SD3	.008	.928	1.630	14	.125	9.419	5.777
			1.630	13.981	.125	9.419	5.777
WTSD2	.989	.335	.170	16	.867	0.991	5.835
			.170	14.535	.867	0.991	5.835

*There is significant difference in top soil moisture content at 5% level of significance

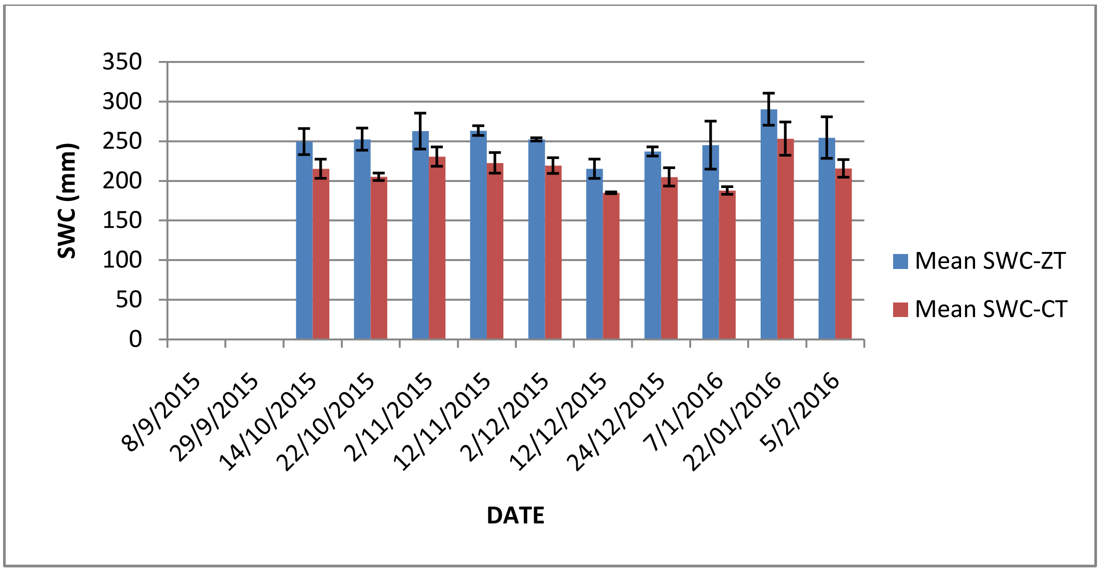

Fig A.1: Soil moisture Content and variation at the root zone (0-60cm) for the early onset (SD1). The error bars indicate standard deviation.

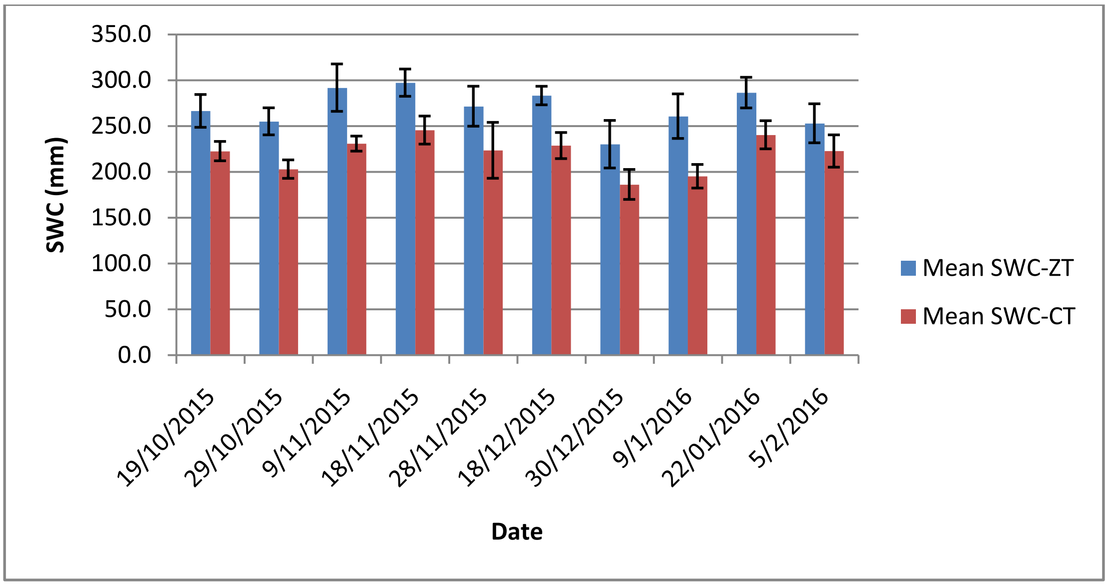

Fig A.2: Soil moisture content and variation at the root zone (0-60cm) for the normal onset (SD2). The error bars indicate standard deviation.

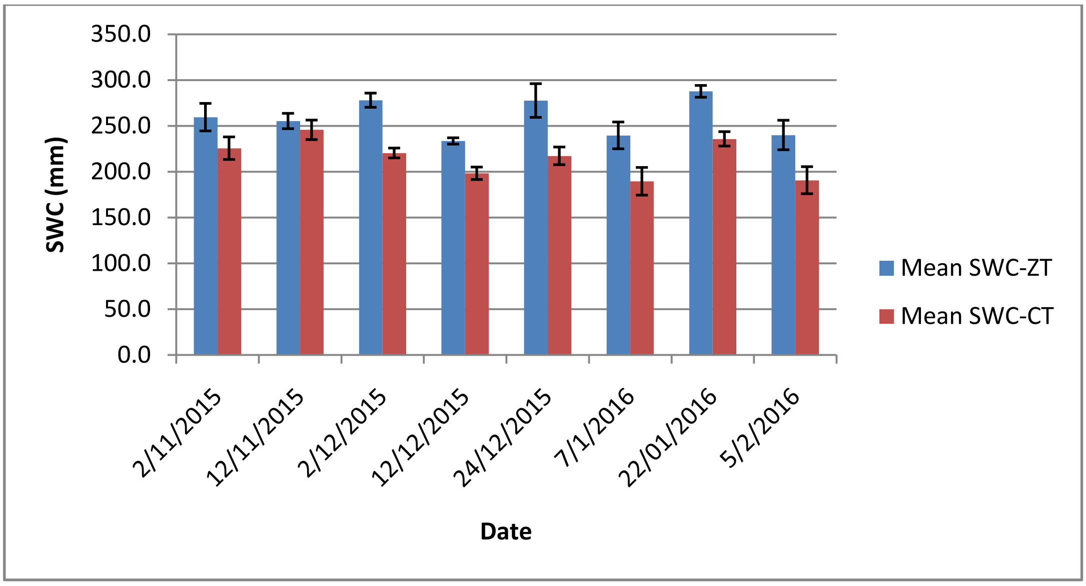

Fig A.3: Soil moisture content and variation at the root zone (0-60) for the late onset (SD3). The error bars indicate standard deviation.

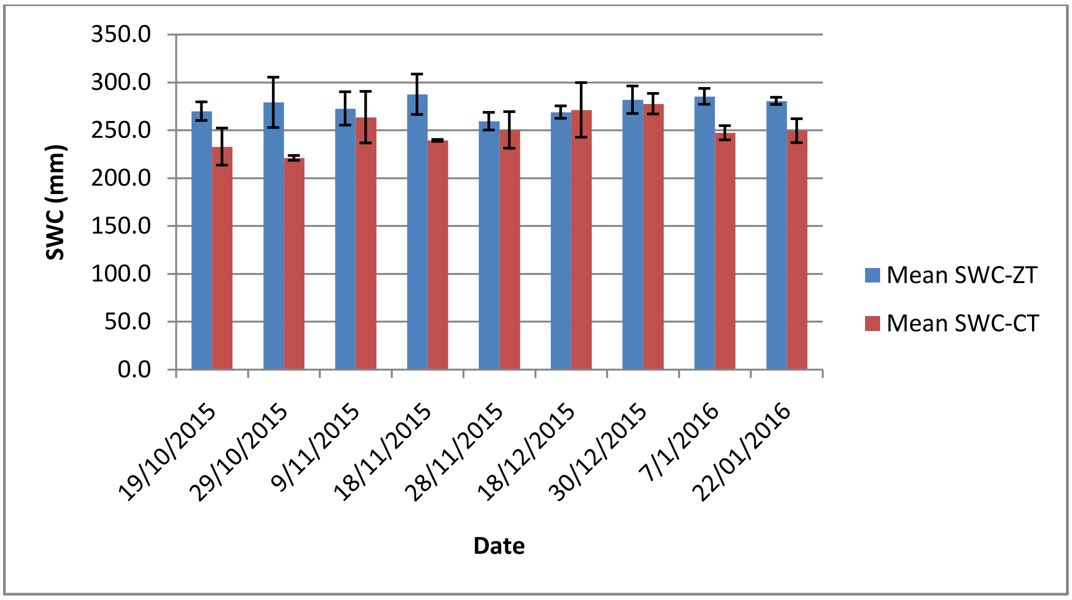

Fig A.4: Soil moisture content and variation at the root zone (0-60cm) under water regime (WTSD2). The error bars indicate standard deviation.

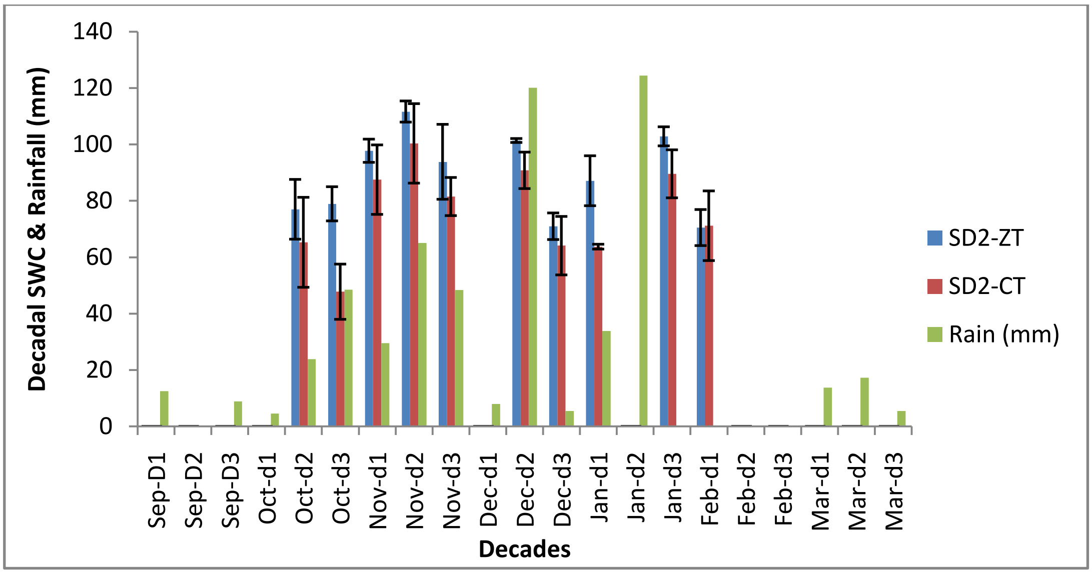

Fig A.5: Relationship between the decadal rainfall and top soil moisture content (0-25cm) for both the SD2-zero tillage and conventional tillage plots. The error bars indicate standard deviation.

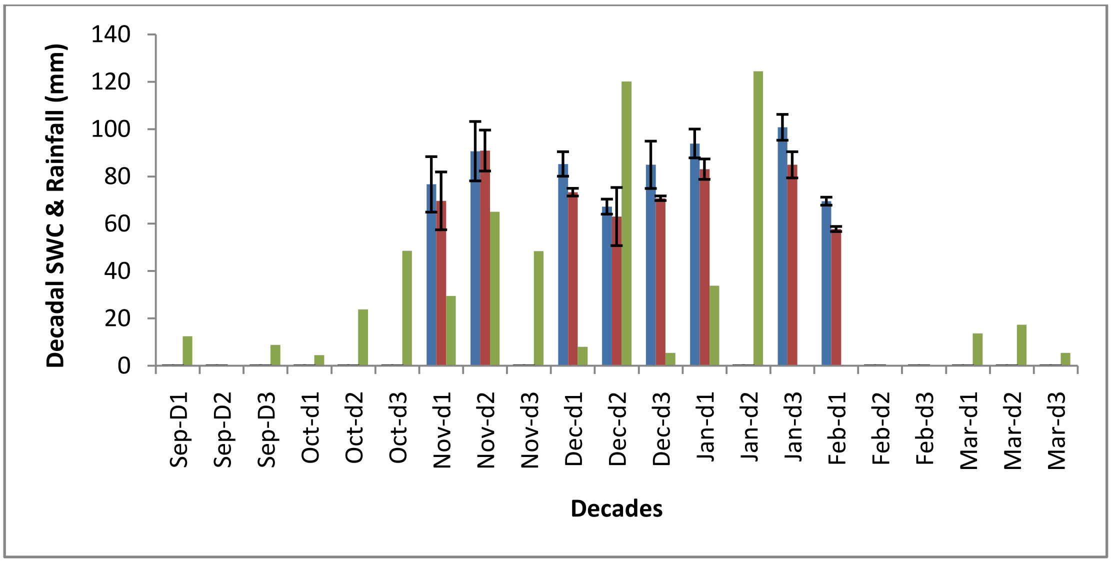

Fig A.6: Relationship between the decadal rainfall and top soil moisture content (0-25cm) for both the SD3-zero tillage and conventional tillage plots. The error bars indicate standard deviation.

Appendix B: Crop and Crop Characteristic

Water Stressed Conventional Tillage SD1-CT (75DAS)

Equivalent on Zero Tillage SD1-ZT (75DAS)

Plate B.1: Comparison of the effect of soil moisture availability to crop under conventional and zero tillage (Photo taken on 12th Dec 2015). (Source: Author, 2015)

Appendix C: Climate Characteristic

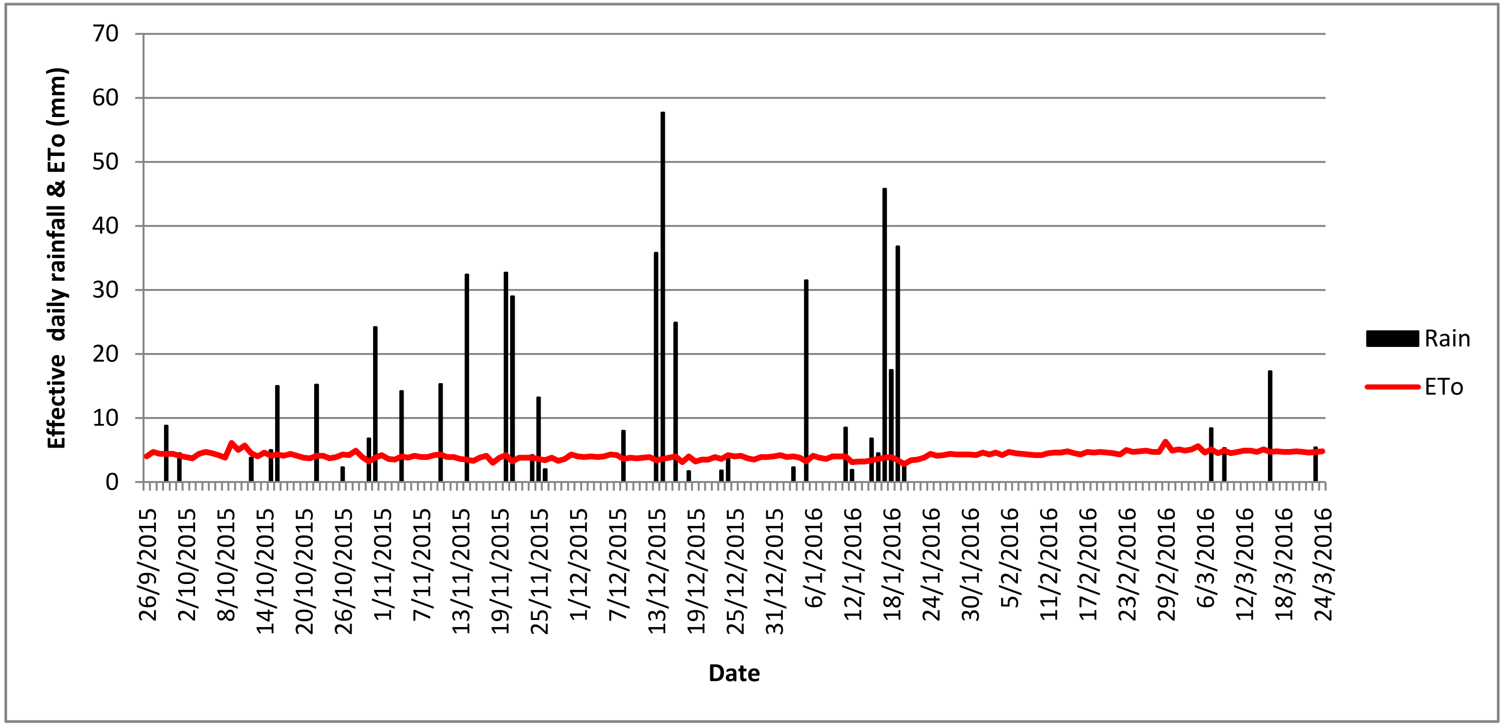

Fig C.1: Relationship between observed effective Daily Rainfall and ETo for the crop growth season.

Appendix D: Tillage practices and their Effect on Soil.

Plate D.1: Conventional tillage – Dry ploughing for seed bed preparation resulting to wind erosion and exposing the soil to evaporation (Farms adjacent to Lengetia Farm Ltd). (Author, 2015)

Plate D.2: Zero Tillage- Sowing operation in progress using a pneumatic seeder at Lengetia Farm Ltd. (Author, 2015)