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ESTIMATING CROP WATER REQUIREMENT AND YIELD OF OKRA IN BIOCHAR AMENDED SOIL

BY

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THIS THESIS IS SUBMITTED TO THE UNIVERSITY OF GHANA,

LEGON IN PARTIAL FULFILMENT OF THE REQUIREMENT

FOR THE AWARD OF MPHIL AGRICULTURAL ENGINEERING DEGREE

DEPARTMENT OF AGRICULTURAL ENGINEERING

SCHOOL OF ENGINEERING SCIENCES

JULY, 2016

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DECLARATION

I, Adam Yakubu, the author and conductor of this research, do hereby declare that the work done, estimating crop water requirement and yield of okra in biochar amended soil, except references cited in the document are the original copies of my work under supervision in the agricultural engineering department of the university of Ghana – Legon, compiled and submitted in July 2016. This work has not been submitted in any format for the award of any degree in any university.

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ABSTRACT

Vegetable crop production in Ghana over the past years has been a challenge due to water scarcity. The unpredictable and insufficient rainfalls has been a drawback on improving crop production and yield. This study aimed at estimating crop water requirement (CWR) and yield of okra in biochar amended soil. The FAO 56 dual crop coefficient approach was used to estimate CWR of a local variety of the test crop, okra (*Abelmoschus esculentus* L.). Models were developed to predict crop coefficient (k_c) and yield using ground based remote sensing technique.

The experiment was conducted at the University of Ghana (UG) Forest and Horticultural Crops Research Centre (FOHCREC) in Kade. Two irrigation treatments, namely full irrigation (FI) and deficit irrigation (DI) and four biochar amounts were applied in 32 plots. k_c at the initial, crop development, mid-season and late season growth stages determined are 0.28, 0.67, 0.91 and 0.86 under FI treatment and 0.32, 0.54, 0.98 and 0.8 for DI treatment though only FI data was presented under results. Seasonal accumulated water use by okra (ET_c) was 273 mm under FI treatment and 246 mm under DI treatment. There were no significant differences in total above ground dry biomass yield (Y_{TBM}) in the different biochar amounts under FI and DI treatments at ($P \leq 0.05$). There were significant difference in okra fresh fruit yield (Y_{FF}) in three biochar amounts only under DI treatment but no significant difference in Y_{FF} in all four biochar amounts under FI treatments was recorded.

From the results, it was concluded that biochar had effect on Y_{FF} under stressed and or limited water situations, thus DI and hence DI should be practiced in water scarce situations and areas especially when biochar is used. Premixing biochar with phosphorous fertilizer before incorporating into the soil also gave a better result in terms of high okra Y_{FF} over the alternative method of applying phosphorous fertilizer separately after biochar incorporated into the soil.

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DEDICATION

I dedicate this thesis to my family especially the late Hulaima Nasara Adam with love and appreciation of their support and encouragement throughout the study period.

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ACKNOWLEDGEMENT

I thank God almighty for his mercy and the good health given to me to carry out this work successful. My sincere gratitude to Dr. Stephen Abenney-Mickson, my principal supervisor and head of department who made it possible and enrolled me as a student on his project (WEBSOC) to collect data for my thesis write-up. His supervisory role too was very commendable as he dedicated time for me on both the field work and the write-up, not forgetting his critique that has shaped this write-up to its current stature. I thank Dr. Edward Benjamin Sabi who served as my co-supervisor and also paved way for me to access data for my thesis from WEBSOC project.

In the course of the field work, guidance and assistance from Dr. Eric Oppong Danso saw me through as well as his time and dedication towards my research work till submission to my main supervisors for further comments and corrections.

I acknowledge the great works of scholars in the agricultural engineering department especially in the persons of Dr. E. Y. Kra, Dr. A. A. Mahama, Dr. M. N. Josiah, Dr. P. K. Amoatey and all other staff members of the department who encouraged and guided me throughout my study period in the university. I also thank Prof. M. Yangyuoru for his great contributions, motivations and guidance on my topic as well as time dedicated for my consultations even during off working days.

Outside the academic fraternity, I acknowledge the effort and good works of my relations and friends who supported me both in material and financial terms especially the likes of Mr. Benjamin Afful, Mr. Paul Opoku, Mr. Abdul Razak Musa, Mrs. Hafsa Adam and Mr. Musa Bukari.

Finally, I thank all those who helped as well as the scholars who are yet to read this material and help towards making this thesis successful but whose names could not be mentioned here. My sincere acknowledgement to the above mentioned and to thank you all for your effort and time.

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TABLE OF CONTENTS

CONTENTS PAGE

University of Ghana http://ugspace.ug.edu.gh

University of Ghana http://ugspace.ug.edu.gh

CHAPTER FOUR RESULTS……………………………………………..51

University of Ghana http://ugspace.ug.edu.gh

University of Ghana http://ugspace.ug.edu.gh

LIST OF FIGURES

University of Ghana http://ugspace.ug.edu.gh

University of Ghana http://ugspace.ug.edu.gh

LIST OF TABLES

University of Ghana http://ugspace.ug.edu.gh

LIST OF ABBREVIATIONS AND SYMBOLS

ASTER – Advanced Space borne Thermal Emission and Reflection Radiometer

CROPWAT – Crop Water (SOFTWARE)

CWR – Crop Water Requirement

DGL –Development Growth Length

DI – Deficit Irrigation

DoF – Degree of Freedom

FAO – Food and Agricultural Organization of the United Nations

FAO-56 – Food and Agricultural Organization of the United Nations Paper Number 56

FAOSTAT – Food and Agricultural Organization of the United Nations Statistics

FC – Field Capacity

FI – Full Irrigation

FOHCREC – Forest and Horticultural Crops Research Centre

GPS – Geographical Positioning System

IGL – Initial Growth Length

LAM – Leaf Area Meter

LGL – Late Season Growth Length

LSD – Least Significant Difference

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METRIC – Mapping Evapotranspiration at high Resolution and with Internalized Calibration

MGL – Mid-Season Growth Length

MODIS – Moderate-resolution Imaging Spectroradiometer

MS – Mean Square

NDVI – Normalized Difference Vegetation Index

P-M – Penmann-Monteith

R^2 – Coefficient of Correlation

RMSE – Root Mean Square Error

SAMIR – Satellite Monitoring of Irrigation

SEBAL – Surface Energy Balance Algorithm for Land

SEBS – Surface Energy Balance System

SS – Sum of Squares

SSA – Sub - Saharan Africa

TDR – Time Domain Reflectometry

U.S.A – United States of America

UG – University of Ghana

UN – United Nations

UNESCO – United Nation Educational, Scientific, and Cultural Organization

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V.r – Variance

WEBSOC – Water, Energy-from-Biomass, Soil, Organics, and Crop

A – Area covered by crops used in destructive sampling [ha or m^2]

A_g – Area of ground covered by leaf [m^2]

A_l – Area of leaf [m^2]

D – Soil water deficit [mm]

D_g – Downwards drainage [mm]

e_a – Actual vapor pressure [kPa]

E_{pan} – Pan evaporation [mm day^{-1}]

e_s – Saturation vapor pressure [(kPa]

$e_s - e_a$ – Saturation vapor pressure deficit [kPa]

ET – Evapotranspiration [mm day^{-1}]

ET_c – Crop Evapotranspiration [mm day^{-1}]

ET_o – Reference Evapotranspiration [mm day^{-1}]

FF – Fresh okra fruit harvested [tons or kg]

G – Ground heat flux [MJ m^{-2} day^{-1}]

H – Sensible heat flux [MJ m^{-2} day^{-1}]

I – Irrigation [mm]

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K_c	– Crop coefficient
K_{cb}	– Basal crop coefficient
$K_{cb\ ini}$	– Basal crop coefficient at the initial crop growth stage
$K_{cb\ late}$	– Basal crop coefficient at the late season crop growth stage
$K_{cb\ mid}$	– Basal crop coefficient at the mid-season crop growth stage
K_e	– Soil Evaporation coefficient
K_p	– Pan evaporation coefficient, dependent on type of pan used
LAI	– Leaf Area Index
LE	– Latent heat flux [MJ m^{-2} day^{-1}]
p	– Fraction of soil water depleted by crop in the root zone [0-1]
P	– Precipitation [mm]
RAW	– Readily Available Water [mm]
R_f	– Surface runoff [mm]
RH	– Relative humidity [kPa]
R_n	– Net radiation [MJ m^{-2} day^{-1}]
S_g	– Capillary rise from the lower layer to the crop root zone [mm]
SWC	– Soil Water Content [mm]

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T – Temperature [°C]

T_c – Crop transpiration [mm day^{-1}]

TAW – Total Available Water [mm]

TBM – Total above Ground Biomass [kg]

u_2 – Wind speed at 2 m height [m s^{-1}]

WP – Water Productivity [kg m^{-3}]

WP_{FF} – Water productivity of fresh okra fruit [kg m^{-3}]

WP_{TMB} – Water productivity of biomass produced [kg m^{-3}]

Y_{FF} – Yield of total fresh okra fruit harvested [kg m^{-2}]

Y_{TBM} – Yield of total dry above ground biomass [kg m^{-2}]

Z_r – Rooting depth [m]

γ – Psychrometric constant [kPa °C^{-1}]

Δ – Slope of vapour pressure curve [kPa °C^{-1}]

ΔW – Change in soil water storage in the root zone [mm]

Θ_{FC} – Soil water content at field capacity [mm]

Θ_{WP} – Soil water content at wilting point [mm]

ΣET_c – Sum amount of water used by crop in evapotranspiration [mm or m]

ϵ_a – Apparent relative permittivity

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CHAPTER ONE

INTRODUCTION

1.1 Background

The ever increasing population of Ghana within its fixed landmark area has put high demand on water and food. The current world's population which has also been projected to increase to 9.5 billion by 2050, demands an increase in agricultural production of 70 % or more between 2005 and 2050 (Lal, 2015). Agricultural crop production coupled with improved crop yield could help reduce the current and future high demand for food.

Crop growth, development and yield depend tremendously on water and this has contributed to making agriculture the world's largest consumer of water. In Ghana, the major form of crop farming depends on rainfall, but its onset and intra - seasonal distribution is characterized by marked fluctuations (Mawunya *et al*., 2011). The most alarming negative effect of unpredictable rainfall on crop yield is severe in the dry season in Ghana. In order to increase and improve on crop yield, it is necessary to practice conservation and effective use of water for agricultural crop production especially in the dry season which is marked with water scarcity.

Successful crop production in the dry season is possible through irrigation. While irrigation is known to effectively aid in continuous crop production and address the problem of limited precipitation in the dry season, it is important to select the suitable type of irrigation to further address the problem of water scarcity. Drip system of irrigation provides higher application efficiency as a means of saving water (Simonne *et al*., 2011). Scheduling irrigation, that is how much water to apply and when to irrigate does not just augment the effectiveness of saving irrigation water but it also ensures effective crop water use and save crop production cost as well.

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Vegetable crop production in Ghana has improved from peasant farming to commercial farming and currently provides source of food and income to the local Ghanaian farmer. The escalated increase in prices of vegetables during the dry season is an indication of the high demand on such crops.

Okra (*Abelmoschus esculentus* L.) is a vegetable crop well noted for its edible fruit and grows well in the tropical, subtropical and warm areas of the world. It is known for its nutritional and medicinal values and also its low caloritic value. The local varieties in Ghana have been reviewed in Oppong-Sekyere *et al*. (2012). World production statistics as at the year 2013 was 8,689,499 tonnes, India being the largest producer (6,350,000 tonnes) while Ghana was ranked the ninth largest producer (63,860 tonnes) globally and sixth largest producer in Africa (FAOSTAT, 2013). Okra can be cultivated all year round provided there is no limitation to water supply and solar radiation. The crop can be cultivated in various soil types but thrives in well drained soils.

Crops loose water to the atmosphere through evapotranspiration. Evaporation is one part of the evapotranspiration process which is defined as the loss of water from wet vegetative parts and soil surface through vaporization while transpiration is the other process defined as the vaporization of liquid water contained in plant tissues through the opening of the stomata pores in the leaves (Allen *et al*., 1998). Several factors affecting evapotranspiration as defined by Allen *et al*. (1998) are:

- Climatic factors that affect evapotranspiration principally are solar radiation, air temperature, wind speed and humidity.
- Crop factors that mainly affect evapotranspiration are crop type, variety and crop growth stage.

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- Environmental and management practices such as poor soil fertility, limited fertilizer and pesticide application affect crop growth and adversely affect the crop evapotranspiration. Crop canopy cover, plant density and soil moisture content also affect evapotranspiration.

Reference crop evapotranspiration (ET_o) is the evapotranspiration rate from a hypothetical grass reference crop, not short of water while crop evapotranspiration (ET_c) under standard condition is evapotranspiration from crops free from disease and pest attack, well fertilized and growing in large fields under optimum soil water and achieving full production under the given climatic conditions (Allen *et al*., 1998).

Computation of ET_o primarily involves the use of climatic data. Several models in the past used to compute ET_o included, Thornthwaite, Blaney Criddle, Priestley Taylor, Kimberly, Penman, Hargreaves, Hargreaves–Samani models. The Food and Agriculture Organization (FAO) of the United Nations (UN) proposed method, FAO Penman-Monteith equation has been accepted worldwide as the recommended model for computing ET_o which contains all the basic agro climatological parameters and it provides more consistent ET_o values with actual crop water use data worldwide (Allen *et al.*, 1998).

ET_c can be computed using direct methods i.e. pan evaporation method, lysimeter method, and indirect method using remote sensing.

Crop coefficient (k_c) is the ratio of crop evapotranspiration to reference evapotranspiration which is affected by the crop type, climate, soil evaporation and crop growth stage. Remote sensing of crop coefficient for estimating ET_c provides actual k_c data that eliminate uncertainties of different climatic and crop management effects on already determined k_c values for real time irrigation scheduling. Crop canopy reflectance indices e.g. Normalized Difference Vegetation index (NDVI) are used in remote sensing to determine crop coefficient for ET_c computations. Remote sensing

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method of determining k_c and ET_c has been done by many researchers including (Allen *et al*., 2003; Kamble *et al*., 2013; Zwart and Bastiaanssen, 2007).

Two approaches used in computing ET_c are the single crop coefficient (k_c) approach and dual crop coefficient ($k_{cb} + k_e$) approach. The single crop coefficient integrates the combined effect of crop transpiration and soil evaporation into a single k_c while the dual crop coefficient is used to separate the transpiration effect of the crop from the evaporation effect of the soil or growth media. For research purpose, the dual crop coefficient approach is suitable (Allen *et al*., 1998). ET_c using the crop coefficient approach is determined by multiplying ET_o by the crop coefficient (k_c).

Crop Water Requirement (CWR) is the total amount of water needed to compensate all the water losses through evapotranspiration at a defined crop growth stage. A fair knowledge of ET_c is a pre-requisite for estimating crop water requirement. In other words, to estimate crop water requirement, one must first of all determine ET_c. The values of ET_c and CWR are identical whereby ET_c represent water loss from the crop, CWR represent the amount of water required to compensate for water loss through ET_c (Allen *et al*., 1998).

CWR varies with varying crop growth stage. The four crop growth stages are initial growth stage, crop development stage, mid-season growth stage and the late season growth stage characterized by different crop coefficients and hence different amounts of water loss through evapotranspiration. As crops grow and undertake development, evapotranspiration increases and therefore the crop water requirement also increases. At mid growth stage, crop evapotranspiration reaches its peak value and remains constant for some period of time. The value decreases during final crop growth stage as the crop begins to shed off dry leaves after senescence of leaves set in where the amount of water required at that stage reduces. Crop water use at the four growth stages

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sum up to the crop water requirement for the whole growing season given in millimetres (mm) of water.

The ability of the plant to draw water from the soil for evapotranspiration and other activities depends on three main factors namely, hydraulic conductivity of soil, gradient between soil water suction and root suction and the crop rooting density (Hillel, 1998). These factors can be improved by the addition of soil conditioners.

Biochar is a soil conditioner produced from the pyrolysis of crop residue and biomass. Biochar is reported to improve soil physical properties and hydraulic properties of the soil as well as improve soil water holding capacity (Abdel-Nasser *et al*., 2007; Eldardiry and Abd El-Hady, 2015; Yangyuoru *et al*., 2006). It also improves soil nutrient retention and was found to enhance phosphorous fertilizer retention in the soil for crop use by Cui *et al*. (2011). Biochar was found to be more effective on crop yield when combined with a mineral fertilizer than applying biochar alone into the soil (Albuquerque *et al*., 2013; Lehmann *et al*., 2011).

Crop yield is defined as the vegetative parts of the crop harvested for use. The vegetative parts include the root, shoot, leaves and fruit in vegetable production. Crop yield is determined by several factors. Two major factors determining crop yield are water and nutrient. Yield data are used to model many crop phenology. Okra yield could be determined as total above ground biomass or total fresh okra fruits harvested. Total above ground biomass is defined as the sum total of vegetative parts of crop and fruits harvested above the soil surface. Yield produced per unit amount of water used is termed water productivity. It measures the effectiveness of the quantity of water used in producing the yield.

Emergence of remote sensing technique such as Normalized Difference Vegetation Index (NDVI) has made it possible to predict crop yield using vegetative indices with promising results

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(Christensen and Goudrian, 1993). A number of research works on crop yield estimate using remotes sensing includes Lopresti *et al*. (2015) and Panda *et al*. (2010). Many of the models developed for estimating crop yield are empirical since there were challenges to developing a universal model for predicting crop yield (Gommes, 1998).

1.2 Problem Statement

Rainfed agriculture is unreliable and ineffective for crop production due to current challenges posed by global warming and climate change which has led to crop failure and yield reduction. Even in areas with appreciable precipitation in the wet seasons, the onset and end of the rainy season is usually unpredictable. Water scarcity in dry season poses a bigger challenge on crop production especially vegetable crop production. Another drawback in tackling low crop production as result of water scarcity is lack of information on irrigation water requirement of okra cultivated in the study area and other sub regions of the country. Information on crop coefficient of okra for computing ET_c and an effective means of determining k_c in the study area is not available. Measures to effectively use and conserve the scarce water and mineral fertilizer in the soil have not been given maximum attention and no solutions have been proposed.

To minimize the impacts of the unpredictable and insufficient precipitation on crop production, there is the need to adopt irrigation as an alternative source of water for vegetable crop production especially okra. Drip system of irrigation is most suitable for enhancing effective water application to crops while saving substantial amounts of water that could have been lost to the atmosphere through evaporation from soil surface. In order to enhance crop yield and effective savings of water through drip system, it is equally important to supply the right amount of water needed by the crop, through crop evapotranspiration estimates. Determination of k_c of okra will aid in

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computing ET_c and hence better estimates of crop water requirements. Application of ground based remote sensing technique will help model and produce actual k_c values of okra void of uncertainties of tabulated k_c in literature determined under different environmental and crop management effects at different agro-climatological areas to aid irrigation scheduling. To improve on soil physical properties for conserving mineral fertilizer and the scarce water, biochar was applied to the soil to improve on okra yield.

1.3 Aim and Objectives

The overall aim of this research was to estimate crop water requirement and yield of okra in biochar amended soil at the University of Ghana (UG) Forest and Horticultural Crops Research Centre (FOHCREC) in Kwaebibrem District (Kade), in the Eastern Region of Ghana.

The following specific objectives helped to achieve the overall aim:

a. Estimation of crop coefficient of okra empirically and model developed to predict crop coefficient of okra using handheld remote sensing device called RapidSCAN CS-45.
b. Estimation of water requirement of okra at Kade from the empirically derived crop coefficient and computed reference crop evapotranspiration at the study area.
c. Determination of actual yield of okra in biochar amended soil under full and deficit irrigation and develop a model for okra yield prediction using remote sensing information.
d. Determination of phosphorous fertilizer and higher biochar amount (10 t ha^{-1}) combination method to attain higher yield.
e. Determination of water productivity of okra under full and deficit irrigation.

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CHAPTER TWO

LITERATURE REVIEW

2.1. Background

Substantial research has been carried out in determining water requirement of okra and various agricultural crops such as the research works done by (Aghdasi *et al.*, 2011; Hashim *et al.*, 2012; Oppong Danso, 2014). Different methodologies have been used to estimate crop water requirement by the application of direct methods and remote sensing techniques. The ideologies behind the different methodologies of estimating crop water requirement are necessary and important as one of the means to enhancing effective crop water use, optimize agricultural water management strategies and also address the problem of water scarcity effects on yield in agricultural crop production.

In the light of determining crop water requirement (CWR), it has been observed from literature that preferences have been given to geographical commercial crops of interest such as wheat, cotton, barley, rice and maize by most researchers probably due to the major economic benefit of such crops to the researchers. It has also been observed that little has been done on determination of water requirement of okra especially in Ghana and Sub Saharan Africa (SSA). The popular referenced FAO paper number 56 which serves as a guideline for computing crop water requirements compiled by Allen *et al*. (1998) also has limited information on crop coefficients and water requirement of okra. Kumar *et al*. (2010) found out no attention was given to okra production and its improvement by the international research programme in the past because it was considered a minor crop.

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Different methods of determining crop water requirement through computation of crop evapotranspiration (ET_c) are the direct and indirect (remote sensing) methods. A study on canopy reflectance –based crop coefficient derivation using a hand held remote sensing device (Handheld Exotech radiometer) by Jayanthi *et al*. (2007) concluded that remote sensing has the potential to offer not only effective but also more efficient means of optimizing water use due to its ability to derive actual crop water requirement, inclusive of their variability in space and time.

Ground based remote sensing technique was applied in this study because of its many advantages over the satellite based remote sensing method by eliminating errors and challenges usually encountered in the satellite based method Jayanthi *et al*. (2007).

2.2 Crop Water Requirement

Crops lose water to the atmosphere through evapotranspiration and the amount needed to replace the water loss is termed Crop Water Requirement.

Oppong Danso (2014) estimated seasonal water requirement of okra in a sandy soil in south east Ghana and had the values 233 mm, 236 mm, 269 mm and 233 mm with an average of 243mm for four seasons on a drip irrigated field. Panigrahi and Sahu (2013) determined water use of okra under partial root zone furrow irrigation and had 250 mm, 232 mm and 279 mm under three different treatments in India. Hashim *et al.* (2012) researched on crop water requirement of some winter and summer crops in Saudi Arabia under centre pivoted irrigation system and had 502 mm for okra as its water requirement. Jayapiratha *et al.* (2010) also determined water requirement of okra to be 359 mm and 212 mm under drip irrigation scheduled at 30 minutes and 15 minutes respectively.

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The importance of determining crop water requirement is to guide the farmer and the irrigation engineer to supply the right amount of water needed by the crop. This in effect will enhance efficient water use and address the problem of low crop production resulting from water scarcity especially in arid and semi-arid parts of the world.

2.2.1 Determination of Crop Water Requirement

There are two main methods of determining crop water requirement, namely the direct method and indirect method. The direct methods includes mass transfer using Bowen ratio, secondly, soil water balance method using lysimeter or soil moisture measuring devices and the energy balance method on the other hand. Indirect methods include remote sensing technique which uses ET_o x k_c approach as outlined in Allen *et al*. (1998) where k_c values are empirically determined or obtained from referenced sources like FAO 56.

Remote sensing method involves the acquisition of vegetative indices data (NDVI) from either ground based or satellite based radiometers which are modelled into k_c and then multiplied by ET_o to determine crop water requirement. ET_o in either of the methods could be calculated using FAO Penmann-Monteith equation, Thornthwaite, Blaney-Criddle, Priestley Taylor, Kimberly, Penman, and other ET_o models.

Remotes sensing method is normally preferred to the direct method due to its spatial data acquisition on both micro and large scale level of crop production, less laborious and effective operational time. It also addresses the uncertainties of already tabulated k_c values used in the direct method.

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Remote sensing is categorized into satellite based measurements (Active) using images produced from satellites to deduce NDVI and ground based measurements (Passive) using radiometers, usually handheld on the ground surface to deduce NDVI. Whereas the theory behind direct method is the soil water balance equation (Equation 2.1), remote sensing method is theoretically backed by surface energy balance equation (Equation 2.3).

2.2.2 Direct Method of Estimating Crop Water Requirement

The use of lysimeters is the most popular direct method of determining crop evapotranspiration and has been employed in many research works in the past including (Hashim *et al*., 2012; Wegehenkel *et al.*, 2008).

Fisher (2012) determined crop water requirement and crop coefficients of cotton with electronic weighing lysimeter applying the weight differences of the soil water i.e. weight of lysimeter after water application minus weight of lysimeter before application of irrigation water or rainfall and then converted the weighed value to depth of water in millimetres (mm) for the given time. Wegehenkel *et al*. (2008) carried out similar work in estimating crop evapotranspiration using the soil water balance model. The lysimeter works on the principle of soil water balance model in estimating ET_c by accurately measuring other parameters equated to ET in the soil water balance equation given by Equation 2.1.

$$ET = P + I + \Delta W + S_g - D_g - R_f \tag{2.1}$$

Where,

ET – Evapotranspiration [mm day^{-1}],

P – Precipitation [mm],

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I – Irrigation [mm],

ΔW – Change in soil water storage in the root zone [mm],

S_g – Capillary rise from the lower layer to the crop root zone [mm],

D_g – Downwards drainage [mm],

R_f – Surface runoff [mm].

In a drip irrigation system where the field is irrigated to its field capacity or below its field capacity under deep water table, S_g, D_g, R_f are assumed zero. And therefore;

$$ET = P + I + \Delta W \qquad (2.2)$$

Where parameters are defined in Equation (2.1).

Though the lysimeter has been used widely as a direct method of determining crop water requirement and crop coefficients, it has registered some errors from the fact that it is difficult to achieve actual field soil conditions equal to that in the lysimeter soil conditions. In other words, the lysimeter method produces results which do not represent actual cropped field conditions.

Historically, the requirement of making the vegetation or crop both inside and outside of the lysimeter be perfectly matched (same height and leaf area index) has not been achieved in the majority of works done with the lysimeter and this has resulted in severe errors and are unrepresentative of actual evapotranspiration and crop coefficient (K_c) data (Allen *et al.*, 1998). The lysimeter method could not also account for the weight of the sample crop growing in the lysimeter separately. Increase in biomass formation is directly proportional to increase in crop weight and there is no mechanism of weighing instantaneously the sample crop growing in the lysimeter separately and non-destructively, instead the sum weight of the crop and water added are recorded in one unit. Thus, the additional weight of the crop in the lysimeter has effect on the total weighted data recorded in the lysimeter which is usually not accounted for. Also the effect of

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heterogeneous soil characteristics on large fields cannot be accounted for as the lysimeter is constructed at varying sizes which are usually smaller and incomparable to actual cropped field sizes *in situ*. Data from lysimeters are therefore representative and not the actual on field of varying soil characteristics and physical properties.

Cost implication and labour intensity of lysimeter method of determining CWR is very high as it costs approximately US$1700 in the year 2001 in U.S.A. to construct a moderate sized lysimeter requiring the effort of two people and 40 hours of labour to install using minimal excavation and hand tools (Fisher, 2012).

Pan evaporation method of estimating reference evapotranspiration (ET_o) has also been used in the past to estimate crop water requirement. The pan evaporimeter is subject to combined effects of radiation, wind, temperature, and humidity and can thus be correlated with evapotranspiration from the field in which it is placed (Hillel, 2004). The main drawback of this method as a direct method of estimating evapotranspiration is its inaccuracies during heavy rainfall events where the evaporation pan gets filled and spill. How much water evaporated before such heavy rainfall events cannot be accounted for and also the intrusion of birds and other animals drinking from such pans cannot be completely eliminated.

An advancement of the direct method of computing crop water requirement is the use of a models such as the one developed by Clarke *et al*. (1998) known as CROPWAT, a computer model that compute CWR from ground based input data based on FAO 56 (Allen *et al*., 1998) methodology. The challenge in using CROPWAT for computing CWR is meeting the data input required by the software. It is usually difficult to meet the requirement for the input data set of the software for new crop varieties without predetermined characteristics. Most of the input data required are predetermined parameters such as crop data (rooting depth, k_c, yield response factor, crop growth

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length, and critical soil water depletion fraction) as well as sometime soil data are also required as input parameters in the software making the method complex and expensive.

The most accurate and widely accepted method of computing crop water requirement is the ET_o x k_c approach as outlined in the FAO 56 publication by Allen *et al*. (1998) using empirically derived k_c values (Kamble *et al*., 2013). Lhomme *et al*. (2015) also proposed a new model and suggested for it to be used in place of the FAO 56 two - step approach for computing crop water requirements. Though standard crop coefficients of various crops have been reported in the FAO 56 publication (Allen *et al*., 1998), crop coefficient of okra was not included.

2.2.3 Indirect Method of Estimating Crop Water Requirement

Remote sensing is a method of collecting information related to objects or areas without getting direct contact with the object or area under study (Aggarwal, 2013). The procedure in remote sensing as an indirect method of estimating CWR make use of surface energy balance equation which relates the proportion of the solar radiation reaching and reflected from the canopy of vegetation and the soil surface. The surface energy balance equation is used to determine ET which is equivalent to the energy needed to evaporate water molecule from the evaporation surface termed latent heat flux (LE), Equation 2.3 where L is latent heat of vaporization of water.

$$R_n = LE + H + G \tag{2.3}$$

Where,

R_n – Net radiation [MJ m^{-2} day^{-1}],

LE – Latent heat flux [MJ m^{-2} day^{-1}],

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H – Sensible heat flux [MJ m^{-2} day^{-1}],

G – Ground heat flux [MJ m^{-2} day^{-1}).

2.2.3.1 Satellite Based Remote Sensing Method of Estimating Crop Water Requirement

Satellite based remote sensing for computing ET make use of images produced by the various satellites attached to airplanes and other satellites at a defined image pixel and resolution. Satellite based images have been used in models to estimate crop evapotranspiration in literature for the past years. Aghdasi *et al*. (2011) determined crop water requirement using Moderate-resolution Imaging Spectroradiometer (MODIS) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images fed into Surface Energy Balance System (SEBS) Algorithm developed by Su (2002).

Other models have been developed using MODIS, ASTER and other remotely sensed images from the various satellites to compute evapotranspiration. Others include Satellite Monitoring of Irrigation (SAMIR) developed by Lepage *et al*. (2009). Bastiaanssen *et al*. (1998) also developed a model in the Netherlands known as the Surface Energy Balance Algorithm for Land (SEBAL) which is a digital image - processing model for calculating evapotranspiration and has been applied in research work done by (Allen *et al*., 2003; Zwart and Bastiaanssen, 2007) to estimate ET_c. A variant of SEBAL is METRIC (Mapping Evapotranspiration at high Resolution and with Internalized Calibration) which is also an image-processing model for calculating ET_c as a residual of the surface energy balance developed by Allen *et al*. (2005). METRIC has also been used to estimate ET_c by (Carrillo-Rojas *et al*., 2016; Mkhwanazi and Chávez, 2013).

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Errors in terms of quality of images produced in times of bad weather conditions and the particular satellite revolution time to deduce NDVI by the satellite based methods are inevitable. At an instance when SEBAL and METRIC were compared to lysimeter method of estimating CWR, higher errors were recorded in SEBAL than METRIC in a study conducted by Mkhwanazi and Chávez (2013). In general, satellite based remote sensing data for computing crop evapotranspiration lack some credibility and accuracy sometimes due to the fact that it is difficult to tell what happens immediately after a satellite overpass or what happened after an orbit till the next orbit of the satellite revolution. Secondly, the cloud cover has a great influence on the quality of image produced by the satellite and this can affect the data produced by the satellite based method for estimating crop water requirement.

2.2.3.2 Ground Based Remote Sensing method of Estimating Crop Water Requirement

Ground based remote sensing is effective in the development of canopy reflectance based crop coefficients and its subsequent method for estimating crop water requirements. Jayanthi *et al*. (2007) observed that ground based remote sensing has been restricted to alfalfa, grain crops, and cotton when the corresponding reflectance data for some vegetable crops, tubers and roots were deficient and not readily available. Ground based remote sensing method of estimating CWR is most effective and preferable for studying small fields and mixed cropped fields over satellite based method.

Numerous researches have been done using ground based remote sensing devices. Some of these devices including SDL 1800, two-band sensor used in a research by (Oppong Danso, 2014; Razzaghi *et al.*, 2012), Exotech 4-band radiometer used by (Jayanthi *et al.*, 2007; Kang *et al.*, 2002). Others included Field Spec Pro, hand-held radiometer used in a research by (Duchemin *et*

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al. 2006; Er-Raki *et al*., 2007), hand-held Agricultural Digital Camera applied in a research work by Johnson and Trout (2012).

RapidSCAN CS-45 handheld crop sensor is another ground-based remote sensing device used for crop canopy reflectance measurements. The RapidSCAN CS-45 represents the latest advancement in active crop canopy sensing solutions which is a completely self-contained active crop canopy sensor that integrates a data logger, graphical display, GPS, crop sensor and power source into one, small compact instrument (Holland Scientific, 2012). The sensor is unaffected by ambient illumination allowing it to take accurate measurements day or night due to its internal polychromatic light source (Holland Scientific, 2012).

Though most of the ground based handheld devices are digital and display crop canopy reflectance data in vegetative Indices (NDVI), the RapidSCAN CS-45 was used for this research because of its self-illumination property making it independent on solar radiation (Holland Scientific, 2012). The RapidSCAN CS-45 has a limitation of not being able to measure individual NDVI data of mixed crops on the same field. To ensure accurate result, the crop field to be scanned should be cleared of weeds or any other foreign vegetation and this has made its application a bit laborious though it’s many advantages.

The basic difference between the ground based and the satellite based remote sensing is, ground based remote sensing measures what happens in the real world while the satellite based forms a limited representation of the real world (Bakker *et al*., 2001).

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2.3 Reference Evapotranspiration (ET$_o$)

Reference evapotranspiration (ET$_o$) as defined by Allen *et al.* (1998) is the evapotranspiration rate from a reference surface not short of water where the reference surface is a hypothetical grass reference crop with an assumed crop height of 0.12 m with a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23. Reference evapotranspiration can be estimated directly using pan evaporimeter and lysimeter. The pan evaporation is related to the reference evapotranspiration by Equation 2.4.

$$ET_o \;=\; K_p \; x \; E_{pan} \tag{2.4}$$

Where,

ET$_o$ – Reference evapotranspiration [mm day^{-1}],

K$_p$ – Pan evaporation coefficient, dependent on type of pan used e.g. Class A pan,

E$_{pan}$ – Pan evaporation [mm day^{-1}].

Several models have also been developed using climatic data as input parameters to compute ET$_o$. Among others are the Thornthwaite, Blaney- Criddle, Priestley Taylor, Kimberly, Penman, Hargreaves, Hargreaves–Samani models and Penman-Monteith models. On the other hand, computer programmes have also been developed to compute ET$_o$, among others including the one developed by Gocic and Trajkovic (2010). Many of the models are empirical and do not contain all the agro-climatic parameters influencing atmospheric demand on evapotranspiration. The accepted model recommended by FAO for computing ET$_o$ is the FAO Penman-Monteith model. The FAO Penman-Monteith model for computing ET$_o$ closely approximate grass ET$_o$ at the location evaluated, physically based, and incorporates both physiological and aerodynamic parameters (Allen *et al*., 1998).

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Climatic data are usually obtained from a meteorological station. Four basic climatic data are required to compute ET_o, namely Net radiation (R_n), Temperature (T), Relative humidity (RH) and Wind speed (u_2). All other supporting climatic parameters required to compute ET_o using the FAO Penman-Monteith equation are outlined in Allen *et al*. (1998). ET_o values symbolizes the atmospheric demand on crop evapotranspiration, thus when ET_o values are higher, the crop loses more water to the atmosphere through ET_c and vice versa.

2.4 Crop Coefficient

Crop coefficient (K_c) is defined as a ratio of the crop's evapotranspiration to reference evapotranspiration given by the relation in Equation 2.5. Crop coefficient (K_c) integrates the characteristics (crop height, albedo, crop canopy resistance and soil evaporation) that differentiate the field cultivated crop from reference grass (Allen *et al*., 1998).

$$K_c = \frac{ET_c}{ET_o} \tag{2.5}$$

Where,

K_c – Crop coefficient,

ET_c – Crop evapotranspiration [mm day^{-1}],

ET_o – Reference evapotranspiration [mm day^{-1}].

Crop coefficient determined empirically is the best way to address the uncertainties of the generalized crop coefficients tabulated in Allen *et al*. (1998). Also standard time-based crop coefficients may fail to represent the actual crop water use, in situations when deviations in weather or agronomic constraints appreciably change crop development patterns from standard conditions (Kang *et al*., 2002). The two types of crop coefficient used in computing ET_c are the single crop coefficient (K_c) and the dual crop coefficient ($K_{cb} + K_e$).

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The first approach known as single crop coefficient is used to characterize the evaporation and transpiration difference between the field crop and reference grass into a single effect. The second approach known as dual crop coefficient involves separating the soil evaporation coefficient (K_e) from the transpiration effect of the crop called basal crop coefficient (K_{cb}) given by Equation 2.6. The basal crop coefficient, K_{cb}, is defined as the ratio of ET_c to ET_o when the soil surface layer is dry but where the average soil water content of the root zone is adequate to sustain full plant transpiration and it represents the baseline potential K_c in the absence of the additional effects of soil wetting by irrigation or precipitation (Allen *et al.*, 1998).

$$K_c = K_{cb} + K_e \tag{2.6}$$

Where,

K_c – Crop coefficient,

K_{cb} – Basal crop coefficient,

K_e – Soil evaporation coefficient.

2.4.1 Direct and Remotely Sensed Crop Coefficients

Crop coefficients have been modelled through different procedures in the direct and remote sensing method. The application of the direct method of determining crop coefficient is that of the lysimeter method where actual evapotranspiration (ET_c) determined directly from the lysimeter is divided by reference evapotranspiration (ET_o) to derive crop coefficient (K_c). Basal crop coefficients have also been modelled using leaf area index (LAI) in the direct and remote sensing method (Allen *et al*., 1998; Duchemin *et* al., 2006; Ritchie and Burnett, 1971). Leaf area used in computing LAI could be determined directly by using graduated rule, tape measure or the use of computer software as used in this study. Similar software such as NIH Image and ImageJ has been

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used to analyse scientific images discussed in Schneider *et al*. (2012). On the other hand, models have been developed by Zheng and Moskal (2009) and Zhu *et al.* (2013) using remote sensing techniques as an indirect method of determining leaf area non-destructively but Zheng and Moskal (2009) discredited the use of remote sensing in determining LAI. Digital camera used in this experiment to aid in leaf area measurement with the aid of a computer software has been suggested by Jonckheere *et al*. (2004).

Ground based remote sensing has utilized canopy reflectance in parts of the electromagnetic spectrum to develop crop coefficients using vegetation indices. The mechanism by which crop uses the incident solar energy for photosynthesis and the degree of ground shading by the crop canopy forms the basis of determining canopy-based crop coefficients (Jayanthi *et al*., 2007). Canopy reflectance based method of computing crop coefficient as used in Razzaghi *et al.* (2012) and Oppong Danso (2014) has been intensively reviewed and validated by Jayanthi *et al*. (2007) as a practical and accurate indicator of actual crop evapotranspiration (ET_c).

K_c determined empirically in this research has the advantage of addressing the uncertainties of standardized crop coefficients established in literature. Ground based remote sensing method of estimating ET_c can be used to study crops on smaller cropped fields as well as different crop plots on the same field which could have been a challenge and a drawback on the satellite based method.

2.5 Crop Evapotranspiration (ET_c)

Both the direct and remote sensing technique have been used to establish the relation between reference evapotranspiration (ET_o) and crop coefficient (K_c) to estimate crop evapotranspiration (ET_c). The crop coefficient approach is widely used to estimate crop evapotranspiration. It is

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determined by multiplying the empirically determined crop coefficient (K_c) by the reference evapotranspiration given in Equation 2.7.

$$ET_c = K_c \text{ x } ET_o \tag{2.7}$$

$$K_c = K_{cb} + K_e \tag{2.8}$$

Where,

ET_c – Crop evapotranspiration [mm day^{-1}],

ET_o – Reference evapotranspiration [mm day^{-1}],

K_c – Crop coefficient,

K_{cb} – Basal crop coefficient,

Ke – Soil evaporation coefficient.

2.6 Irrigation

Irrigation is the practice of supplying water to crops artificially to permit farming in arid regions and to offset drought in semi-arid or semi humid regions (Hillel, 2004). Even in areas with ample precipitation, irrigation can be applied to supplement the uneven spatial distribution of precipitation.

There are two main categories of irrigation systems, namely surface irrigation system and pressurized system of irrigation. Surface irrigation system includes furrow, border strip and basin irrigation while the pressurized system of irrigation includes sprinkler and drip (trickle) irrigation.

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In Ghana, there are two main crop growing season namely, wet and dry season. The dry season poses severe stress on crop production and reduction in yield drastically due to limited rainfall. Irrigation therefore enhances crop cultivation as well as increasing crop yield especially in the dry season usually stretching from November to March each year in Ghana.

2.6.1 Irrigation Scheduling

Irrigation scheduling is defined as when to irrigate and how much water to apply to a crop. Irrigation scheduling is very important in any irrigation practice because it serves as a guide in supplying the right amount of water required by the crop at the right time and to improve on Water Productivity (WP). Irrigation is usually scheduled based on soil moisture content after a fraction of soil moisture has been depleted by the crop. Soil water content (SWC) measurements and estimates for irrigation scheduling in the past years were done using neutron scattering, gravimetric, gypsum block and tensiometer methods which had a lot of disadvantages (Blonquist Jr. *et al*., 2006). Recent advances in technology has made it possible to measure *in situ* soil water content using models and sensors. Time Domain Reflectometry (TDR) is a setup device with sensors used to measure soil moisture content as used in this experiment and other research works including (Kameyama *et al*., 2014; Plauborg *et al*., 2005; Oppong Danso *et al*., 2015).

TDR has been calibrated for almost all agricultural soils and is a widely used and established technique for continuous measurements of soil moisture content. TDR is however affected by conductivity of soils and biochar (Kameyama *et al*., 2014). Though biochar formed at high pyrolysis is conductive, high pyrolysis temperature at 400 °C and 600 °C were found to have same apparent relative permittivity (ϵ_a) to that of non-amended soil at a given water content (Kameyama

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et al., 2014). This validated the direct use of the TDR on the biochar prepared at pyrolysis temperature of 500 °C in this experiment without further calibration.

Full Irrigation (FI) and deficit irrigation (DI) scheduling involve the initiation of irrigation when the crop has depleted a particular fraction (p) of total available soil water (TAW) in the root zone. The fraction (p) is defined as the average fraction of total available soil water (TAW) that can be depleted from the root zone before drought stress occurs (Allen *et al*., 1998). Irrigation scheduled at FI and DI could be aimed at ascertaining their effect on crop yield and water productivity.

Many research works applying different levels of irrigation at varying fractions of soil water depletion showed an improved and positive response of crop yield to the frequent irrigation levels as found in Konyeha and Alatise (2013). On the other hand, Jayapiratha *et al.* (2010) and Kang *et al*. (2002) recorded high crop yield, biomass and water productivity at low and less frequent irrigation levels.

2.7 Soil Amendment

Soil is the home of crops and other micro-organisms playing an important role in crop growth and development. Soil is a non-renewable natural resource on human time scale with vulnerability to degradations including depletion of the soil organic carbon pool, loss of soil fertility and elemental imbalance, acidification and salinization which can be amended by restorative land use and adoption of recommended management practices (Lal, 2015). Irrigated lands in SSA countries have been reported to have lost 7 % of their potential productivity to land degradation (Duku *et al*., 2011).

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Soil conditioners are highly cross-linked polyacrylamides with 40 % of the amides hydrolyzed to carboxylic groups which do not directly interact with the soil matrices but rather their aqueous gels serves as moisture reservoirs for crop use in the soil (Yangyuoru *et al*., 2006). The ability of the crop to withdraw water and nutrients from the soil depends on condition of the soil including its texture, porosity, infiltration capacity, water holding capacity and soil hydraulic conductivity. Soil physical quality is a contributing factor to sustainable agriculture crop production and its indicators include porosity, water transmission and retention as plant-available water capacity, aeration, effective rooting depth, soil heat capacity and temperature regime (Lal, 2015). On a condition that the hydraulic conductivity of the soil is high and there is an appreciable amount of water at a higher potential in the soil than the root zone, water will be drawn by the root of the crop from the soil with ease.

Africa's land degradation is attributed to failure on the part of the farmers to practice farming system that retain soil fertility (Ason *et al*., 2014). Crop growth and yield response to water and nutrient is linked to the properties of the soil in which such crops are grown since the soil is the reservoir for storing water and mineral nutrients essential for crop growth (Ason *et al*., 2015).

One of the means to improve on soil water holding capacity is to improve its physical properties and this can be achieved through soil amendment. Thus in coarse textured soils with large pore spaces, amendment with materials from plant biomass and synthetic soil conditioners have the potential of reducing the pore spaces and hence increase its water holding capacity (Abdel-Nasser *et al*., 2007; Abd El-Hady, 2015). It therefore means that soil conditioner has the property of gluing loose soil particles together in aggregates as well as coating aggregate surfaces (Yangyuoru *et al*., 2006). Eldardiry and Abd El-Hady (2015) observed that an increment in moisture retention was

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directly proportional to increased application rate of the soil conditioner used which resulted in high yield and water productivity.

Different materials have been used to condition soil for agricultural purposes including natural and synthetic soil conditioners. Some of the conditioners in use are coco-peat, wood shavings, Terawet, cow dung, Teraflow, biochar, poultry manure, bentonite etc. Poultry manure, cow dung and biochar have been used as amendment material for different soils in a pot experiment by Ason *et al*. (2015) and their results showed an enhanced growth of maize crop on the amended soils compared to the un-amended soils. The positive effect observed on the crop growth could be attributed to the moisture and nutrient retention by the amendment material used known as Zytonic soil conditioner.

2.7.1 Biochar as a Soil Amendment Material

Biochar is define as thermal decomposition of plant biomass in partial or total absence of oxygen to produce char, CO_2 and combustible gases intended specifically for application to soil, that is, according to its purpose (Sohi *et al*., 2010). Duku *et al*. (2011) also defined biochar as a form of charcoal produced through the thermochemical process of biomass under low oxygen conditions known as pyrolysis. Biochar is usually produced from crop residue and its utilization and application is similar to that of green manures and cover crops used in soil fertility management (Omotayo and Chukwuka, 2009). Duku *et al*. (2011) observed that Ghana's forest resources provide a major source of biomass that could contribute considerably to biochar production. Major crop residues generated in the country which can be used to prepare biochar include straw or stalk of cereals such as rice, maize, sorghum, millet, and cocoa pod husk. Agro-industrial by-products such as corncob, cocoa husk, coconut shell and husk, rice husk, oil seed cake, sugarcane bagasse

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and oil palm empty fruit bunch also provide source of biomass for biochar production (Duku *et al*., 2011).

In Ghana and many parts of SSA, rice and maize are observed to be inclusive of the major staple foods produced and consumed by the majority of people and their by-products, i.e. biomass can be used to prepare biochar. Biochar from rice straw and other crop residues can be used to ameliorate acidic soils usually found in sub-tropical regions of the globe by increasing the soil's pH and thereby improving soil fertility (Yuan *et al*., 2011; Van Zwieten *et al*., 2010), while its ability to retain water in the soil is also evident in a study done by (Hariz *et al*., 2015). It has also positively affected crop yield as reported by Asai *et al*. (2009).

The incorporation of biochar into agricultural soil changes the soil's physical properties, which leads to changes in the soil's hydraulic properties, such as water retention and permeability, and alters the soil moisture environment in agricultural fields (Asai *et al*., 2009; Githinji, 2013; Kameyama *et al*., 2014). Albuquerque *et al*. (2013) and Lehmann *et al*. (2011) also reported that biochar combined with mineral fertilizer has a significant effect as compared to only biochar on plant yield.

In terms of nutrients retention in the soil, Ding *et al*. (2010) found out that biochar could be used as a potential nutrient-retaining additive in order to increase the utilization efficiency of chemical fertilizers. The presence of biochar can decrease phosphorous (P) adsorption on Fe-oxides and enhance P availability in soils (Cui *et al*., 2011). Plant growth in a media is influenced by how readily the media releases water and nutrient to the plant root. Biochar not only have the potential to retain the available nutrient but releases the essential plant growth nutrients as well as alleviate Aluminium toxicity in the soil (Alling *et al*., 2014).

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While the majority research has indicated that biochar improves soil physical properties with corresponding increase in soil available moisture content, Hardie *et al*. (2014) found no evidence to suggest biochar application influenced soil porosity by either direct pore contribution, creation of accommodation pores, or improved aggregate stability and also no significant effect of biochar application on soil moisture content.

2.8 Crop Yield and Water Productivity

The basic objectives of site-specific management of agricultural inputs are to increase profitability of crop production, improve product quality, and protect the environment (Adamchuk *et al.*, 2004). All crop management practices are geared towards maximizing the effective use of the scarce agricultural inputs to obtain higher yield at minimum cost. Many of the agricultural management practices are measured against yield response to ascertain the efficiency of a specific management strategy, and profitability.

All agricultural input strategies practiced with the aim to obtain higher yield also target economical and feasible means of measuring yield. Yield determination is normally done through destructive sampling of crops whereby the above ground biomass is harvested fresh and oven dried to constant weight. Destructive sampling is the method of harvesting crop or crop vegetative parts for data collection. This method though produces accurate results, is tedious, time consuming and uneconomical in terms of biomass destruction.

Just like the remote sensing method involved in crop water requirement, there exist satellite based and ground based remote sensing approaches in developing crop yield prediction models such as the ones developed by (Lopresti *et al.*, 2015; Sultana *et al.*, 2014). Crop yield can be estimated ahead of final harvest using prediction models.

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Yield produced per unit amount of water used is termed water productivity (WP). Water productivity is an index that defines whether the amount of water used produces high yield or not. High WP denotes high yield produced using minimum amount of water where the amount of water used is given as the irrigation water supplied, crop transpiration or the amount of water used in crop evapotranspiration.

Hashim *et al*. (2012) determined water productivity of okra and had the value 1.72 kg m^{-3} using centre pivoted irrigation system. Oppong Danso *et al*. (2015) also had water productivity of 5.2 kg m^{-3} and 6.5 kg m^{-3} for okra fruit under drip irrigation with placed manure and drip irrigation with fertigation and also had values of 1.4 kg m^{-3} and 2.0 kg m^{-3} for water productivity of okra total biomass under drip irrigation with placed manure and drip irrigation with fertigation. Konyeha and Alatise (2013) on the other hand determined okra water productivity and had 1.25 kg m^{-3} and 0.59 kg m^{-3} under irrigation treatment at 75% and 25% respectively.

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CHAPTER THREE

MATERIALS AND METHODS

3.1 Experimental Site Description

Okra water use and yield estimation experiments were conducted using a local variety called “Nyuigzovi” during the dry season from December 2015 to March 2016. The experiment was carried out on a field area of 0.08 ha at the University of Ghana (UG) Forest and Horticultural Crops Research Centre (FOHCREC), Kade (latitude 06°8.61’N and longitude 0°54.16’W) in the Eastern Region of Ghana. Kade lies 114 m above sea level with a mean temperature range between 25 °C to 38 °C in a deciduous forest zone with an annual rainfall of 1300 mm – 1800 mm (Nkansah, 2011). The area is dominated by Haplic Acrisol soils (FAO/UNESCO, 1990), according to Nkansah (2011).

3.2 Experimental Soil Properties

The experimental soil in the field was sampled and analyzed in the laboratory and its texture classified as sandy clay loam. The soil used in the experiment was low in organic matter and other nutrients. Field capacity of the soil was determined to be 235.2 mm and wilting point of 117.2 mm. Physical and chemical properties of the sample soil are given in Table 3.1.

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Table 3.1. Soil physico-chemical properties

Chemical Parameter	**Value**
pH_H_2O	5.5
Electrical conductivity [mS cm^{-1}]	0.36
Total nitrogen [%]	0.12
Phosphorous [mg $100g^{-1}$]	< 0.4
Potassium [mg $100g^{-1}$]	14.8
Organic matter [%]	2.3
Physical Parameter	**Value**
Clay < 0.02-0.2 mm [%]	20.3
Silt, 0.002-0.02 mm [%]	11.0
Fine sand, 0.02-0.2 mm [%]	48.3
Coarse sand, 0.02-0.2 mm [%]	18.0

The soil in the field was observed to lack some major nutrients especially Nitrogen (N), Phosphorous (P) and Potassium (K).

3.3 Experimental Biochar Characteristics

Rice straw biochar was prepared under standard conditions in the laboratory through fast pyrolysis, at a temperature of 500 ^{o}C. High temperature pyrolysis results in recalcitrant biochar and hence does not release nutrients to the soil because they are not easily broken down by soil microbes (Brewer *et al*., 2011). Characteristics of the biochar used are given in Table 3.2.

Table 3.2. Rice straw biochar characteristics used for experiment

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	pH	Dry Matter	Organic Matter	Total Nitrogen	Phosphorous ($0.33\%\ P_2O_5$)	Potassium ($2.13\%\ K_2O$)	Magnesium (0.22% MgO)
unit		%	%	%	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}
Value	10.3	91.75	34.9	1.0	1420	17700	1330

The biochar prepared contained a lot of potassium (K) due to the high pyrolysis temperature used.

3.4 Experimental Treatments

Experimental treatments consisted of combination of irrigation method and biochar amount. Irrigation methods were full irrigation (FI) and deficit irrigation (DI) while the biochar amount used were 0 t ha^{-1}, 5 t ha^{-1}, 10 t ha^{-1} and 10 t ha^{-1}_P, where 10 t ha^{-1}_P is Phosphorous (P) premixed with 10 t ha^{-1} biochar. Irrigation and biochar treatment combination used are given in Table 3.3.

Table 3.3. Irrigation and biochar treatment combinations

	Main Treatment Factors		
	Biochar amount	Irrigation method	
Treatment level	Biochar level	Irrigation level	
1	0 t ha^{-1}	DI	FI
2	5 t ha^{-1}	DI	FI
3	10 t ha^{-1}	DI	FI
4	10 t ha^{-1}_P	DI	FI

Note that biochar application rate were selected to suit experimental design objectives. Different application rates can also be used.

The first treatment combination level consisted of no biochar under full irrigation plots as well as another no biochar treatment under deficit irrigation plots serving as the control.

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The second treatment combination was made up of five tonnes biochar per hectare in full irrigation plots as well as another five tonnes of biochar per hectare under deficit irrigation plots.

The third treatment combination level consisted of ten tonnes of biochar per hectare under full irrigation treatment as well as another ten tonnes of biochar per hectare under deficit irrigation plots.

Treatment level four was made up of ten tonnes of biochar per hectare soaked with phosphorous (P) fertilizer before incorporating into the soil for full irrigation plots and deficit irrigation plots. This was done to study the P combination effect on yield because the field soil were low in P. The P was used on the 10 t ha^{-1} biochar to examine its effect on yield because higher biochar amount have been reported by Ason *et al.* (2015) and Eldardiry and Abd El-Hady (2015) to have greater effect on nutrient and soil moisture retention.

3.5 Experimental Design

A field size of 72 m x 11 m (0.08 ha) was used and demarcated into thirty two (32) plots. Each plot was demarcated into an area of 5 m x 3.6 m (18 m^2). Completely randomized block design was used with four replications of treatment combinations in four blocks. Data was processed and analyzed using Microsoft package (excel) and GenStat 11th edition statistical software to find any significant difference among treatments using least significant difference (LSD) test.

3.6 Site Preparation and Layout

The experimental field area was slashed, cleared off plant debris manually, ploughed and harrowed with a farm tractor. The field was demarcated and the layout is as shown in Figure 3.1. Beds were

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prepared, levelled and raised to 0.20 m above the ground surface. There were thirty-two (32) plots in four (4) blocks prepared for sowing okra. Sixteen (16) plots for full irrigation treatments and the other sixteen (16) plots for deficit irrigation treatments combined with the four (4) biochar treatments in each case.

The plots were separated by 0.5 m and 1 m buffer strips between plots and rows to serve respectively as walkway as well to minimize nutrients being carried away from one plot to the other through surface runoff during any high rainfall event.

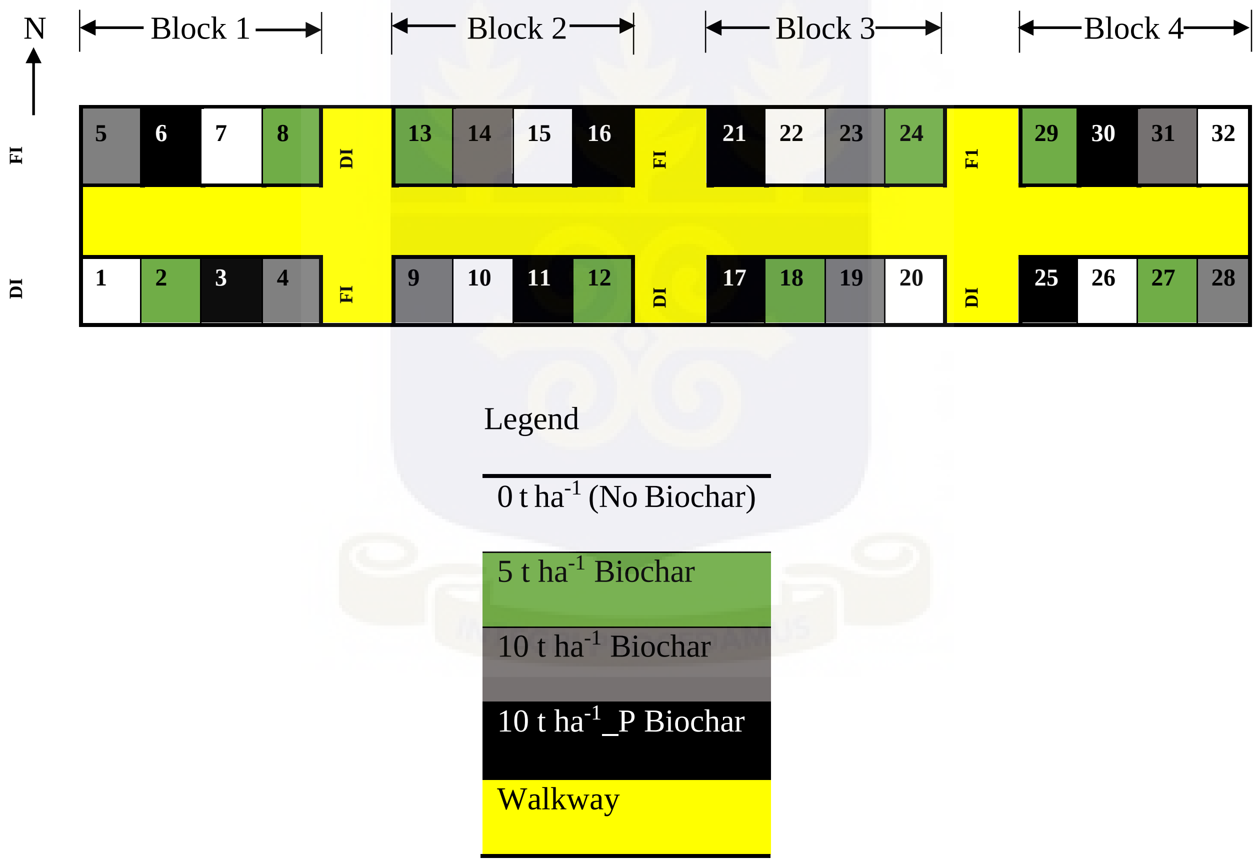

Figure 3.1. Schematic diagram of experimental field layout

Drip irrigation system and Time Domain Reflectometry (TDR) probes were installed (Figures 3.2 and 3.3) and TDR probes extended with cables to borders of the plots to ensure soil moisture content measurement at full crop canopy growth stage.

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Figure 3.2. Irrigation lines installed on plots

Figure 3.3. TDR probes with extended cable

TDR probes were installed closer to the emitters as well as the crops to measure moisture depleted by the crops growing in the soil and very close to the TDR probe and emitter of the drip line.

3.7 Biochar Application and Irrigation System Installation

Rice straw biochar of particle size < 2 mm was slightly moistened to avoid being carried away by wind during incorporation into the soil. The biochar was then spread evenly on the soil surface of the various plots, mixed thoroughly and incorporated into the soil to a depth of 15 cm below the soil surface. Hand mechanical tools such as pick axe, hoe, shovel and rake were used to apply and incorporate the four different biochar amounts into the soil in each plot.

Irrigation system was made up of filter, main lines, laterals, stop corks and drip lines. Water was pumped from a nearby dam through a connection to the main irrigation lines and distributed to the laterals using control valves on the field which was then delivered to the drip line installed on each plot. Each plot had 8 drip lines installed, accommodating an average of 72 okra crops per plot with emitter distance of 0.6 m and drip lines separated by 0.5 m.

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3.8 Sowing of Okra

The plots were initially irrigated to create a wetting pattern beneath the drippers on the soil surface to serve as a guide to creating hill for okra sowing. Sowing was done on December 10, 2015 with 3 seeds per hill. Local variety of okra "Nyuigzovi" was sowed at 0.6 m between rows and 0.5 m crop spacing. After germination, crops were thinned out to one crop per hill.

3.9 Soil Water Content Measurement

Soil water content was measured (Figure 3.4) by connecting a transmission cable from the TDR probes installed in the soil to the TDR central processing unit and another cable connecting the TDR central processing unit to a handheld monitor (field computer). Required data input to the TDR through the handheld monitor are the length of the TDR probes inserted into the soil which was 0.8 m and length of the cable connected from the TDR probes to the handheld monitor (field computer) which was 4.5 m. After inputting the two data points, i.e. the probe length and cable length, the TDR processes the data and display volumetric soil water content value on the field computer's screen as an output data as well as store the data in the TDR data logger. The volumetric soil water content measured was then converted to depth of water in millimetres by dividing the volumetric water content value by the area covered by probes in the soil. TDR was used directly without calibration because it has been calibrated for almost all agricultural soils including biochar prepared at the given temperature (500 °C) used in this experiment.

Moisture content was initially measured to determine field capacity of the various biochar treatments in all the plots before sowing okra. Moisture content measurements were taken frequently after drainage to obtain a constant value marking field capacity after the soil on the field was saturated by one heavy rainfall. After sowing the okra seeds, soil moisture content

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measurements were taken at two days intervals to check soil water depletion level for irrigation scheduling.

Figure 3.4. Measuring SWC with TDR

From Figure 3.4, TDR central processing unit is standing on the ground while the handheld monitor (field computer) was held by the user with cable connected from the field computer to the TDR central processing unit and to the extended cable from the installed probes in the plot.

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3.10 Irrigation Scheduling and Water Use

Irrigation was scheduled, thus when to irrigate and how much water to irrigate based on calculated soil water deficit (D) by measuring the soil water content (SWC) after the crop has been allowed to deplete some fraction (p) of the total available water content (TAW). Irrigation was initiated whenever the deficit (D) was greater than the readily available water content (RAW).

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3.10.1 Scheduling Full and Deficit Irrigation

Field capacity (FC) and wilting point (WP) were pre-determined after biochar incorporation with the help of TDR measurements. SWC was measured prior to each irrigation regime. Rooting depth (Z_r) was taken as the length of TDR probe (0.8 m). Total available water content (TAW), readily available water (RAW) and soil water deficit (D) were calculated using Equations 3.1-3.3.

$$TAW = 1000(\theta_{FC} - \theta_{WP})Z_r \qquad (3.1)$$

Where,

TAW – Total available soil water in the crop root zone [mm],

θ_{FC} – Soil water content at field capacity [m^3 m^{-3}],

θ_{WP} – Soil water content at wilting point [m^3 m^{-3}],

Z_r – Rooting depth of crop [m]. Given as 0.8 m, i.e. length of TDR probe inserted into soil.

$$RAW = p * TAW \qquad (3.2)$$

Where,

RAW – Readily available soil water, i.e. the fraction of TAW that a crop can access in the root zone without suffering water stress [mm],

p – Fraction of TAW depleted by crop in the root zone before water stress occur. p was taken as 0.3 for FI treatment and 0.7 for DI treatments i.e. the crop was allowed to deplete 30 % of TAW in FI treatments and 70 % of TAW in DI treatments before irrigating to FC.

The amount of water needed to irrigate back to FC was determined by comparing the soil water depleted by the crop to the readily available water in the soil. Thus whenever the amount depleted

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by the crop (okra) was greater than the readily available soil water, the soil was irrigated back to field capacity where the amount depleted was the soil water deficit (D). Soil water deficit was determined using Equation 3.3.

$$D = FC - SWC \tag{3.3}$$

Where,

D – Soil water deficit [mm], i.e. amount of soil water depleted by crop and would be needed to refill the soil back to FC,

FC – Field capacity of the soil [mm],

SWC – Soil water content at the time of TDR measurement [mm].

3.11 Post-Planting Cultural Practices

Selective cultural practices including irrigation, weed control, pruning, nutrient management, and disease and pest control were undertaken at a defined time interval to promote healthy crop growth and yield formation.

Weedicides was not used, rather weed control was done through hand picking and the use of mechanical cultivation tools i.e. hoes and cutlasses. All 32 sample plots were weeded frequently to avoid errors produced by weeds canopy reflectance during okra canopy spectral reflectance measurement with RapidSCAN CS-45. Mechanical weed control using hoes (Figures 3.5a and 3.5b) has the advantage of loosening soil particles to improve soil physical properties as well as mounding to ensure proper aeration, infiltration and reduction of soil crusting.

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Figure 3.5a. Weeding 14 days after sowing

Figure 3.5b. Weeding 28 days after sowing

In weeding each plot, care was taken not to cut the drip lines with the hoe and this made the task tedious and time evolving especially when each drip line was lifted while weeding.

During the dry season marked with dry vegetation, pest attack was severe on the limited available green crops i.e. the cultivated okra. Pesticide and fungicide were applied at the same time at two-weeks intervals till flowering stage using a pesticide called “Akape” (Anty ataa) and a fungicide called “Dizcozeb 80 WP” at the prescribed application rate by the manufacturer for okra.

Fertilizer was applied at three different stages using Nitrogen (N), Phosphorous (P) and Potassium (K) fertilizer. Phosphorous fertilizer was applied using two different methods at 60 kg h^{-1} at pre-planting stage by pre-mixing the soaked phosphorous fertilizer with one treatment level of the biochar (10 t ha^{-1}) and the second method involved spreading the phosphorous on the surface of the remainder plots which was dissolved by irrigation water and rainfall into the soil for plant use. Secondly, Nitrogen (Urea) was applied in two folds, i.e. two weeks after germination and immediately at flowering stage at a rate of 50 kg ha^{-1} in each case. Finally, Potassium was applied at a rate of 60 kg ha^{-1} after flowering to boost fruit yield.

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3.12 Reference Evapotranspiration (ET_o)

Daily ET_o is a climatic parameter required to compute and estimate daily crop water use. The FAO Penmann-Monteith (P-M) equation was used to compute daily ET_o. The model uses climatic parameters which were obtained from an automatic weather station (Campbell scientific, Logan, USA), Figure 3.6 located 300 m from the cropped field at the research centre.

The basic climatic parameters required for ET_o computation using FAO Penmann-Monteith equation are Net radiation (R_n), Temperature (T), Relative humidity (RH) for computing vapor pressure deficit (e_s - e_a) and Wind speed (u_2). All other supporting climatic parameters needed for the ET_o computation using the FAO P-M model are outlined in Allen *et al*. (1998).

Figure 3.6. Automatic weather station at the research centre

Microsoft excel spread sheet was used to compute daily ET_o using climatic data from the meteorological station. Mean monthly ET_o values were determined from mean daily climatic data.

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Rainfall during the experimental period was recorded as total monthly rainfall. FAO Penman Monteith equation for computing ET_o is given by Equation 3.4.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{3.4}$$

Where,

ET_o – Reference evapotranspiration [mm day^{-1}],

R_n – Net radiation at the crop surface [MJ m^{-2} day^{-1}],

G – Soil heat flux density [MJ m^{-2} day^{-1}],

T – Mean daily air temperature at 2 m height [°C],

u_2 – Wind speed at 2 m height [m s^{-1}],

e_s – Saturation vapor pressure [kPa],

e_a – Actual vapor pressure [kPa],

$(e_s - e_a)$ – Saturated vapor pressure deficit [kPa],

Δ – Slope of vapor pressure curve [kPa $°C^{-1}$],

γ – Psychrometric constant [kPa $°C^{-1}$].

3.13 Determination of Leaf Area Index (LAI)

Leaf area index is a vegetation biophysical parameter and a dimensionless variable defined as a ratio of leaf area per unit ground surface area (Zheng and Moskal, 2009). Basically there are two methods of measuring LAI, namely the direct method and indirect method. The indirect method involves remote sensing of the various kinds. Though remote sensing is preferred due to its less labour intensiveness and other advantages in LAI estimates, it is not reliable due to seasonal change, crop health condition, local climate condition and stand density (Zheng and Moskal,

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2009). Remote sensing and the use of hemispherical photography in estimating LAI has been reviewed in Jonckheere *et al*. (2004) and they suggested the use of a digital camera with high dynamic range to overcome a number of described technical problems related to indirect LAI estimation.

The direct method involved collecting destructive sample of leaves and measuring area of leaves with a measuring device or software. Leaf area was determined in this experiment using a software known as Leaf Area Meter (LAM) shown in Figure 3.7.

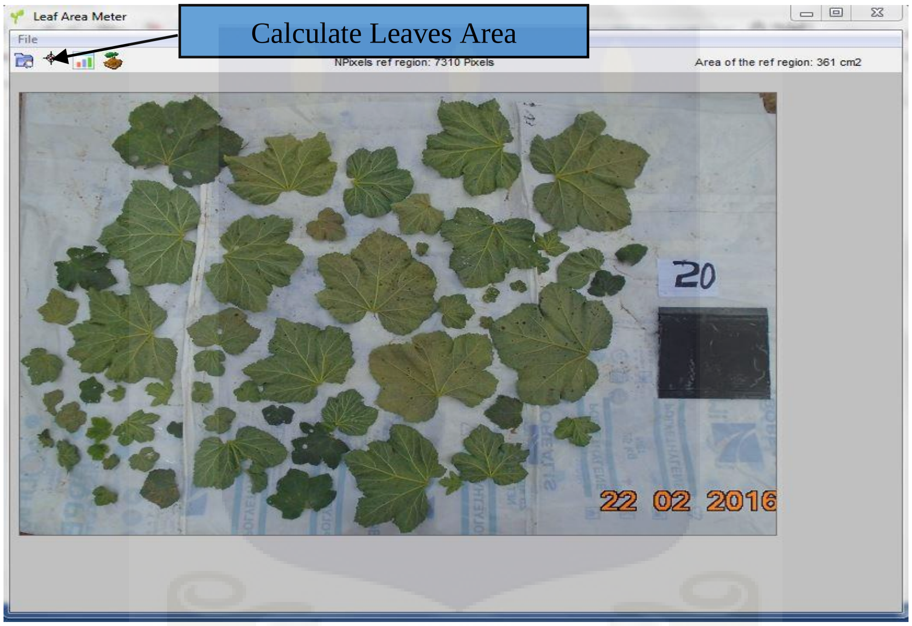

Figure 3.7. LAM software interface uploaded with okra leaves image

Sample leaves were detached from okra crop (destructive samples) and spread on a white flat surface and photographs taken with a digital camera. It took about 10 hrs involving three people to sample all the leaves for photography in each of the five destructive sampling days.The leaves images were uploaded into the LAM software to estimate leaf area of each plot's destructive sample**.** Leaf area values determined using the software were divided by ground area covered by leaves to obtain leaf area index (LAI) given by Equation 3.5.

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$$LAI = \frac{A_l}{A_g} \qquad (3.5)$$

Where,

LAI – Leaf area index [$m^2\ m^{-2}$],

A_l – Area of leaf [m^2],

A_g – Area of ground covered by leaf [m^2].

3.14 Determination of Crop Coefficient

The relationship between basal crop coefficient (K_{cb}) and LAI and has been modelled by Allen *et al*. (1998), Duchemin *et al*. (2006) and Ritchie and Burnett (1971). The Ritchie and Burnett (1971) model given by Equation 3.6 was used in this experiment to derive k_{cb} from LAI because their test crop (cotton) belonged to the same *malvaceae* family with okra (Oppong Danso, 2014).

$$K_{cb} = \frac{T_c}{ET_o} = -0.21 + 0.70\, LAI^{1/2}, 0.1 \leq LAI \leq 2.7 \qquad (3.6)$$

Where,

K_{cb} – Basal crop coefficient accounting for crop transpiration,

T_c – Crop transpiration [mm day^{-1}],

ET_o – Reference evapotranspiration [mm day^{-1}],

LAI – Leaf area index given by equation 3.5 above.

$K_{c\ initial}$ given as $k_{cb\ initial}$ in this experiment was validated following the FAO 56 methodology that involves two stages to estimate $k_{c\ initial}$. The first stage involved using Figure 30b of FAO 56 (Allen *et al.*, 1998) with a known two variables namely ET_o and irrigation interval to estimate $k_{c\ initial}$ by plotting the known two variables on the figure. Secondly, the estimated $k_{c\ initial}$ was adjusted using

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Equation 60 of FAO 56 (Allen *et al.*, 1998). Figure 30b of FAO 56 used is given in Appendix A and Equation 60 of the FAO 56 is given as Equation 3.7. Soil type used in the experiment is a fine textured soil with a fraction of soil surface wetted by irrigation or rain (f_w) value of 0.4 from Table 20 of FAO 56 (Allen *et al*., 1998).

$$k_{c\ ini} = f_w * k_{c\ ini}(Table, Figure) \tag{3.7}$$

Where,

f_w – Fraction of surfaced wetted by irrigation or rain [0 - 1],

$K_{c\ ini}$ (Table, Figure) – $K_{c\ initial}$ from Table 12 or Figure 30b of FAO 56 (Allen *et al*., 1998).

3.14.1 Basal Crop Coefficient – Normalized Difference Vegetation Index Relationship

Okra canopy spectral reflectance was measured using handheld remote sensing device (RapidSCAN CS-45) shown in Figure 3.8 (Source: Holland Scientific, 2012) at weekly interval. The procedure in RapidSCAN CS – 45 is versatile, mobile and independent of solar radiation and cloud cover because of its self-illumination property. The RapidSCAN CS-45 has a field view of 45° by 10°, and does not depend on a specific standard height to be raised in scanning crop canopy. A minimum height of 0.3 m from the crop canopy to the device's sensor is recommended by the manufacturer in the user manual. It has a sensor to canopy height range of 0.3 m to above 3 m high. It was raised at a height of 2 m vertically up (Figure 3.9) to scan okra canopy. Spectral reflectance measurements started seven days after crop emergence till late season when the experiment was ended.

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RapidSCAN CS-45 HANDHELD CROP SENSOR

Features:
- Three Spectral Bands
- Self-contained Light Source
- Internal GPS
- Logs over 25,000 data points

Built-in Agronomic Models:
- N-Rate
- Relative Crop Vigor
- Forage Biomass
- Crop Yield
- LAI

Applications:
- Protein Estimation
- Crop Assessment
- Nutrient Application
- Pasture Management
- And More...

Figure 3.8. RapidSCAN CS-45 (radiometer)

Figure 3.9. Scanning okra canopy with radiometer

Normalized Difference Vegetation Index (NDVI) data measured using the ground based remote sensing device was plotted against k_{cb} to produce k_{cb} - NDVI model. The model equation is used as a prediction model for estimating k_{cb} when NDVI data is given.

3.15 Crop Water Requirement

Crop water requirement was estimated by the two step approach of FAO 56 (Allen *et al*., 1998). The procedure involves determination of ET_o and then multiplying the value of ET_o by a tabulated or empirically derived crop coefficient either the single or dual crop coefficient.

ET_o values were computed using data from the automatic weather station sited at the research centre and close to the cropped field. Crop water requirement of okra which is equal to ET_c of okra

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was then estimated as a product of the ET_o and the empirically derived okra basal crop coefficient (K_{cb}) using the FAO dual crop coefficient given by Equation 3.8.

Dual crop coefficient approach proposed by Allen *et al*. (1998) which separate the crop coefficient into two parts namely, basal crop coefficient (K_{cb}) and soil evaporation coefficient (K_e) was used in the experiment. Basal crop coefficient (K_{cb}) accounts for transpiration by crop, while soil evaporation coefficient (K_e) accounts for water loss through evaporation from the growth media or soil surface.

K_e is largely affected by irrigation frequency and crop canopy cover. K_e is considerable where the soil is wet most of the time from irrigation or rain and restricted on the other hand where the soil surface is dry (Allen *et al*., 1998). In this experiment, soil evaporation coefficient (K_e) was negligible due to the fact that irrigation intervals were large, scheduled between four day and seven days based on TDR measurements. Secondly, the effect of drip irrigation wetting only small portion of the soil just at the base of the crop also contributed to soil surface dryness most of the time. Therefore $k_c = k_{cb}$ in the dual crop coefficient approach in this experiment.

$$ET_c = (K_{cb} + K_e) \text{ x } ET_o \tag{3.8}$$

Where,

ET_c – Crop evapotranspiration [mm day^{-1}],

K_{cb} – Basal crop coefficient,

K_e – Soil evaporation coefficient,

ET_o – Reference evapotranspiration [mm day^{-1}].

Where k_e was negligible in our experiment, ET_c was computed using Equation 3.9.

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$$ET_c = K_{cb} \text{ x } ET_o \tag{3.9}$$

Where Parameters are defined in equation 3.7 above.

3.16 Determination of Crop Yield

Okra yield in the various biochar amounts was determined under FI and DI treatments separately. Destructive sampling was done by uprooting three okra crops in each plot from one half of the plot ignoring border plants. The uprooted crops were plugged off their leaves and branches, chopped into sizeable biomass and packaged into envelopes for oven drying in all five destructive samples done every two weeks. The Leaves, branches, stem, flowers and fruits dried were summed and weighed to estimate total above ground biomass (TBM). Total above ground biomass per unit ground area covered by the respective crops is termed Total above ground biomass yield (Y_{TBM}) given by Equation 3.10.

Okra fresh fruits (FF) were harvested at two days intervals and sample harvested in each plot weighed separately for FF yield determination. After weighing the FF, representative samples of FF for each plot were selected and oven dried. The weight of one oven dried FF was multiplied by total fruit harvested in each plot to determine total dry fruits weight for each plot. All samples were dried at a temperature of 75 ^{o}C to constant weight. Fresh fruit (FF) yield was also determined from weighed fresh okra fruit as the sum total of FF harvested divided by the total area covered by harvested crops given by Equation 3.11.

$$Y_{TBM} = \frac{TBM}{A} \tag{3.10}$$

Where,

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Y_{TBM} – Total above ground biomass yield [t ha^{-1} or kg m^{-2}],

TBM – Total above ground biomass produced [ton or kg],

A – Area covered by crops used in TBM sampling [ha or m^{2}].

$$Y_{FF} = \frac{FF}{A} \tag{3.11}$$

Where,

Y_{FF} – Fresh fruit yield [t ha^{-1} or kg m^{-2}],

FF – Total okra fresh fruit harvested [ton or kg],

A – Area covered by crops used in FF sampling [ha or m^{2}].

Actual yield data was plotted against correspondent NDVI data measured on same days of the five different destructive sampling events and a line fitted to deduce a yield prediction model. Equation of the line fitted was used as model equation for predicting okra yield.

3.17 Water Productivity

Water productivity (WP) was computed by dividing the total crop yield by unit millimetre of water used to obtain that yield. The amount of water used was the estimated crop evapotranspiration (ET_c). Water productivity was computed for total above ground dry biomass and fresh okra fruit harvested given by Equations 3.12 and 3.13. WP was determined for both FI and DI treatments.

$$WP_{TBM} = \frac{Y_{TBM}}{\sum ET_c} \tag{3.12}$$

Where,

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WP_{TBM} – Water productivity of TBM [kg m^{-3}],

Y_{TBM} – Yield of TBM [t ha^{-1} or kg m^{-2}],

ΣET_c – Sum total amount of water used by crop in evapotranspiration [mm or m].

$$WP_{FF} = \frac{Y_{FF}}{\sum ET_c} \tag{3.13}$$

Where,

WP_{FF} – Water productivity of FF [kg m^{-3}],

Y_{FF} – Yield of FF [t ha^{-1} or kg m^{-2}],

ΣET_c – Sum total amount of water used by crop in evapotranspiration [mm or m].

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CHAPTER FOUR

RESULTS

4.1 Crop Coefficient

Leaf Area Index (LAI) determined with the help of the LAM software was used to estimate K_{cb}. K_{cb} was assumed to be equal to k_c using the dual crop coefficient approach due to the fact that k_e was negligible in the experiment. LAI which was measured at two weeks interval for five different time schedule correlated linearly with k_{cb}. k_{cb} data recorded for the five different destructive sampling days was plotted against their correspondent NDVI data and a line of best fit plotted to produce a model equation. Weekly k_{cb} were then derived from the k_{cb} -NDVI model equation since NDVI data were measured weekly. Daily k_{cb} values were interpolated from the derived weekly k_{cb} values. K_{cb} for the four growth stages were then obtained from the graph of the derived daily k_{cb} values plotted against days after sowing (DAS).

4.1.1 Basal Crop Coefficient – Normalized Difference Vegetation Index Relationship

A graph of the derived k_{cb} values plotted against the correspondent NDVI values (Figure 4.1) deduced a K_{cb} – NDVI prediction model (Equation 4.1). The model equation had coefficient of correlation (R^2) of 0.98 and a root mean square error (RMSE) value of 0.03 and was used to predict k_{cb} using NDVI data. The K_{cb}–NDVI relationship reported for FI treatments is given by Figure 4.1. All graphs for DI treatment are presented in Appendix D.

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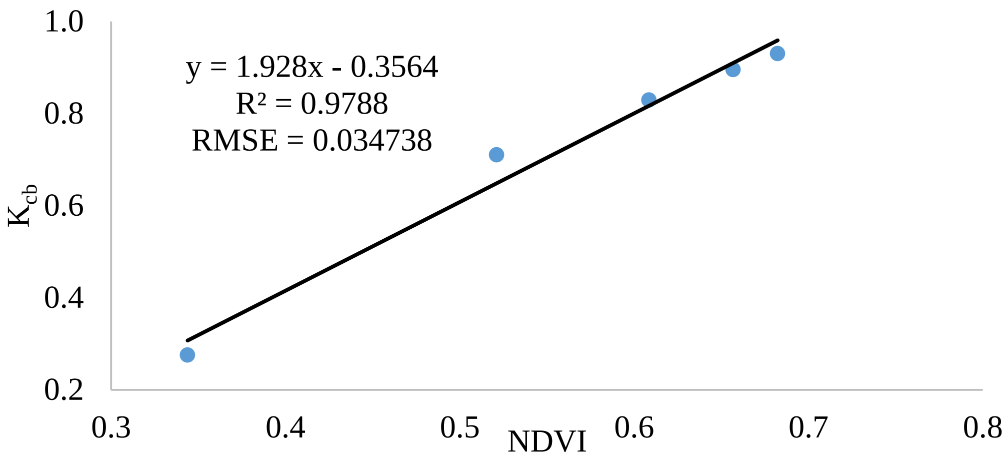

Figure 4.1. Relationship between k_{cb} and NDVI for FI treatments

$$K_{cb} = 1.928NDVI - 0.3564 \tag{4.1}$$

Where,

K_{cb} – Basal crop coefficient,

NDVI – Normalized Difference Vegetation Index.

To predict k_{cb}, substitute measured NDVI data into Equation 4.1.

4.2 Crop Growth Stages and Length of Growth Stages from the Experiment

Crop growth stages considered were the initial, crop development, mid-season and late season growth stages as outlined in the FAO 56 (Allen *et al*., 1998). Variation of k_{cb} for the four growth stages of the test crop (okra) over the growing season is shown in the crop coefficient curve (Figure 4.2). The four growth lengths and their correspondent k_{cb} values were deduced from the k_{cb} curve and compared to the method proposed by FAO 56 (Allen *et al*., 1998). $K_{c\ initial}$ determined from

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Figure 4.2 was compared with method of using Figure 30b (Appendix A) and Equation 60 of FAO 56 (Allen *et al.*, 1998) to determine $k_{c \text{ initial}}$.

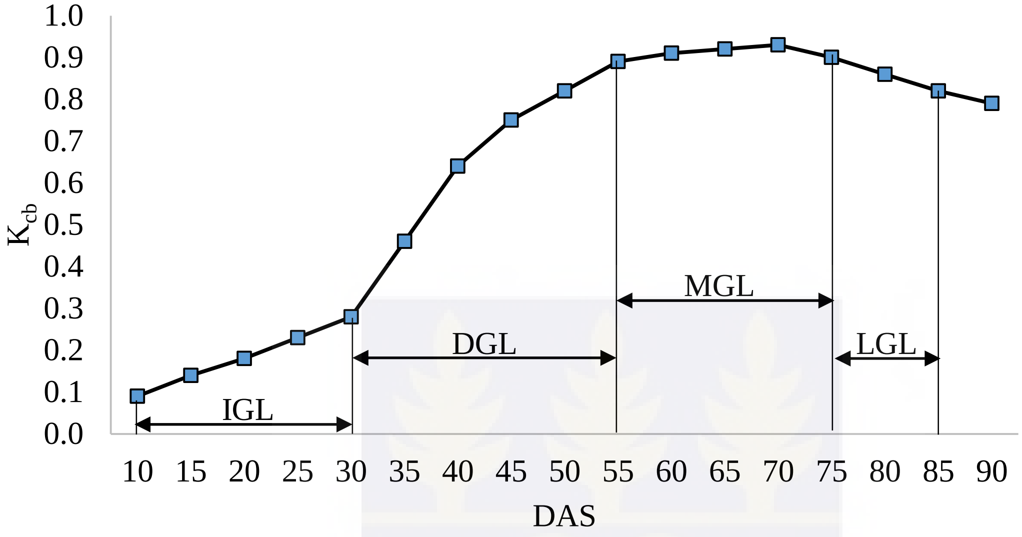

Figure 4.2. Crop coefficient (K_{cb}) curve for full irrigation (FI) treatment

Note: IGL, DGL, MGL and LGL are initial growth length, crop development growth length, mid-season growth length and late season growth length respectively. DAS is days after sowing.

Crop coefficients and growth length derived from the k_{cb} curve are given in Table 4.1.

Table 4.1. Crop coefficients and growth length in FI treatments

Crop growth stage	k_{cb}	Length of growth stage (days)
K_{cb} initial	0.28	20
K_{cb} development	0.67	25
K_{cb} mid-season	0.91	20
K_{cb} late-season	0.86	10

K_{cb} is basal crop coefficient which is equal to K_c in this experiment.

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4.3 Climate Data and Reference Evapotranspiration (ET_o)

Computed ET_o values from climate data using FAO P-M equation were recorded in monthly average values from December 2015 to March 2016 (Table 4.2). The highest ET_o value was recorded in January 2016 while the lowest was recorded in March 2016 delineating the intensity of the harmattan in January in the dry season. Vapour pressure deficit was observed to be the major driver of the atmospheric demand on crop evapotranspiration.

The highest vapour pressure deficit resulted in the highest ET_o which was recorded in January and the lowest ET_o value was recorded under the lowest vapour pressure deficit as well in March that marked the end of the growth period. In situations where there were equal values of vapour pressure deficit, wind speed was the next determining factor on higher ET_o values followed by temperature.

Net radiation was linearly correlated to ground heat flux while temperature was linearly correlated with wind speed. Temperature and wind speed were observed to increase throughout the growing season from December 2015 to March 2016. January recoded the highest rainfall.

Table 4.2. Climate data and computed ET_o during the growing season

Month	R_n (MJ m^{-2} day^{-1})	G (MJ m^{-2} day^{-1})	T (°C)	$(e_s - e_a)$ (kPa)	u_2 (m s^{-1})	ET_o (mm day^{-1})	Rainfall (mm)
December	7.55	0.75	26.48	2.47	3.29	5.25	0.00
January	7.39	0.74	27.30	2.47	4.31	6.10	36.83
February	8.97	0.90	28.82	2.23	4.44	5.71	15.24
March	10.20	1.02	29.21	1.54	4.77	4.38	16.51

Note that rainfall data is not a parameter for computing ET_o using FAO P-M equation.

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4.4 Okra Water Requirement

Crop water use of okra varied from the beginning to the end of the experiment. Considering the four growth stages, the value of okra water use, thus crop water requirement varied in both FI and DI treatments throughout the growing season characterized by varying crop coefficients at those specific growth stages.

Okra water use in FI treatments for initial, crop development, mid-season and late season growth stages were 29.4 mm, 102.18 mm, 103.92 mm, and 37.67 mm respectively. Okra water use in DI treatments for initial, crop development, mid-season and late season growth stages were 36.6 mm, 65.88 mm, 111.92 mm and 35.04 mm respectively. Accumulated seasonal water use in FI treatment was 273.17 mm and that of DI treatment was 246.44 mm.

4.5 Crop Yield

Crop vegetative parts harvested, thus the fruits, stems, leaves, branches, and flowers were oven dried and used to determine total above ground dry biomass yield (Y_{TBM}). Fresh okra fruit yield (Y_{FF}) was also determined from total harvested fresh fruits under all biochar and irrigation treatment combinations. Yield was expressed in kg m^{-2} and ET_c expressed in m in order to express water productivity (WP) in kg m^{-3}.

A graph of total above ground dry biomass yield (Y_{TBM}) produced was plotted against the corresponding NDVI for all the five destructive samples (Figure 4.3) with an R^2 of 0.94 and RMSE of 0.08 in FI treatments and a yield prediction model (Equation 4.2) deduced for estimating okra yield.

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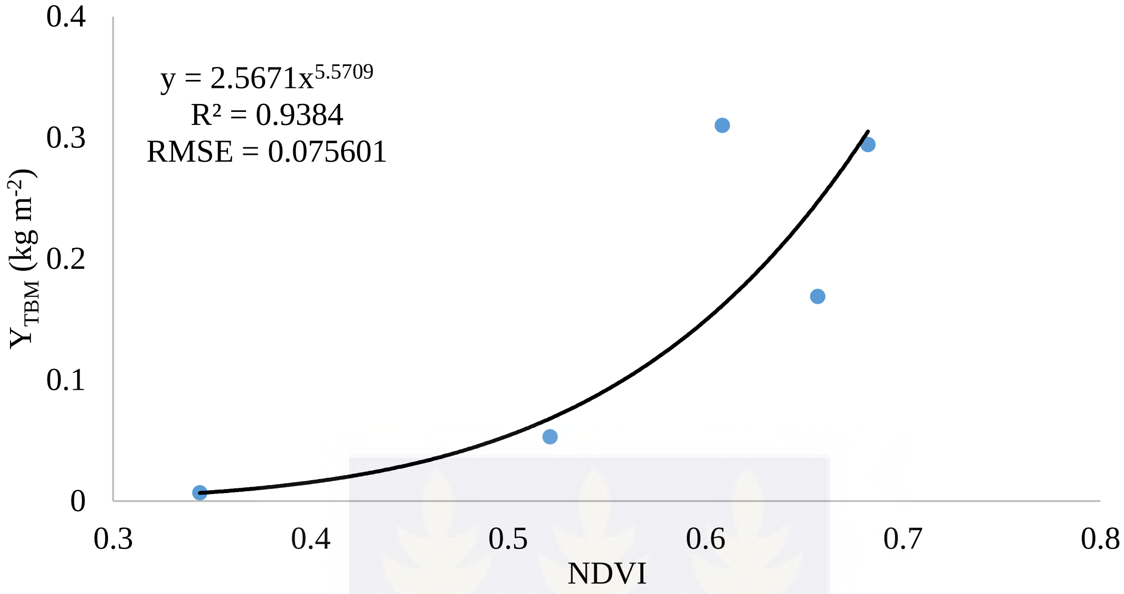

Figure 4.3. Relationship between Y_{TBM} and NDVI for FI treatment

$$Y_{TBM} = 2.5671NDVI^{5.5709} \qquad (4.2)$$

To estimate Y_{TBM}, substitute NDVI data into the model (Equation 4.2).

4.5.1 Statistical Analysis of Crop Yield

Total above ground dry biomass yield (Y_{TBM}) and total fresh fruit yield (Y_{FF}) in all four biochar amounts from the five destructive samples were subjected to statistical analysis using one way analysis of variance (ANOVA) to determine any significant difference in mean values under Least Significant Difference (LSD) at 95% confidence level, $P \leq 0.05$. Results of ANOVA was used to determine the effect of biochar amount on total above ground dry biomass yield (Y_{TBM}) and total fresh fruit yield (Y_{FF}) in both FI and DI treatments statistically (Table 4.3).

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It was observed that higher values of yield were recorded under FI in all biochar treatments. There was significant difference between yields (Y_{FF}) only in DI treatments under the different biochar amounts. ANOVA analysis tables are given in Appendix C.

Table 4.3. Effect of biochar amount on Y_{TBM} and Y_{FF} in FI and DI treatments

Biochar amount (t ha^{-1})	Y_{TBM} (t ha^{-1})		Y_{FF} (t ha^{-1})	
	FI	DI	FI	DI
0	7.46	5.59	6.47	3.61 a
5	6.61	6.38	5.36	4.45 b
10	6.96	6.42	6.50	6.03 a
10_P	7.23	5.95	6.99	6.57 a
LSD$_{0.05}$	**2.593**	**2.292**	**2.539**	**2.308**

Values with common alphabet attached within column shows a significant difference at $P \leq 0.05$ from LSD test. This means there is a significant difference in Y_{FF} under DI between 0 t ha^{-1} and 10 t ha^{-1}, 10 t ha^{-1} and 10_P t ha^{-1} and finally between 10 t ha^{-1} and 10_P t ha^{-1} biochar respectively.

4.6 Water Productivity

Water productivity expressed in kg m^{-3} was estimated as a ratio of total yield (kg m^{-2}) per the sum amount of water used by the crop (m) through ET_c in producing that yield. Yield could be expressed in t ha^{-1} or kg m^{-2} and unit amount of water could be expressed in millimetres (mm) or metres (m) but kg m^{-2} for yield and m for ET_c was used in order to express water productivity in units of kg m^{-3}.

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Water productivity of total above ground dry biomass (WP_{TBM}) and fresh okra fruits harvested (WP_{FF}) were determined for FI and DI treatments and the results are shown in Table 4.4. Both Y_{TBM} and Y_{FF} produced where higher in FI treatment as well as the amount of water used by the crop (ET_c) in producing that yield. WP_{TBM} and WP_{FF} were also higher in FI treatments than DI treatment but there were no significant difference in either yield or water productivity between FI and DI treatment.

Table 4.4. Summary of key results

Irrigation treatment	Y_{TBM} (kg m^{-2})	Y_{FF} (kg m^{-2})	Σ ET_c (m)	WP_{TBM} (kg m^{-2})	WP_{FF} (kg m^{-2})
FI	0.834	0.633	0.273	2.896	2.198
DI	0.728	0.516	0.246	2.716	1.925

Values tabulated are mean values obtained from five destructive samples in all biochar treatments.

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CHAPTER FIVE

DISCUSSION

5.1 Leaf Area Index

Leaf area determined using LAM software in the experiment was used to estimate LAI. The direct method of determining leaf area (destructive sampling) as used in this experiment was very laborious and time consuming.

LAI determined in the experiment ranged from 0.54, 1.76, 2.78, 2.59, and 2.05 for the five destructive samples respectively. The values correspond to the four growth stages, i.e. from initial growth stage to the late growth stage which agreed with the range of values reported by Ritchie and Burnett (1971) for use in their k_{cb} – LAI model.

The minimum LAI, 0.54 was obtained during the first destructive sampling, thus 30 DAS. The highest LAI value, 2.78 was recorded 58 DAS marking full okra canopy growth stage. The value of LAI then declined after full canopy growth stage delineating the trend in crop coefficient and crop water use which are also higher from the beginning and reduces towards the end of the crop growth cycle.

5.2 Crop Coefficients

Given the relationship between ET_c and ET_o in defining k_c, Equation 2.5, it is observed from the linear relationship that, increased ET_o will result in decreased k_c while increased ET_c will result in increased k_c and vice versa. The dual crop coefficient approach was used to separate k_{cb} from k_e

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for research purpose though k_e in the experiment was negligible due to infrequent irrigation that resulted in surface of the soil dry most of the time (Allen *et al*., 1998).

The computed k_{cb} values plotted against correspondent NDVI produced a linear relation with an R^2 of 0.98 and RMSE of 0.03 for FI treatment. The R^2 value show a strong correlation between k_{cb} and NDVI. The RMSE value shows how the predicted k_{cb} values are closer to the actual k_{cb} values when using the model equation and hence measures the strength of the model equation. The high R^2 value in the linear regression was due to the fact that both NDVI and k_{cb} values were low at the initial growth stage, increased as the crop developed and attained a peak value at full crop canopy and then decreased towards the late season. The reduction in NDVI values at the late season were as a result of reduction in photosynthesis and green leaf effect on incident radiation reflection.

Similarly, the reduction in k_{cb} values at the late season were as a result of reduction in transpiration by the crop as well as reduction in leaf surface area when leaves senescence and leaf fall started, marking the end of growth period.

5.2.1 Basal Crop Coefficient – Normalized Difference Vegetation Index Relationship

The k_{cb} - NDVI model, i.e. Equation 4.1, was used to estimate k_{cb} from weekly NDVI data. Similar linear relationship between k_{cb} and NDVI have been modelled by (Aghdasi, 2010; Duchemin *et al*., 2006).

Weekly k_{cb} values estimated with the model developed in this experiment were interpolated to obtain daily k_{cb} values and plotted against DAS (Figure 4.2). This was done to estimate daily crop water use and crop growth length from the plotted graph (K_{cb} curve). The four growth stages k_{cb} values determined from the plotted k_{cb} curve were tabulated (Table 4.1).

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The initial k_c estimated from the k_{cb} curve was very close to the $k_{c\ initial}$ value obtained from the FAO 56 (Allen *et al*., 1998) proposed method. The value for $k_{c\ initial}$ determined from Figure 30b of FAO 56 was 0.75 which was then adjusted by using Equation 60 of FAO 56 to produce a $k_{c\ initial}$ value of 0.3. $K_{c\ initial}$ determined from the k_{cb} curve was 0.28 which was approximately equal to 0.3 as that of FAO 56 methodology for FI treatments.

The mid-season growth stage goes through effective full crop canopy cover to the start of crop maturity and one of the means to determine the occurrence of effective full crop canopy cover was when LAI reached 3.0 according to Allen *et al*. (1998). The corresponding mean value of NDVI when LAI approximately reached 3.0 was 0.65 i.e. the peak mean NDVI value recorded during the growing season.

The value of NDVI i.e. 0.65 when LAI approximately reached 3.0 in the experiment was substituted into the derived k_{cb} -NDVI models (Equation 4.1) which produced a $k_{c\ mid}$ value of 0.89 for FI treatments using the FAO 56 methodology. The value obtained for $k_{c\text{-}mid}$ from FAO 56 methodology was 0.89 while the experimental $k_{c\text{-}mid}$ was 0.91. The FAO 56 value i.e. 0.89 was compared with the experimental $k_{c\text{-}mid}$ value derived from the k_{cb} curve (Figure 4.2). The experimental $k_{c\ mid}$ estimated from the k_{cb} curve (Table 4.1) was a little higher than that obtained from the FAO 56 (Allen *et al.*,1998) approach and that of Oppong Danso (2014) who also had 0.89 for $k_{c\ mid}$ for okra on a drip irrigated field. The $k_{c\ mid}$ determined in this experiment was very close to values obtained by Panigrahi and Sahu (2013) who experimented on okra under partial root-zone furrow irrigation. The estimated $k_{c\ mid}$ in this experiment again closely agreed with the value obtained by Kisekka *et al*. (2010) who had 1.0 for $k_{c\ mid}$. The differences could be as a result of irrigation frequency, management practices, difference in agro-climatic conditions and

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difference in okra variety used but the closeness of the values in literature serves as guide to validate results obtained in this experiment.

$K_{c\ late}$ determined in this experiment i.e. 0.86 also agreed closely to that obtained by Oppong Danso (2014) who had 0.98 for $k_{c\ late}$ and Kisekka *et al*. (2010) who also reported a value of 0.9 for $k_{c\ late}$. The experimental $k_{c\ late}$ value, 0.86 seemed to be underestimated when compared with both Oppong Danso (2014) and Kisekka *et al*. (2010) probably due to difference in fertigation, irrigation frequency, cultural practices, differences in okra variety and climate. Again it only serves as a guide to validating the experimental result based on the little variation or difference between the values of $k_{c\ late}$ obtained for okra.

5.3 Crop Growth Length

Four growth lengths (days) and their corresponding k_c values were determined from the k_{cb} curve (Figure 4.2) and compared to Oppong Danso (2014) and Kisekka *et al*. (2010). From the K_{cb} curve plotted, the initial growth stage was determined from five days after emergence to the point where the curve suddenly rises up from the assumed horizontal plane.

Crop development stage was determined from average of the values from the base foot of the sudden risen curve to a point where it started moving in a horizontal–like plane at the peak of the curve which marked the mid-season growth stage.

The mid-season growth length delineated the peak horizontal – like part of the k_{cb} curve to the point where the curve started falling as shown in Figure 4.2.

The late season growth length was marked with the point from which the curve started falling down from the mid-season stage to the point where the experiment was ended.

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The four different growth lengths namely initial, crop development, mid-season and late season estimated from the k_{cb} curve in this experiment did not match exactly with that of Oppong Danso (2014) and Kisekka *et al*. (2010) though they also had different okra growth lengths for all the four growth periods. Kisekka *et al*. (2010) had 25 days: 25 days: 25 days: 15 days respectively for initial: crop development: mid-season: late season growth stages. Oppong Danso (2014) on the other hand had 23 days: 26 days: 30 days: 7 days for initial: crop development: mid-season: late season growth stages respectively as against that observed in this experiment, 20 days: 25 days: 20 days: 10 days for initial: crop development: mid-season: late season growth stages respectively. The observed differences in crop growth length from Oppong Danso (2014) and Kisekka *et al*. (2010) and that of this experiment resulted from the different climatic regions characterized by different evaporative demand of the atmosphere and irrigation frequency as well as the okra varietal difference.

5.4 Okra Water Requirement

Crop evapotranspiration serves as a guide to estimating crop water requirement. The amount to supply back to the cropped field following water loss to the atmosphere through evapotranspiration is termed crop water requirement. Under standard conditions with high atmospheric demand on evaporation, crop evapotranspiration could be high and therefore require substantially high amount of water to compensate the losses through ET_c. On the other hand where crop evapotranspiration is low, it means that smaller amount of water is required by the crop to replace the losses through evapotranspiration. This is to say ET_c depends partly on ET_o and crop coefficient (K_c) and management practices. Crop water use may be higher due to high evaporative demand of the

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atmosphere on ET but that does not guarantee a correspondent higher yield as a result of the higher crop water use.

Okra water requirement differed for the various crop growth stages characterized by different crop coefficients. It was low at the initial growth stage, increased at the crop development stage and reached a peak value at mid-season stage. It was observed to reduce at the late season due to crop ageing, senescence and leaf fall.

Higher values of crop water use (ET_c) and accumulated seasonal okra water use were recorded in FI treatment throughout the growing season over the DI treatments which recorded lower values at each growth stage except at the mid-season stage where DI recorded higher ET_c over FI treatment. The higher okra water use recorded at the mid-season in DI treatment than FI treatment was as a result of high hydraulic conductivity in partial wetted soils. This scenario has also been observed by Kang *et al*. (2000) and Panigrahi and Sahu (2013).

Accumulated seasonal water used for FI and DI treatments were 273.17 mm and 246.44 mm. The seasonal water use values obtained in this experiment agreed closely with range of values obtained by Panigrahi and Sahu (2013) who had 250 mm, 232 mm and 279 mm under three different treatments of partial root zone furrow irrigation in an un-amended soil in India but varied slightly with Oppong Danso (2014) who recorded a seasonal okra water use of 236 mm for drip irrigation.

The difference was due to the difference in atmospheric demand on evaporation. An ET_o value could serve as a guide to measure the atmospheric demand on evaporation. For instance, while an average ET_o of 5.4 mm day^{-1} was recorded at the research centre during the December-March growing period, Oppong Danso (2014) recorded lower average ET_o of 4.4 mm day^{-1} in an experiment conducted at the same monthly interval i.e. December to March in a different agro-

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climatological zone. This is partly the reason for the higher seasonal okra water use in this experiment than that of Oppong Danso (2014). The difference in accumulated seasonal water used was therefore related to the difference in ET_o values. High ET_o value means high atmospheric demand on evaporation and hence high crop evapotranspiration which resulted in the higher seasonal okra water use in this experiment. The possibility of the soil type also having effect on the crop evapotranspiration was also envisaged as different soil types have different water and nutrient retention capacity for crop use.

5.5 Crop Yield in Biochar and Irrigation Treatments

Crop yield is vital in any agricultural management strategy. All management techniques in crop production are geared and aimed towards achieving higher output of agricultural crop in terms of yield. Soil and water management strategies have been developed to achieve higher yield using optimized water application techniques such as drip irrigation system to save substantial amounts of water while aimed at increasing yield and water productivity.

Soil amendment materials have been shown to improve crop yield by improving on the soil water holding capacity, nutrient retention and soil physicochemical properties.

Yield was estimated in the four biochar treatments in both FI and DI treatment and subjected to statistical analysis using GenStat 11th edition software (Statistical tool). Total above ground biomass yield (Y_{TBM}) and fresh fruit yield (Y_{FF}) were determined and analyzed numerically and statistically (Table 4.3).

There were no significant difference in Y_{TBM} in all the four biochar treatments under FI and DI treatments at $P \leq 0.05$ through LSD test probably due to the fact that the biochar had limited effect

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on Y_{TBM} at the first season or early stages of application. Major *et al*. (2010) observed a similar situation whereby maize grain yield did not significantly increase in the first year of the biochar application, but increased in the subsequent years.

Numerically there were higher values of Y_{TBM} recorded in all biochar treatments in FI than DI treatments. The irrigation method had effect on okra water use and yield. In any case FI was found to have greater Y_{TBM} as compared to DI though there was no significant difference statistically. The higher yield recorded in the higher irrigation treatment, thus FI over the DI treatment agreed with findings of Konyeha and Alatise (2013) who recorded higher yield in higher irrigation treatment of 75% over a lower irrigation treatment of 25%. Kang *et al.* (2000) also observed that under limited irrigation situations, treatment with high moisture content increased ET_c and biomass yield.

Highest Y_{TBM} was recorded in 0 t ha^{-1} biochar in FI treatments while 10 t ha^{-1} biochar recorded the highest Y_{TBM} in DI treatment (Table 4.3). The trend in the result of Y_{TBM} produced indicated that biochar application rate had effect on soil water retention and crop yield under limited water conditions than optimal water availability conditions. Similar results obtained by Yangyuoru *et al*. (2006) also showed that differences in maize yields in an amended soil over the control were due to the improved water retention ability of the soils amended with polymeric absorbents (Soil conditioner).

In terms of okra fresh fruit yield (Y_{FF}), biochar application rate did not have any significant effect on Y_{FF} in FI treatment but there were significant difference in all biochar treatments in DI treatments at $P \leq 0.05$ from LSD test except the 5 t ha^{-1} which showed no significant difference with the other three biochar amounts. Again, biochar effect on Y_{FF} in DI treatments was in the order of increasing biochar amount whereby the highest yield was recorded in10 t ha^{-1}_P followed

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by 10 t ha^{-1} (Table 4.3). This has also been observed by Ason *et al*. (2015) and Eldardiry and Abd El-Hady (2015) where a particular soil conditioner application rate was directly proportional to the water retention which resulted in high yield and water productivity in that order of increasing soil conditioner application rate.

The trend in Y_{FF} in DI treatment (Table 4.3) means that under deficit irrigation or water limitation conditions, higher biochar amounts or higher biochar application rates have a positive impact on water and nutrient retention in the soil for crop use. The highest Y_{FF} recorded in the 10 t ha^{-1}_P was as a result of the biochar ability to retain and release the attached phosphorous fertilizer to the crop which has also been observed by Ding *et al*. (2010). This agreed with a study by Ason *et al*. (2014) who reported that, the effect of Zytonic soil conditioner combined with fertilizer on growth of their test crops were significant as compared to the control. Alburquerque *et al*. (2013) and Lehmann *et al*. (2011) also reported that biochar combined with mineral fertilizer has a significant effect as compared to only biochar on plant yield. The presence of biochar can decrease P adsorption on Fe-oxides and enhance P availability in soils (Cui *et al*., 2011). Alling *et al*. (2014) in their study concluded that biochar not only have the potential to retain the available nutrient but releases the essential plant growth nutrients as well as alleviate Aluminium (Al) toxicity in the soil.

5.6 Water Productivity

Water productivity (WP) determined in the study was reported for total above ground dry biomass (WP_{TBM}) and fresh okra fruits harvested (WP_{FF}) in Table 4.4. The WP for biomass produced (WP_{TBM}) was approximately 2.90 kg m^{-3} for FI treatments and 2.72 kg m^{-3} for DI treatments. The WP for fresh okra fruit harvested (WP_{FF}) was approximately 2.20 kg m^{-3} for FI treatments and

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1.93 kg m^{-3} for DI treatments (Tale 4.4). Thus WP_{FF} closely agreed with the value obtained by Hashim *et al*. (2012) who had 1.72 kg m^{-3} as WP for okra assuming all values are approximated to 2 kg m^{-3}.

The WP_{FF} recorded in this study was lower than that of Oppong Danso *et al*. (2015) who had 5.2 kg m^{-3} and 6.5 kg m^{-3} for okra fruit under drip irrigation with placed manure and drip irrigation with fertigation. The higher WP_{FF} observed in Oppong Danso (2014) was due to the difference in nutrient treatments and irrigation frequency. Oppong Danso (2014) also had value of 1.4 kg m^{-3} as WP of okra total biomass under drip irrigation with placed manure and 2.0 kg m^{-3} for WP of okra total biomass under drip irrigation with fertigation. The WP_{TBM} values in both FI and DI treatments were a little higher than Oppong Danso (2014) probably due to the effect of the biochar retaining water and nutrient for okra use with a correspondent improved biomass formation right from germination of okra.

Konyeha and Alatise (2013) on the other hand determined okra water productivity and had 1.25 kg m^{-3} and 0.59 kg m^{-3} under irrigation treatment at 75% (High irrigation) and 25% (Low irrigation) respectively. Again in this research, WP_{FF} in FI and DI treatments were higher than Konyeha and Alatise (2013) but followed the same trend of higher irrigation treatment resulting in higher water productivity value as observed in this study.

The obtained WP_{TBM} agreed with values reported by Panigrahi and Sahu (2013) who had 2.87 for 25% available soil moisture depletion and 2.93 for 50% available soil moisture depletion under alternate partial root zone irrigation. They recorded higher WP_{FF} (8.41 kg m^{-3} and 9.18 kg m^{-3}) than the experimental WP_{FF} probably due to effect of the differences in irrigation and nutrient treatments as well as length of fresh okra fruit harvest period.

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The effect on high yield obtained in FI treatments was reflected in its higher WP than that recorded in DI treatments which has also been observed in Konyeha and Alatise (2013). From Table 4.4, it was observed that using deficit irrigation could save 10.97% water but would yield 14.56% less Y_{TBM} compared to full irrigation treatment. It was also observed that, implementing deficit irrigation would have saved 10.97% water but reduced fresh fruit yield (Y_{FF}) by 22.67%.

It was clear that if the farmer could decide to save 10.97 % of water required by the crop he will then compromise a loss in Y_{TBM} of about one half the percentage of water saved when DI treatment was used. On the other hand the farmer could save 10.97 % of water required by the crop and compromise with a loss in Y_{FF} of about twice the percentage of water saved when DI treatment was used.

The prediction model developed from the graph of Y_{TBM} against NDVI provided room for estimating yield using NDVI data. The prediction model obtained from the experiment, Equation 4.2 had a RMSE of 0.08 showing a strong correlation between actual and predicted values. The predicted model also produced an R^2 of 0.94 when fitted with a power series regression, making the model desirable over linearly fitted regression model which would have produced low R^2 value. Linear model was not fitted because, at the initial growth stage, Y_{TBM} increases with increasing NDVI value until late season or maturity season where NDVI values decreased, while Y_{TBM} still increased as a result of the additional fruit yield on Y_{TBM}.

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CHAPTER SIX

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

The research aimed at estimating crop water requirement and yield of a local variety of okra in biochar amended soil to address the problem of low crop productivity in the dry season due to water scarcity. Measures to curtail such low crop productivity involved selecting an efficient irrigation method since crop water use and development were dependent on irrigation in the dry season. Drip irrigation was selected for its higher water application efficiency and water saving over the other forms of irrigation in okra production.

To find an effective way of achieving optimum crop production in water scarce situations, i.e. the dry season, two main treatments namely biochar amount and irrigation method were applied. Irrigation method consisted of full irrigation and deficit irrigation scheduling and four biochar amounts of 0 t ha^{-1}, 5 t ha^{-1}, 10 t ha^{-1}and 10 t ha^{-1}_P were applied to estimate the crop water use and yield variations in the different treatments. Biochar was used because of its capacity to improve on the physico-chemical properties of the soil, soil water and nutrient retention in the soil. The following contributions to knowledge and findings were made:

- Crop coefficients at the various crop growth stages were determined and model developed for predicting crop coefficient using ground based remote sensing technique.
- Model equation developed could be used in future studies for predicting okra k_c at the various crop growth stages.

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- Reference evapotranspiration (ET_o) from the December to March growing season were computed following FAO 56 (FAO P-M equation) approach using weather data accessed from an installed automatic weather station at the research centre.
- Using the modelled k_{cb} - NDVI relations, daily k_{cb} were computed and k_{cb} curves plotted.
- Okra growth length and corresponding k_c values were estimated from the k_{cb} curve and compared with FAO 56 method of determining k_c and growth length at the various crop growth stages.
- Okra water requirements, thus okra water use at the four growth stages as well as seasonal accumulated okra water use were estimated in full irrigation and deficit irrigation treatments.
- Actual yield were measured from destructive samples for total above ground biomass yield (Y_{TBM}) as well as fresh fruit yield (Y_{FF}) i.e. fresh okra fruits harvested was also measured.
- Models were developed to predict okra yield using NDVI data from the remote sensing.

6.2 Conclusions

Following the above contributions to knowledge and findings, the following conclusions were made:

- Okra water requirement was determined as 273.17 mm for FI treatment and 246.44 mm for DI treatment in biochar amended soil from derived crop coefficient of okra and ET_o.
- Okra seasonal water use was high in FI treatments than DI with a difference of 26.73 mm observed between FI and DI (Table4.4) with no significant difference in yield. This draws to the conclusion that DI could be selected as it represents water stressed condition in crop production.

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- The highest mean yield of total dry biomass was determined as 7.46 t ha^{-1} and the highest mean yield of okra fresh fruit was determined as 6.99 t ha^{-1} under FI treatments (Table 4.3).
- There were no significant differences in total dry biomass yield (Y_{TBM}) in all biochar treatments under FI and DI treatments hence biochar had no significant effect on Y_{TBM}.
- There were no significant differences in fresh fruit yield (Y_{FF}) in all biochar treatment under FI treatment.
- There were significant differences in fresh fruit yield (Y_{FF}) in DI under three biochar treatments with the exception of 5 t ha^{-1} which means that biochar ability to improve okra fruit yield was more predominant in limited water situations i.e. DI treatment.
- Phosphorous premixed with biochar gave the highest significant okra fruit yield under DI treatment.
- Prediction models obtained from the experiment can be used to estimate k_{cb} as well as forecast okra yield un-destructively ahead of harvest period in the near future.

6.3 Recommendations

- Biochar is recommended to improve okra fruit yield in limited or scarce water situations.
- Based on the yield results obtained under the biochar amounts used in this study, it is recommended that further studies be conducted using different biochar amounts to ascertain if higher biochar amount results in higher okra fruit yield under DI treatment.
- Ground based remote sensing is a possible means of studying crop phenology and should be encouraged at both micro and large scale okra cultivations.

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- Premixing phosphorous with biochar is recommended for achieving higher okra fruit yield but further studies should be conducted on premixing Nitrogen (N), Potassium (K) or other single major nutrients with biochar to determine its effect on okra fruit yield as well.
- Estimating crop water requirement and yield of okra in other sub regions of Ghana with different agro-climatic conditions is recommended for further studies in the future.

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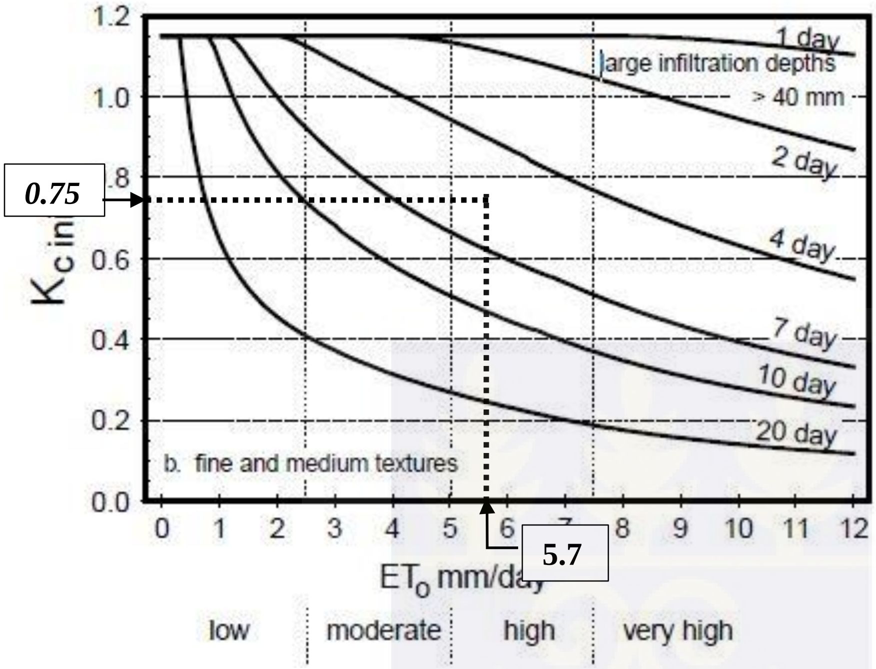
APPENDICES

Appendix A. Figures used to Compare $K_{c\ ini}$ and Soil Classification Based on its Texture



(Source: Allen *et al*., 1998)

Figure A1. FAO-56 Figure 30b used to determine average $K_{c\ ini}$ as related to the level of ET_o and the interval between irrigations greater than or equal to 40 mm per wetting event, during the initial growth stage for medium and fine textured soils.

Note : *$K_{c\ initial}$ read from the figure is written in italic shown in rectangular box (0.75) given ET_o as 5.7 mm day^{-1}and 6 days irrigation interval as input data in our experiment*.

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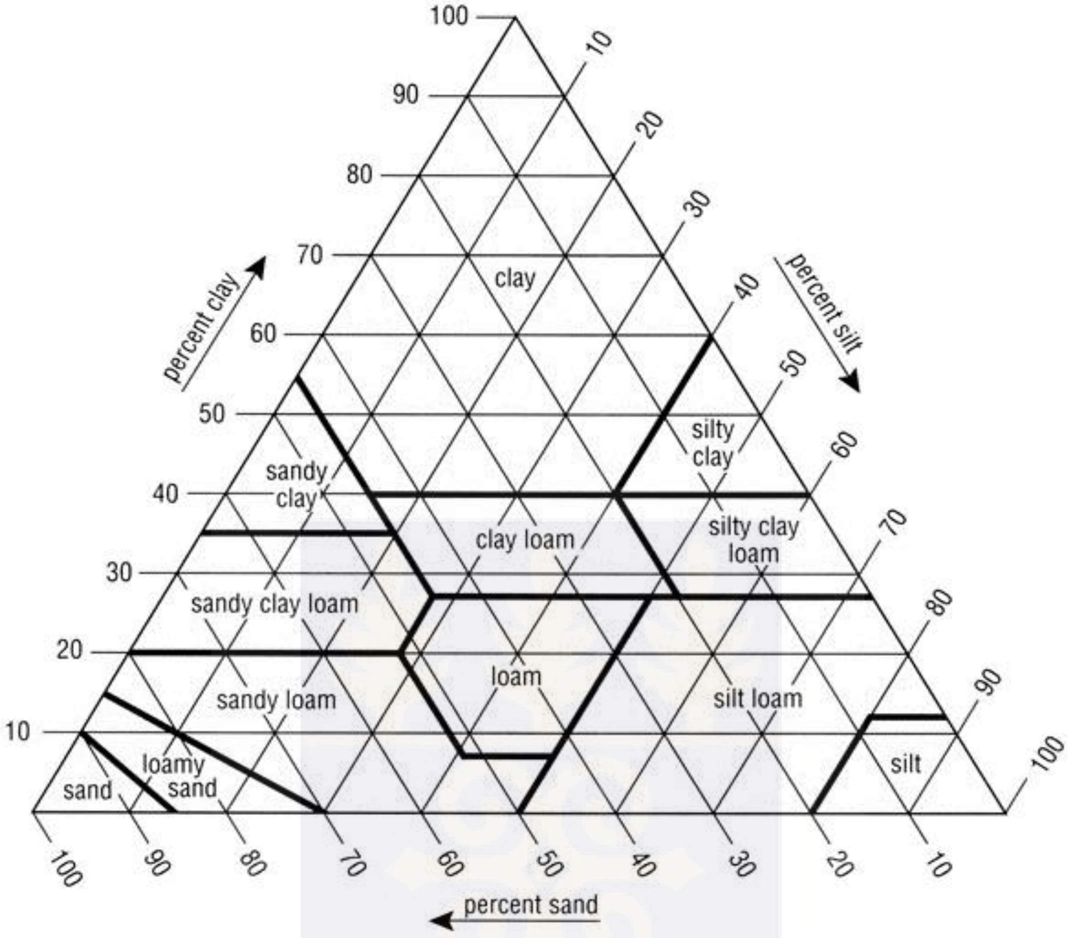

(Source: FAO, 2006)

Figure A2. USDA soil textural triangle chart used to classify experimental field soil in terms of texture

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Appendix B. Spreadsheet for ET_o and Soil Water Deficit (D) Computations

Table B1. Sample spreadsheet for daily ET_o computation using FAO - Penman Monteith equation for one month from daily climate data accessed at the research centre

Date	U_2	T_{max}	T_{min}	RH_{max}	RH_{min}	Solar radiation	ET_o	Tot. Rain
d-m-y	m s^{-1}	°C	°C	%	%	MJ m^{-2}	mm day^{-1}	mm
01-12-15	3.234	34.1	22.35	99	1.447	14.9072	5.358	0
02-12-15	2.646	34.47	24.13	95.7	1.885	14.71756	4.674	0
03-12-15	2.842	32.89	22.93	99	1.212	13.78963	46.31	1.016
04-12-15	4.018	31.9	21.75	100	2.828	12.68442	5.605	26.16
05-12-15	3.332	30.86	21.75	96.7	2.155	11.66804	4.817	0
06-12-15	2.254	31.56	20.55	96.2	2.289	13.49894	3.837	0
07-12-15	2.842	31.55	21.25	94.9	2.02	13.66606	4.536	0
08-12-15	3.332	31.45	21.62	99.2	1.784	12.12187	4.899	0
09-12-15	3.234	33.06	19.94	91.6	0.404	15.234	5.500	0
10-12-15	1.96	32.18	18.79	95.3	0.337	14.90655	3.707	0
11-12-15	3.724	32.79	18.56	99.6	0.404	15.03887	5.906	0
12-12-15	3.038	32.89	19.47	88.9	1.279	14.67059	5.254	0
13-12-15	2.352	32.69	20.58	100	0.471	12.48565	4.086	0
14-12-15	3.528	33.53	21.58	100	0.74	13.92835	5.598	0
15-12-15	3.43	32.98	22.15	99.8	0.741	13.53222	5.337	0

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16-12-15	3.822	33.83	21.18	98.4	0.404	15.61859	6.117	0
17-12-15	3.43	33.35	18.13	92.7	0.202	16.27552	5.904	0
18-12-15	3.528	33.39	15.34	96.6	0.404	16.21272	6.123	0
19-12-15	3.332	32.38	16.89	91.2	1.549	14.86471	5.588	0
20-12-15	2.45	32.66	17.35	92.6	1.683	13.69741	4.460	0
21-12-15	3.136	32.43	20.21	97.6	2.019	13.72418	5.015	0
22-12-15	2.744	33.23	19.67	99.9	2.087	13.75091	4.681	0
23-12-15	3.43	33.5	20.71	99	1.077	13.86545	5.543	0
24-12-15	3.528	33.82	19.23	99.7	7.471	14.61663	5.499	0
25-12-15	3.626	33.06	19.54	99.9	17.5	13.50691	4.886	0
26-12-15	4.312	33.53	20.18	96.5	2.154	12.94096	6.512	0
27-12-15	3.626	32.8	18.16	96.4	8.75	12.83508	5.416	0
28-12-15	3.136	33.07	18.36	95.6	17.24	12.19564	4.541	0
29-12-15	2.94	33.53	18.76	97.2	1.212	12.33174	5.077	0
30-12-15	6.37	35.85	18.83	99.3	0.808	14.21496	9.369	0
31-12-15	2.842	32.79	19.47	99.9	9.96	12.83882	4.387	0
01-01-16	4.606	32.83	21.32	100	5.117	12.25832	6.252	0

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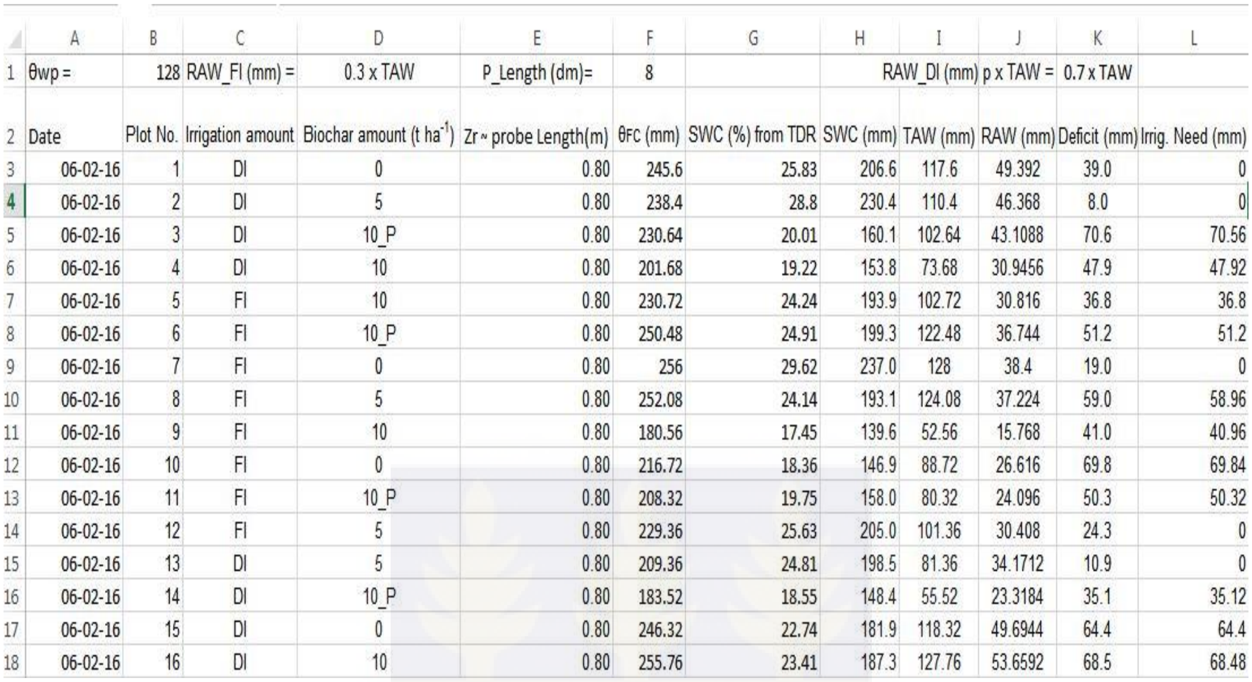
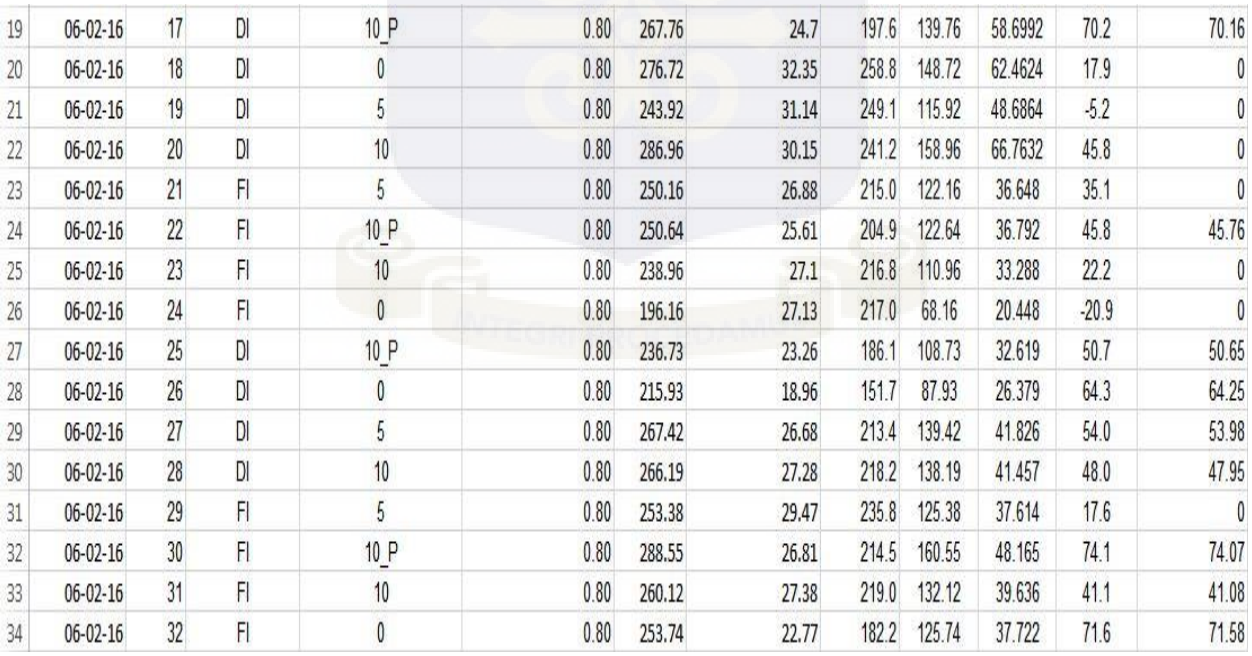
Table B2. Sample spreadsheet used for computing soil water deficit (D) for irrigation scheduling



	A	B	C	D	E	F	G	H	I	J	K	L
1	θ_{wp} =	128	RAW_FI (mm) =	0.3 x TAW	P_Length (dm)=	8			RAW_DI (mm)	p x TAW =	0.7 x TAW	
2	Date	Plot No.	Irrigation amount	Biochar amount (t ha^{-1})	Zr ≈ probe Length(m)	θ_{FC} (mm)	SWC (%) from TDR	SWC (mm)	TAW (mm)	RAW (mm)	Deficit (mm)	Irrig. Need (mm)
3	06-02-16	1	DI	0	0.80	245.6	25.83	206.6	117.6	49.392	39.0	0
4	06-02-16	2	DI	5	0.80	238.4	28.8	230.4	110.4	46.368	8.0	0
5	06-02-16	3	DI	10_P	0.80	230.64	20.01	160.1	102.64	43.1088	70.6	70.56
6	06-02-16	4	DI	10	0.80	201.68	19.22	153.8	73.68	30.9456	47.9	47.92
7	06-02-16	5	FI	10	0.80	230.72	24.24	193.9	102.72	30.816	36.8	36.8
8	06-02-16	6	FI	10_P	0.80	250.48	24.91	199.3	122.48	36.744	51.2	51.2
9	06-02-16	7	FI	0	0.80	256	29.62	237.0	128	38.4	19.0	0
10	06-02-16	8	FI	5	0.80	252.08	24.14	193.1	124.08	37.224	59.0	58.96
11	06-02-16	9	FI	10	0.80	180.56	17.45	139.6	52.56	15.768	41.0	40.96
12	06-02-16	10	FI	0	0.80	216.72	18.36	146.9	88.72	26.616	69.8	69.84
13	06-02-16	11	FI	10_P	0.80	208.32	19.75	158.0	80.32	24.096	50.3	50.32
14	06-02-16	12	FI	5	0.80	229.36	25.63	205.0	101.36	30.408	24.3	0
15	06-02-16	13	DI	5	0.80	209.36	24.81	198.5	81.36	34.1712	10.9	0
16	06-02-16	14	DI	10_P	0.80	183.52	18.55	148.4	55.52	23.3184	35.1	35.12
17	06-02-16	15	DI	0	0.80	246.32	22.74	181.9	118.32	49.6944	64.4	64.4
18	06-02-16	16	DI	10	0.80	255.76	23.41	187.3	127.76	53.6592	68.5	68.48

Table B2 continued...



19	06-02-16	17	DI	10_P	0.80	267.76	24.7	197.6	139.76	58.6992	70.2	70.16
20	06-02-16	18	DI	0	0.80	276.72	32.35	258.8	148.72	62.4624	17.9	0
21	06-02-16	19	DI	5	0.80	243.92	31.14	249.1	115.92	48.6864	-5.2	0
22	06-02-16	20	DI	10	0.80	286.96	30.15	241.2	158.96	66.7632	45.8	0
23	06-02-16	21	FI	5	0.80	250.16	26.88	215.0	122.16	36.648	35.1	0
24	06-02-16	22	FI	10_P	0.80	250.64	25.61	204.9	122.64	36.792	45.8	45.76
25	06-02-16	23	FI	10	0.80	238.96	27.1	216.8	110.96	33.288	22.2	0
26	06-02-16	24	FI	0	0.80	196.16	27.13	217.0	68.16	20.448	-20.9	0
27	06-02-16	25	DI	10_P	0.80	236.73	23.26	186.1	108.73	32.619	50.7	50.65
28	06-02-16	26	DI	0	0.80	215.93	18.96	151.7	87.93	26.379	64.3	64.25
29	06-02-16	27	DI	5	0.80	267.42	26.68	213.4	139.42	41.826	54.0	53.98
30	06-02-16	28	DI	10	0.80	266.19	27.28	218.2	138.19	41.457	48.0	47.95
31	06-02-16	29	FI	5	0.80	253.38	29.47	235.8	125.38	37.614	17.6	0
32	06-02-16	30	FI	10_P	0.80	288.55	26.81	214.5	160.55	48.165	74.1	74.07
33	06-02-16	31	FI	10	0.80	260.12	27.38	219.0	132.12	39.636	41.1	41.08
34	06-02-16	32	FI	0	0.80	253.74	22.77	182.2	125.74	37.722	71.6	71.58

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Appendix C. ANOVA Tables For Y_{TBM} and Y_{FF} under FI and DI Treatments

Table C1. ANOVA for Y_{TBM} in FI treatment

Source of variation	DoF	SS	MS	V.r	F. Probability
Treatment	3	0.016	0.005	0.21	0.890
Block	3	0.252	0.084	3.20	
Error	9	0.236	0.026		
Total	15	0.505			

Table C2. ANOVA for Y_{TBM} in DI treatment

Source of variation	DoF	SS	MS	V.r	F. Probability
Treatment	3	0.019	0.006	0.30	0.823
Block	3	0.167	0.056	2.71	
Error	9	0.185	0.021		
Total	15	0.370			

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Table C3. ANOVA for Y_{FF} in FI treatment

Source of variation	DoF	SS	MS	V.r	F. Probability
Treatment	3	0.056	0.019	0.76	0.543
Block	3	0.342	0.114	4.52	
Error	9	0.227	0.025		
Total	15	0.626			

Table C4. ANOVA for Y_{FF} in DI treatment

Source of variation	DoF	SS	MS	V.r	F. Probability
Treatment	3	0.226	0.075	3.62	0.058
Block	3	0.105	0.035	1.68	
Error	9	0.187	0.021		
Total	15	0.518			

DoF is degree of freedom, SS is sum of squares, MS is mean square, and V.r is variance

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Appendix D. Graphs and Prediction Models Produced from Experiment

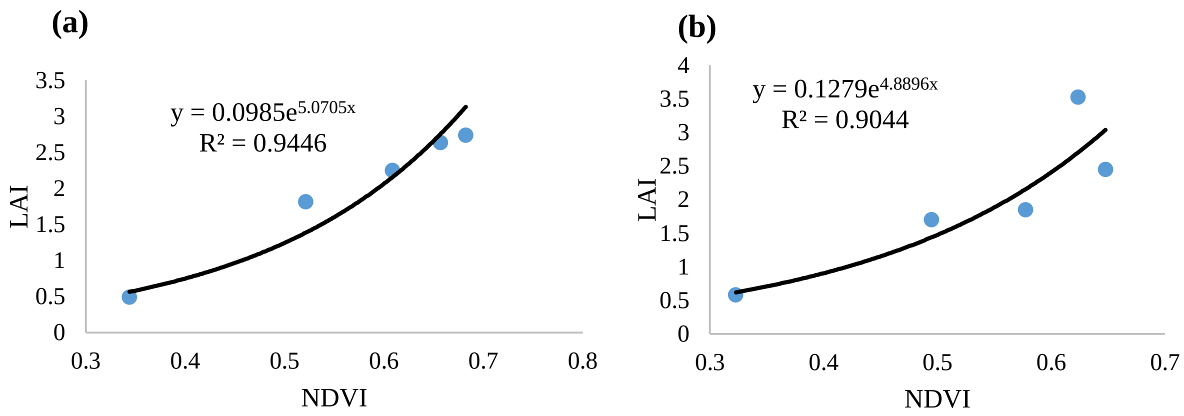

Figure D1. Relationship between LAI and NDVI and model equations for (a) FI and (b) DI treatments

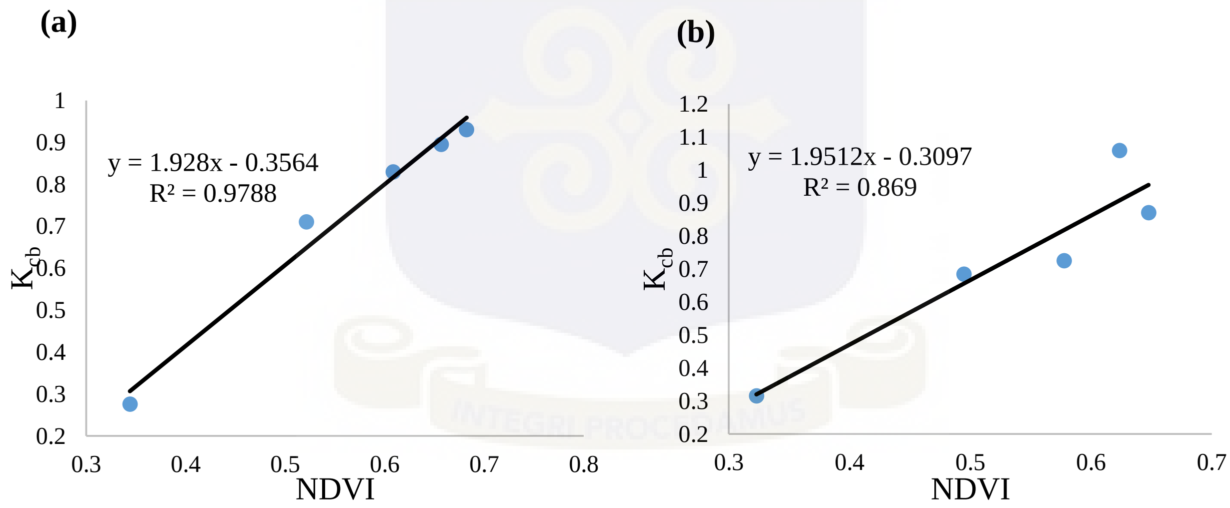

Figure D2. Relationship between k_{cb} and NDVI and model equations for (a) FI and (b) DI treatments

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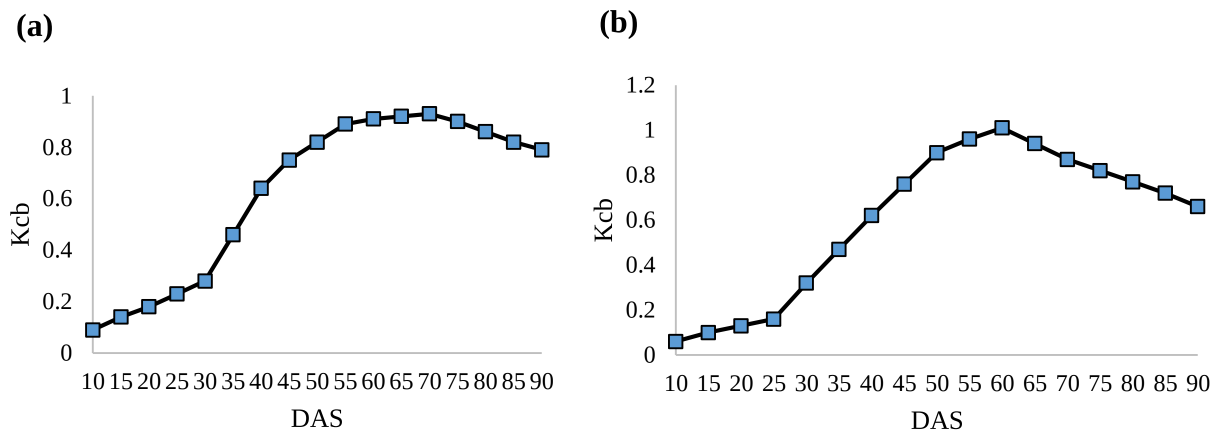

Figure D3. Crop coefficient (K_{cb}) curve for (a) FI and (b) DI treatments

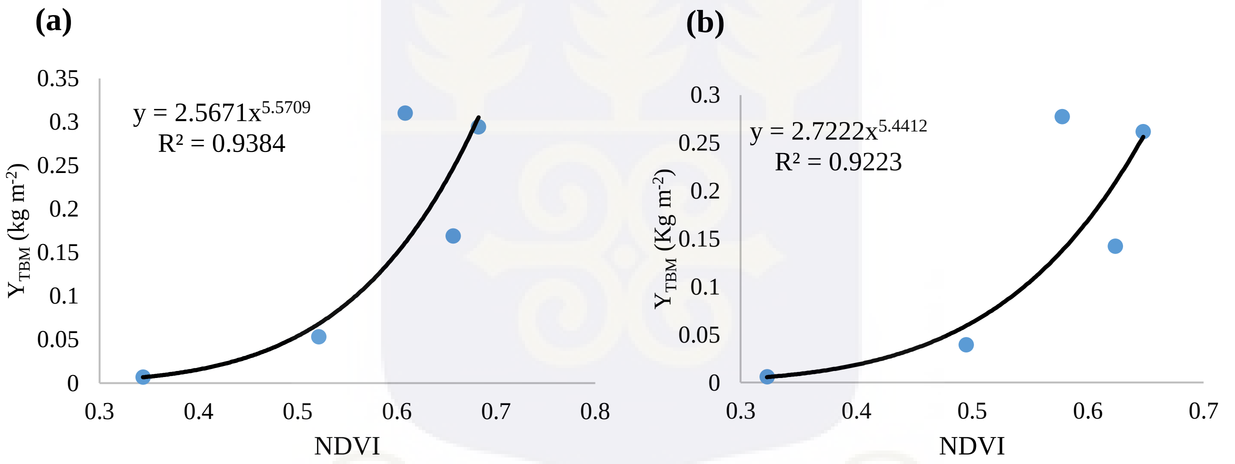

Figure D4. Relationship between total above ground dry biomass yield (Y_{TBM}) against NDVI and model equations for (a) FI and (b) DI treatments

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Appendix E. Field Activities in Photo Gallery

Figure E1. (a) Field slashed and ploughed afterward and (b) Plots demarcated, soil loosened and biochar incorporated

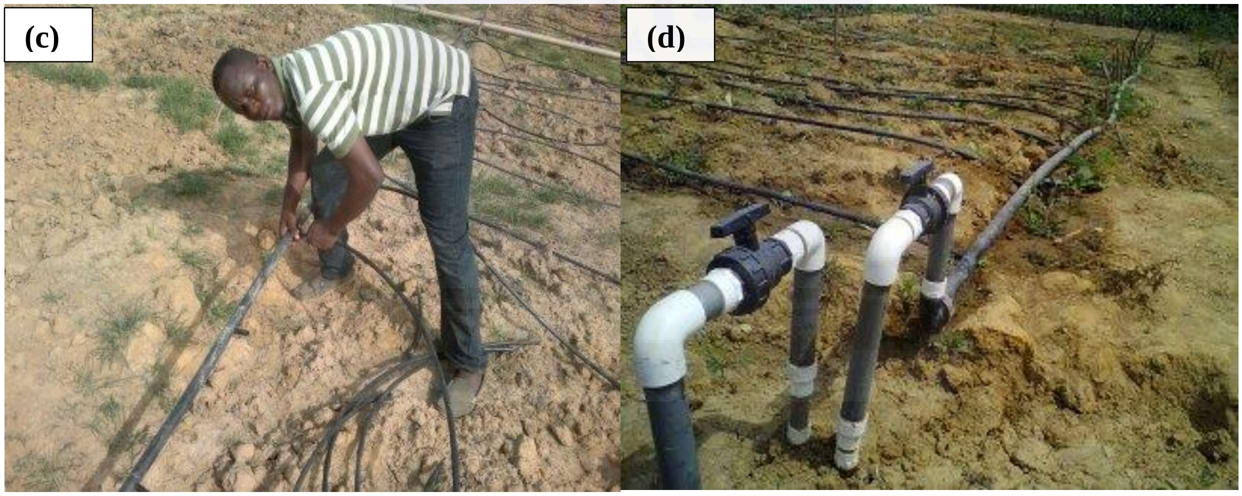

Figure E2. (a) Connecting drip lines to lateral and (b) Stop cork connected to control FI and DI treatments

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Figure E3. (e) Filter connected to main line and (f) Main line connected to water source (dam)

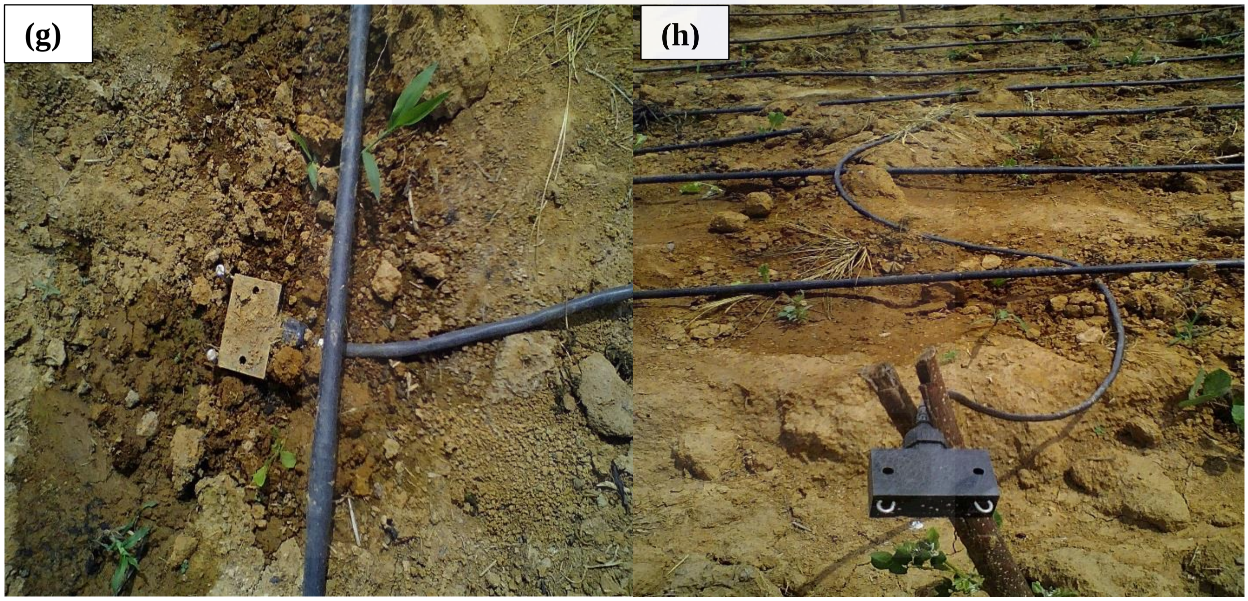

Figure E4. (g) TDR probe installed in soil close to emitter and (h) TDR probes extended with cable to border of plot to allow measurement at full canopy growth stage without entering into plot

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Figure E5. Field layout after irrigation and TDR installations

Figure E6. (i) Okra at sprout stage (10 DAS) and (j) Okra at flowering and fruiting stage

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Figure E7. (k) Measuring SWC with TDR and (l) Measuring okra vegetation index (NDVI) with RapidSCAN CS-45

Figure E8. Okra destructive sample harvested for LAI and Y_{TBM} determination

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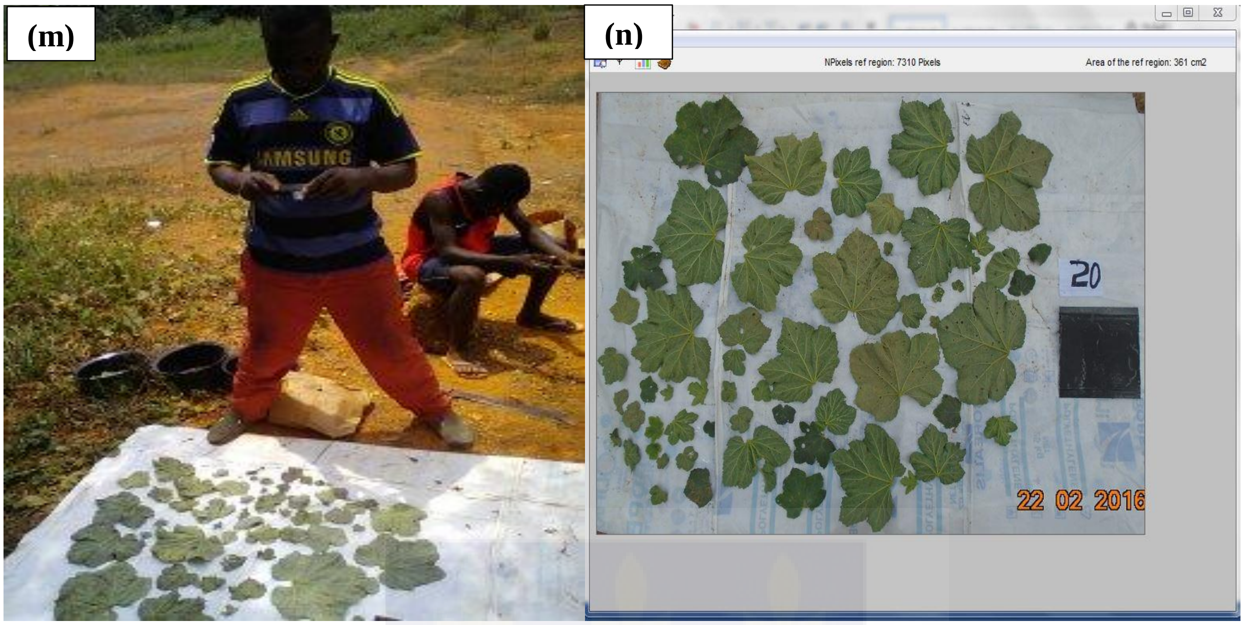

Figure E9. (m) Taking okra leaves photograph for use in LAM and (n) LAM software interface showing okra leaves image uploaded for leaf area determination

Figure E10. (o) Mechanical weed control with hoe and (p) Pesticides and fungi in okra

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Figure E11. (q) Harvesting okra fresh fruit and (r) Weighing total harvested fruits for each plot

Figure E12. Total fresh okra fruits harvested on a given harvest day from 32 plots