EVALUATION OF IRRIGATION AND MULCHING ON THE ESTABLISHMENT OF TRANSPLANTED COCOA

BY

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DECLARATION

I hereby declare that except for references to works of other researchers, which have been duly cited, this work is the result of my original research and that this thesis has neither in whole nor in part been presented to any other University for the award of a degree.

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ABSTRACT

Field experiment was conducted at the University of Ghana Forest and Horticultural Crop Research Centre (FOHCREC) in Kade from October 2017 to March 2018 to evaluate the effect of deficit irrigation on the establishment of transplanted cocoa. The experimental design used was the split plot design and was made up of 3 irrigation levels namely no irrigation (NI), deficit irrigation (DI) and full irrigation (FI) and 2 mulch levels namely mulch (M) and no mulch (NM). The K_c at the end of the experiment was 0.76, 0.78 and 0.96 for NI, DI and FI respectively under no mulch treatment. The K_c for mulch treatment at the end of the experiment was 0.64, 0.71 and 0.80 for NI, DI and FI respectively. The cumulative ET_c at the end of the experiment under no mulch was 376.77 mm, 378.29 mm and 409.83 mm for NI, DI and FI respectively. The cumulative ET_c for mulch treatment at the end of the experiment was 369.16 mm, 389.06 mm and 392.62 mm for NI, DI and FI respectively.

High vigour scores translated to high seedling establishment with NI, DI and FI having an establishment percentage of 92%, 96% and 100% respectively under no much. The percentage establishment of cocoa for NI, DI and FI was 96%, 96% and 100% respectively under mulch. Irrigation and mulch did not have any significant difference in the plant vigour and percentage establishment of cocoa at $P \leq 0.05$. It can be concluded that the effect of Irrigation and mulch could not be seen on seedling survival because of the high rainfall amount and short dry season during the experiment period.

DEDICATION

I dedicate this work to my family and friends for their love and support.

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LIST OF ABBREVIATIONS AND SYMBOLS

CPH	-Cocoa Pod Husk
CR	-Capillary rise
CWR	-Crop Water Requirement
D	-Soil water deficit
DF	-Degree of Freedom
DI	-Deficit Irrigation
DP	-Deep percolation
e_a	-Saturation vapour pressure
e_s	-Actual vapour pressure
ET	-Evapotranspiration
ET_c	-Crop Evapotranspiration
ET_o	-Reference Evapotranspiration
FC	-Field Capacity
FI	-Full Irrigation
G	-Ground heat flux
GDP	-Gross Domestic Product
I	-Irrigation

K_c	-Crop coefficient
LSD	-Least Significant Difference
M	-Mulch
NDVI	-Normalized Difference Vegetative Index
NI	-No Irrigation
NM	-No Mulch
p	-Fraction of soil water depleted by the crop in the root zone
P	-Precipitation
RAW	-Readily Available Water
R_n	-Net Radiation
RO	-Runoff
SS	-Sum of Squares
SWC	-Soil Water Content
T	-Temperature
TAW	-Total Available Water
TDR	-Time Domain Reflectometry
u_2	-Wind speed

WAF -Week after flushing

WP -Wilting Point

Zr -Rooting depth

ΔSF -Change in Subsurface Flow

ΔSW -Change in Soil Water

Δ -Slope of vapour pressure curve

γ -Psychrometric constant

θ_{FC} -Moisture content at field capacity

θ_{WP} -Moisture content at wilting point

CHAPTER ONE

1 INTRODUCTION

1.1 Background

Cocoa (*Theobroma cacao*) is an evergreen tree from the *Malvaceae* family (Afoakwa, 2014) which originated from the wet forest of South America (Bunn *et al*., 2017). Nearly 70% of cocoa production in the world originates from West Africa (Medina & Laliberte, 2017) with products such as chocolate, cocoa power, cosmetic and pharmaceutical products being derived from it (Bart-Plange & Baryeh, 2003).

Cocoa is cultivated within 10° north and south of the equator where conditions such as temperature, rainfall, soil types and pH are suitable for the growth of the cocoa plant (Afoakwa, 2014). Minimum temperature ranging between 18-21 °C and maximum temperature ranging between 18-32 °C are considered ideal for cocoa production. In addition, annual rainfall within 1,500 and 2,500 mm and a soil with pH ranging from 5.0-7.5 is preferable for cocoa production (Afoakwa, 2014).

In Ghana, cocoa is a major crop cultivated in six regions and forms the economic background of the country (Onumah *et al*., 2013; Anim-Kwapong & Frimpong, 2006; Laven & Boomsma, 2012). The cocoa industry is known to contribute significantly to the country's income (Onumah *et al*., 2013; Laven & Boomsma, 2012), provide employment and as a source of income for farmers (Anim-Kwapong & Frimpong, 2006; Nyadanu, *et al*., 2012).

The cocoa industry has been confronted by several problems in the establishment and production stage. Some of these problems include pests, diseases and climate change. Pests and diseases cause about 25% global loss in cocoa production (Enriquez & Soria, 1996). Cocoa is vulnerable to changes in climate and the effect of climate change can be seen in unfavourable weather patterns especially rainfall and temperature. The onset and intra-seasonal rainfall distribution is variable (Mawunya *et al*., 2011). The variation in rainfall and rise in temperatures lead to prolonged drought season and since cocoa is sensitive to drought and irrigation is rare in cocoa farming, mortality of cocoa seedlings at the establishment phase is high (Anim-Kwapong & Frimpong, 2006).

Climate change models have predicted increase in temperatures in the coming years (Anim-Kwapong & Frimpong, 2006) and this will affect the rate at which moisture is lost through evapotranspiration (ET). Crop water requirement (CWR) as defined by Allen *et al*. (1998) is the amount of moisture needed to satisfy the loss due to evapotranspiration from a cropped field and this is done through irrigation scheduling.

1.2 Problem Statement

Climate has been one of the main determinants of agricultural productivity and it is projected to compromise agricultural production. Climate change models have predicted continued increase in temperature and decline in rainfall leading to irregularities in the onset, duration and cessation of the rainfall season (Anim-Kwapong & Frimpong, 2006). Cocoa is extremely sensitive to climate change especially to temperature and rainfall. The projected increase in temperature and decrease in rainfall will prolong drought resulting in water deficits in the soil and increased cocoa seedling deaths during the establishment phase.

To reduce the effect posed by climate change on cocoa seedling deaths during the establishment phase, irrigation and mulch as a way of conserving soil moisture should be employed.

1.3 Aim

The aim of this research was to evaluate the effect of irrigation and mulch on the establishment of transplanted cocoa seedlings.

1.4 Objectives

The objectives of this study are to:

1. Estimate the crop water requirement of cocoa seedlings
2. Determine the effect of irrigation and mulch on plant height and stem girth after transplanting
3. Determine the effect of irrigation and mulch on plant vigour and percentage seedling survival

CHAPTER TWO

2 LITERATURE REVIEW

2.1 History of Cocoa

Cocoa tree (*Theobroma cacao*) is an evergreen tree classified under *Sterculioidea* which is a sub-family of the mallow family *Malvaceae* (Afoakwa, 2014). The botanical name, "*Theobroma cacao*" means "food of the gods" (Barry Callebaut Group, 2018). *Theobroma cacao*, which has its origin from the wet forest of South America (Bunn *et al*., 2017) is the only specie cultivated widely among the genus *Theobroma* (Wood & Lass, 2008; Ojo & Sadiq, 2010).

2.1.1 Cultivation of Cocoa

Cocoa is planted by raising seedlings in the nursery using cocoa beans or vegetative propagation techniques. Vegetative techniques employed include root cutting, budding and grafting (Afoakwa, 2014). Young cocoa plants transplanted onto the field are provided with shade trees. The shade trees protect the cocoa plant from strong winds and sun (Afoakwa, 2014).

The cocoa tree develops a main stem called the chupon and lateral branches known as fan branches (Nair, 2010). The leaves on the cocoa tree are produced on the chupons and the fan branches by series of flushing which regularly occurs in unshaded cocoa trees than shaded cocoa trees (Wood & Lass, 2008). The flush leaves range from pale green to various shades of red (Wood & Lass, 2008). The cocoa tree has a taproot that can grow to a depth of 120-200 cm and main feeding roots that grow laterally (Wood & Lass, 2008; Nair, 2010). The laterals can be located within the top 20 cm of the soil and 40-50 cm when the soil has a deep humic layer (Wood & Lass, 2008).

According to Nair (2010), the cushion, which is a thickened leaf axil on the stem, bears the flower. The flowers according to Chatt (1953), are small, white or pale pink in colour and have no scent. The cocoa fruit (pod) differs in colour, length, surface texture and shape at maturity (Wood & Lass, 2008). The cocoa pod contains the seeds that are covered by the pulp (Nair, 2010).

2.1.2 Climate and Soil

Cocoa is sensitive to changes in climate (Anim-Kwapong & Frimpong, 2006), therefore climatic components such as temperature and rainfall must be considered in order to encourage optimum growth. Cocoa thrives well with temperature ranging from 18-32 °C (Afoakwa, 2014), and is sensitive to soil water deficits and as such, rainfall amount should be between 1,500-2500 mm per year (Afoakwa, 2014). Cocoa grows well in well drained soils with pH values ranging from 5.0-7.5 (Afoakwa, 2014).

2.2 Cocoa Production

2.2.1 Production in the World

West Africa has been the focal point of cocoa production for several years (Mensah *et al*., 2013) with almost 70% of cocoa production in the world coming from West Africa (Medina & Laliberte, 2017). In 2016, Africa contributed about 67.2% of the world's cocoa production followed by the Americas, Asia and Oceania with 16.3%, 15.3% and 1.2% respectively (FAOSTAT, 2017).

2.2.2 Cocoa Production in Ghana

In Ghana, cocoa is an important perennial crop which forms the economic backbone of the country (Onumah *et al.*, 2013; Laven & Boomsma, 2012). According to COCOBOD (2018), the Dutch missionaries were the first to plant cocoa in Ghana in 1815. The Basel missionaries in 1857 planted cocoa at Aburi but these did not lead to the increase of cocoa cultivation (COCOBOD, 2018). However, Tetteh Quarshie in 1879 returned to Ghana and started a farm at Akwapim Mampong in the Eastern Region, which resulted in the spread of cocoa cultivation (COCOBOD, 2018). Today, cocoa is grown in six regions namely, Western, Ashanti, Central, Eastern, Brong Ahafo, and Volta Regions of Ghana (Anim-Kwapong & Frimpong, 2006).

Anim-Kwapong & Frimpong (2006) reported that Ghana experiences a bi-modal rainfall distribution starting from April to July and from September to November with a total annual rainfall of less than 2000 mm in regions where cocoa is grown. Ghana has two dry seasons; the short dry season begins from July to August and the main dry season from November to February/March, which usually causes high seedling mortality at the establishment phase (Anim-Kwapong & Frimpong, 2006).

Ghana is the second largest cocoa producer after Côte d'Ivoire (FAOSTAT, 2017). Cocoa beans production from the year 2000 to 2016 has seen some fluctuations with production from the year 2014 to 2016 being the same (Figure 2.1).

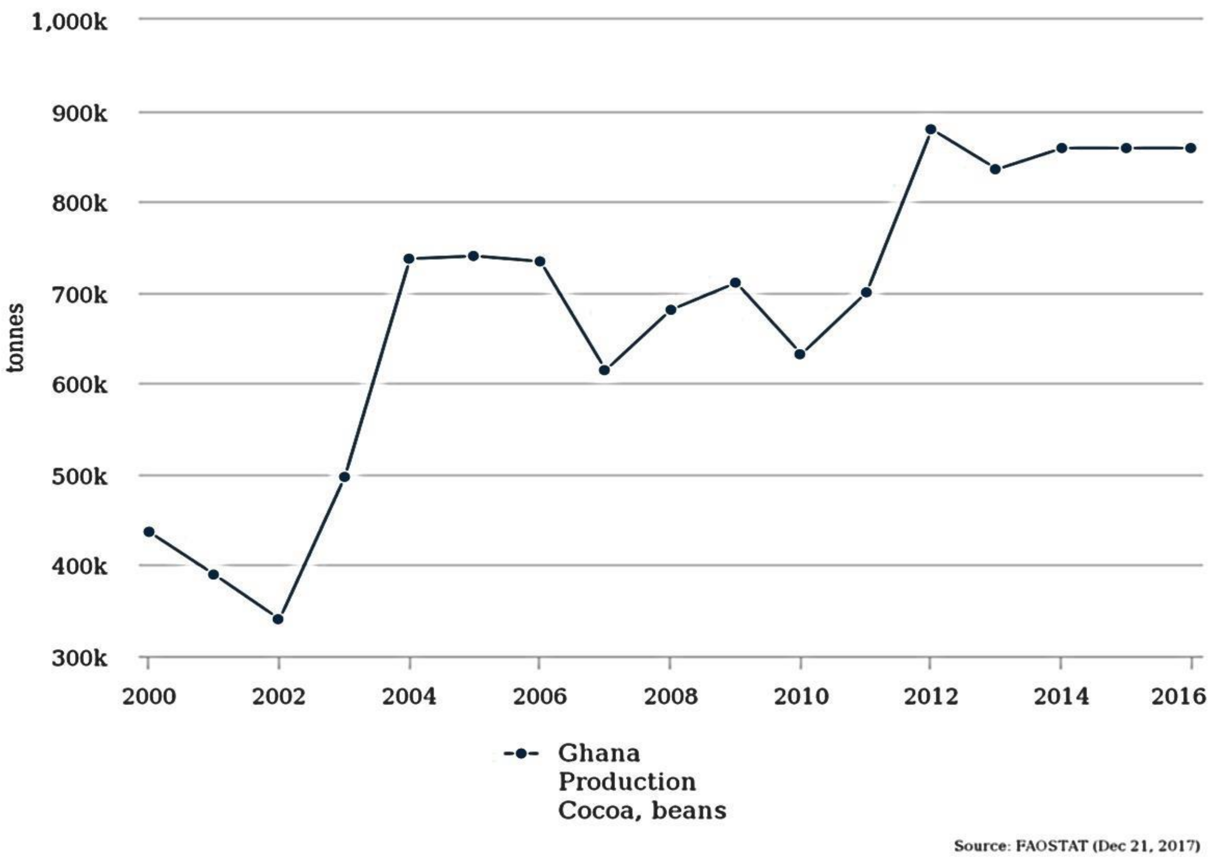

Figure 2.1 Cocoa beans production trend in Ghana (Source: FAOSTAT, 2017)

2.3 Importance of Cocoa Production

The cocoa sector is a major contributor to the economies of cocoa growing countries. The sector is known to contribute significantly to the gross domestic product (GDP) of Ghana (Laven & Boomsma, 2012) and serves as a source of foreign exchange (Onumah *et al*., 2013; Laven & Boomsma, 2012). It provides employment (Onumah *et al*., 2013; Laven & Boomsma, 2012), and a source of income for farmers (Anim-Kwapong & Frimpong, 2006; Nyadanu *et al*., 2012).

Cocoa has a wide range of uses. It is used to produce chocolate bars, mill chocolate, cocoa powder, cosmetics and pharmaceutical products (Bart-Plange & Baryeh, 2003). In health, cocoa is known to improve functions of the heart and alleviate angina pectoris, stimulate the nervous system, facilitate digestion and improve kidney and bowl function (Corti *et al*., 2009). Cocoa-pod husk can be used as animal feed (Oddoye *et al*., 2010), as organic fertilizer in ash form (Ayeni *et al*., 2008), for soap making (Bart-Plange & Baryeh, 2003) and as activated carbon (Cruz *et al*., 2012).

2.4 Challenges in Cocoa Establishment and Production

2.4.1 Pest and Diseases

Several identified pests and diseases are known to affect cocoa establishment and production. In cocoa producing areas around the world, 25% of production losses are attributed to diseases (Enriquez & Soria, 1996). van der Vossen (1997) named black pod, witches' boom, cocoa swollen shoot virus (CSSV), vascular streak Die-back (VSD) and monilia as the major diseases that cause about 16%, 18%, 15%, 9% and 5% of global crop loss respectively.

The black pod disease is known worldwide for its destructive nature attacks on cocoa pods (Anim-Kwapong & Frimpong, 2006). In Ghana, Adu-Ampomah (1994) reported that *P. megakarya*, a causative agent of black pod caused as high as 100% loss in farms they attack. Anim-Kwapong & Frimpong (2006) pointed out that Mirids (capsids) also make the establishment of cocoa difficult.

2.4.2 Climate Change

Cocoa is sensitive to drought (Anim-Kwapong & Frimpong, 2006) and climate change is affecting cocoa production (Medina & Laliberte, 2017). Medina *et al*. (2017) reported that farmers are feeling the consequence of climate change on present-day production. Hutchins *et al*. (2015) stated that there have been revelations from literature, key informant interviews and farmers about challenges cocoa farmers face due to temperature rise and unpredictable rainfall.

Anim-Kwapong & Frimpong (2006) constructed climate change situations for rainfall and temperature using process-based methods for semi-deciduous forest and evergreen rainforest zones of Ghana. The scenario predicted that the mean annual rainfall in the semi deciduous forest zones will decrease by 2.8, 10.9 and 18.6% and the mean annual temperature changes will increase by 0.8, 2.5 and 5.4 °C in the year 2020, 2050 and 2080 respectively (Anim-Kwapong & Frimpong, 2006). Also, a similar trend was observed in the evergreen rainforest zones with mean annual rainfall decreasing by 3.1, 12.1 and 20.2% and the mean annual temperature increasing by 0.6, 2.0 and 3.9 °C in the year 2020, 2050 and 2080 respectively (Anim-Kwapong & Frimpong, 2006).

The predicted temperature increase and rainfall decrease are anticipated to prolong the dry seasons, which will increase cocoa seedling mortality (Medina & Laliberte, 2017; Hutchins *et al*., 2015). Also, Anim-Kwapong & Frimpong (2006) stated that the absence of irrigation in cocoa farming during long periods of drought increases cocoa seedling mortality at the establishment phase. In addition, the sudden occurrence of drought causes flower drop in cocoa which results in poor crop yield thus the need for irrigation which has shown to increase crop yield.

2.5 Efforts to Overcome Cocoa Establishment and Production Challenges

2.5.1 Pest and Diseases

Boadu (2001) studied the evaluation of cocoa types for resistance to capsids. The results indicated that some Nanay hybrids, Parinari hybrids, T hybrids and Parinari clones were likely materials that can be used to develop genotypes tolerant to capsid attack.

2.5.2 Fertilizer Application

Ndubuaku & Kassim (2003) researched on the use of organic and inorganic fertilizers to improve the rate of cocoa seedling establishment in the field in Nigeria. The organic manure used was poultry manure and green manure while the inorganic manure used were single super phosphate and urea. The result showed that some seedling mortality was observed only in the control treatment. In addition, the stem diameter, plant height, leaf area and leaf emergence for the organic fertilizer treatments were significant than that of the inorganic fertilizer treatments by the 32^{nd} week.

Acheampong *et al*. (2015) investigated the influence of shade and organic fertilizer treatments on the physiology and establishment of *Theobroma cacao* clones. The study showed that applying organic fertilizers to the soil improved cocoa plant nutrition and establishment. However, adjusting the overhead shade should be considered during changing weather conditions to maximize fertilizer use by the cocoa plant.

2.5.3 Climate Change

Padi *et al*. (2013) investigated the differential response of cocoa (Theobroma cacao) families to field establishment stress under full sunlight. They used seedling vigour, cocoa seedling survival percentage and increase in the trunk cross-sectional area to select cocoa families that have high survival.

Ofori *et al*. (2014) assessed the genotypic performance of cocoa during establishment under natural drought stress. Their findings revealed that some cocoa genotypes were tolerant to drought, pests and diseases and gave high yield.

Santos *et al*. (2014) studied the molecular, physiological and biochemical responses of Theobroma cacao L. genotypes to soil water deficit. It was identified that growth variables leaf dry biomass (LDB), total biomass (TDB), relative growth rate (RGR) and total leaf area per plant (TLAP) as well as the content of Mg in leaves were important variables in selecting plants at different levels of drought tolerance.

Ofori *et al*. (2015) studied the genetic variation and traits related to drought tolerance in cocoa under shade and no-shade conditions in Ghana. The results showed that there was some genetic variation for traits related to drought tolerance in the available germplasm. In addition, some specific clone's families were able to withstand drought conditions on the Ghanaian field.

Asare *et al*. (2016) assessed farmers access to improved hybrid seeds in Ghana and its implications for the establishment and rehabilitation of cocoa farms. The study showed that over two dry seasons, land use type, farm size and gender played a role on the survival rate of transplanted hybrid cocoa seedlings.

dos Santos *et al*. (2016) used diallel analysis and growth parameters as selection tools for drought tolerance in young cacao plants. The result showed that growth variables stem diameter (CD), total leaf area (TLA), leaf dry biomass (LDB), stem dry biomass (SDB), root dry biomass (RDB), total dry biomass (TDB), root length (RL), root volume (RV) and mean root diameter (RD < 1mm and 1 < 2mm) were variables that could be used in selecting drought tolerant plants.

2.6 Evapotranspiration

2.6.1 Reference Evapotranspiration

Allen *et al*. (1998) defined reference evapotranspiration (ET_o) as the evapotranspiration rate from a reference surface not short of water. The reference surface as described by Allen *et al*. (1998) is a hypothetical crop having a height of 0.12 m, with a fixed surface resistance of 70 sec/m and an albedo of 0.23. The reference evapotranspiration (ET_o) is a climatic parameter and only climatic parameters affect it (Allen *et al*, 1998). The FAO Penman-Monteith method is the accepted method for calculating ET_o (Savva & Frenken, 2002).

2.6.2 Crop Evapotranspiration

Allen *et al*. (1998) defined crop water requirement as the amount of water needed to satisfy the evapotranspiration loss from the cropped field. Crop evapotranspiration (ET_c) can be determined using the crop coefficient approach (Equation 2.1).

$$\boldsymbol{ET_C = ET_O \times K_C} \qquad 2.1$$

where,

K_c is the crop coefficient,

ET_o is the reference evapotranspiration (mm day^{-1}),

ET_c is the crop evapotranspiration (mm day^{-1}) grown in large fields under excellent agronomic and soil water conditions.

The crop coefficient can be either the single crop coefficient or the dual coefficient. The single coefficient (K_c) integrates the difference in evaporation and transpiration between the field crop and the reference grass surface as one effect while the dual crop coefficient (K_{cb}+K_e) separates the crop coefficient into the basal crop coefficient (K_{cb}) and the soil evaporation coefficient (K_e) (Allen *et al.*, 1998). The values of K_c tend to increase from planting until full canopy is attained (Ko *et al.*, 2009).

2.6.3 Direct Methods

Direct methods such as the lysimeter or soil water balance determined from cropped field have been used to estimate evapotranspiration. The water balance method uses water coming in and water leaving the crop root zone (Equation 2.2).

$$\boldsymbol{ET = I + P - RO - DP + CR \pm \Delta SF \pm \Delta SW} \qquad 2.2$$

where,

ET is evapotranspiration (mm day^{-1}),

I is irrigation (mm),

P is precipitation (mm),

RO is runoff (mm),

DP is deep percolation (mm),

CR is capillary rise (mm),

ΔSF change in subsurface flow (mm),

ΔSW is change in soil water content (mm).

In drip irrigation, *RO*, *DP*, *CR* and *ΔSF* are assumed zero because the field is irrigated to or below field capacity.

Several researchers including Gao *et al*. (2009) and Ko *et al*. (2009) have used the water balance method to determine the crop coefficient of different crops.

2.6.4 Indirect Methods

Indirect methods of estimating evapotranspiration include the energy balance method, the mass balance method and remote sensing. The energy balance approach according to Allen *et al*. (1998) is based on the principle of energy conservation, which states that energy arriving at the surface must equal energy leaving the surface within the same period. The energy balance equation is,

$$\lambda ET = R_n - H - G \qquad 2.3$$

where

λET is the latent heat flux (MJ m^{-2} day^{-1}),

R_n is the net radiation (MJ m^{-2} day^{-1}), H is the sensible heat (MJ m^{-2} day^{-1}),

G is the soil heat flux (MJ m^{-2} day^{-1})

2.6.5 Remote Sensing

According to Sivakumar & Hinsman (2004), "remote sensing provides spatial coverage by measuring reflected and emitted electromagnetic radiation across a wide range of wavebands from the earth's surface and surrounding atmosphere".

Several research works have been conducted using remote sensing. Bausch (1995) used remote sensing of crop coefficient to improve the irrigation schedule of corn. Farg *et al*. (2012) developed K_c prediction equations from vegetation indices for various growth stages for wheat. The results revealed that for the developing, mid-season and late-season growth stages, the correlated coefficients (R^2) (0.82, 0.90 and 0.97 respectively) and adjusted R^2 (0.80, 0.86 and 0.96 respectively) were high. El-Shirbeny *et al*. (2014) estimated the potential crop evapotranspiration using remote sensing techniques. The crop coefficient (K_c) was estimated from normalized difference vegetative index (NDVI) and the product between ET_o and K_c was used to estimate ET_c. The estimated value of ET_c varied from 0 to 5 mm/day

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CHAPTER THREE

3 MATERIALS AND METHODS

3.1 Site Description

The field experiment was conducted at the University of Ghana Forest and Horticultural Crops Research Centre (FOHCREC), Okumaning-Kade in the Eastern Region. The research centre lies in the Moist Semi-Deciduous forest zone and is located on latitude 06°8.61'N and longitude 0°54.16'W. The centre is at an altitude of about 114 m above sea level. According to Nkansah *et al.* (2011), the dominant soil type of the research centre is Haplic Acrisol (FAO/UNESCO, 1990).

3.2 Experimental Design and Treatments

The experimental design used was the split plot design with three replicates. The main plot treatment consisted of irrigation level and the subplot treatment consisted of the ground cover type. Irrigation Levels were no irrigation (NI) which served as the control, deficit irrigation (DI) and full irrigation (FI). The ground cover type was mulch (M) and no mulch (NM). All irrigation levels (NI, DI and FI) and cover type (M and NM) were assigned randomly to the main plots and the subplots respectively. Table 3.1 shows the treatment combinations.

Table 3.1 Irrigation and Ground Cover type treatment

	Main Treatment Factors		
	Main Plot	Subplot	
Treatment Level	Irrigation Level	Ground Cover Type	
1	NI	M	NM
2	DI	M	NM
3	FI	M	NM

From Table 3.1, treatment 1 was made up of 'no irrigation' (NI) which is the main plot with mulch and no mulch as the two subplots within it. The combination for this treatment was NI M and NI NM.

Treatment 2 was made up of 'deficit irrigation' (DI) as the main plot with mulch and no mulch as the two subplots within it. The combination for this treatment was DI M and DI NM.

Treatment 3 was made up of 'full irrigation' (FI) as the main plot with mulch and no mulch as the two subplots within it. The combination for this treatment was FI M and FI NM.

3.3 Physio-Chemical Properties

The physio-chemical properties of the soil were determined prior to the start of the experiment. Five points were selected randomly on the experimental field to obtain both disturbed and undisturbed soil samples. The soil samples were taken from the top soil layer at depth 0 – 20 cm.

The undisturbed soil samples were oven-dried at 80 °C to a constant weight and the bulk density was then calculated as a ratio of the dry soil to the volume of soil. The average bulk density of the five samples was taken as the bulk density for the experimental field. The USDA soil textural triangle chart (Appendix C) was used to classify the soil at the experimental field (FAO, 2006).

3.4 Wilting Point and Field Capacity

3.4.1 Wilting Point

A temperature compensated WP4-T dew point potentiometer (METER GROUP Inc., Pullman, WA, USA) was used to determine the wilting point water content from the disturbed bulk soil samples as described in Amoakwah *et al*. (2017). The wilting point water content (g/g) was multiplied by the bulk density to convert it to volumetric water content (cm^3/cm^3). The wilting point (WP) was determined to be 95.36 mm.

3.4.2 Field Capacity

The field capacity (FC) of the experimental field was found using the time domain reflectometry (TDR) instrument. The TDR instrument was connected to the 0.65 cm TDR probes installed at the centre of each plot. The moisture content was measured until a constant value was obtained after the soil has been wetted by one heavy rainfall. This was done two to three days after natural drainage had occurred. The measured constant moisture value obtained was taken as the field capacity. The field capacity determined for NI, DI and FI plots were 186.99, 175.65 and 178.72 mm respectively.

3.5 Field Preparation

The site selected for the research was prepared for transplanting by clearing using a cutlass. Plant debris was removed from the research site and the field was demarcated into main plots and subplots. There were three (3) replications of treatments, leading to nine (9) main plots and eighteen (18) subplots. Each subplot measured 36 m^2, with 9 plants per plot. A 3.5 m and a 3 m buffer strip respectively separated each of the main plot and subplot. The buffer strip was to minimize seepage of irrigation water between plots.

3.6 Transplanting

The cocoa seedlings used for this experiment were 'Akwakora bedi' which is a local variety. Nine month-old cocoa seedlings (Figure 3.1) were transplanted on October 4, 2017 onto the field. The seedlings were transplanted at 3 m × 3 m intervals. Initial data (plant height, stem girth and the chlorophyll content) of the seedlings were taken because they were not uniform.

Figure 3.1 Cocoa seedlings being transported to be transplanted

3.7 Mulching

Cocoa pod husk (CPH) was obtained from a cocoa farm at the research centre, and spread with a rake on a tarpaulin and sun dried (Figure 3.2). The dried cocoa pod husk was applied on the earmarked plots as a side mulch at 4.5 t/ha.

Figure 3.2 Spreading and sun drying of cocoa pod husk

3.8 Irrigation Scheduling

Drip irrigation lines were installed on the field with 3 drip lines on each plot. The emitters of the drip lines were placed close to the plant and TDR probes. The irrigation needs of cocoa seedlings were met by natural rainfall until the onset of the dry season in the second week of December 2017. Two Irrigation regimes namely full irrigation (FI) and deficit irrigation (DI) were scheduled based on soil water deficit (D). For FI treatments, the cocoa seedling was allowed to deplete a fraction (*p*) which is 30% of the total available water (TAW) before irrigating field capacity (FC).

For DI treatments, the cocoa seedling was allowed to deplete 60% of the TAW before irrigating to FC. The D was calculated from the soil water content (SWC) data obtained from the TDR instrument. The length of the TDR probe which was 0.65 m was taken as the rooting depth (Zr). The total available water content (TAW) was determined using Equation 3.1.

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

where,

TAW – Total available soil water content [mm],

θ_{FC} – Moisture content of the soil at field capacity [m^3 m^{-3}],

θ_{WP} – Moisture content of the soil at wilting point [m^3 m^{-3}],

Zr - Crop rooting depth [m].

The readily available water in the soil to the crop was determined using Equation 3.2.

$$\boldsymbol{RAW = p \times TAW} \qquad 3.2$$

where,

RAW – Readily available soil water [mm],

p – fraction of TAW depleted by the crop in the root zone.

For FI and DI, *p* was set to 0.3 (30%) and 0.6 (60%) respectively before irrigation was initiated. The values of *p* were set in order for differences between the treatments to be clear.

Soil water deficit (D) was determined using Equation 3.3.

$$\boldsymbol{D = FC - SWC} \quad 3.3$$

where,

D – Water deficit in the soil [mm],

FC – Field capacity of the soil [mm],

SWC – Water content of the soil [mm].

The *SWC* measurement was done using the TDR device.

3.9 Reference Evapotranspiration (ET_o)

The FAO Penman-Monteith Equation 3.4 was used to compute the reference evapotranspiration. An automatic weather station installed at the research centre provided the data which was used to compute the reference evapotranspiration.

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

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 a height of 2 m [^{o}C],

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

e_s – Saturation vapour pressure [kPa],

e_a – Actual vapour pressure [kPa],

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

Δ – Slope of vapour pressure curve [kPa $^oC^{-1}$],

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

Figure 3.3 Automatic Weather Station at the research station (FOHCREC)

3.10 Remote Sensing Data

The spectral reflectance of the transplanted cocoa seedling canopy was measured using the RapidSCAN CS-45 (Figure 3.4) at weekly intervals. The radiometer, which is handheld, measures crop reflectance in the red and near infrared regions at 670 nm, 730 nm and 780 nm. This was used to compute the Normalised Difference Vegetation Index (NDVI) in Equation 3.5.

$$\boldsymbol{NDVI = \frac{NIR-R}{NIR+R}} \qquad 3.5$$

where,

NIR - canopy reflectance in the near infrared bands of the electromagnetic spectrum,

R – canopy reflectance in the red bands of the electromagnetic spectrum

Figure 3.4 RapidSCAN CS-45 (Radiometer used)

3.11 Agronomic Data

Data collection started when the cocoa plants started flushing which was in the 3rd week after transplanting (WAT). The plant height and stem girth were recorded every 2 weeks as the growth data. The height of the plant was measured from the surface of the ground to the tip of the plant using a ruler. The stem girth was measured 15 cm from the ground surface using a vernier calliper (Padi *et al*., 2013).

3.12 Plant Vigour and Seedling Survival

Plant vigour and seedling survival data were taken at the end of each month. The method described by Padi *et al*. (2013) was used to determine the plant vigour. Padi *et al*. (2013) used the visual assessment which was based on a seven-point ordinal scale to find the vigour of each seedling. The ordinal scale used was,

1 = seedling is dead;

2 = the seedling looks dead, but green tissue can be seen when the epidermis of the stem is scratched;

3 = seedling is alive but has all of its leaves lost;

4 = 25% or less of green leaves are attached to the seedling;

5= about 50% of green leaves are attached to the seedling;

6 = about 75% of green leaves are attached to the seedling;

7 = seedling has all leaves attached and maintain vigour at planting.

Seedling survival was determined by counting the number of seedlings alive and dead per plot.

3.13 Data Analysis

The data collected was analysed using Analysis of Variance (ANOVA) for split plot design. The least significance difference (LSD) at P=0.05 was used to check for any significant difference among the treatments. The statistical software used was the Microsoft Excel package and GenStat 9th edition.

For the plant height and stem girth data, the difference between the initial measurements and subsequent measurements was used for the analysis.

CHAPTER FOUR

4 RESULTS AND DISCUSSION

4.1 Soil Properties

Table 4.1 shows the chemical and physical properties of the soil on which the experiment was conducted.

Table 4.1 Chemical and Physical Properties of the Soil

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

From the analysis, the pH of the soil was 5.5, which falls within the recommended pH value for growing cocoa as stated by Afoakwa (2014). The organic matter in the soil was less than the recommended 3.5% by Afoakwa (2014). The soil texture was classified as sandy clay loam.

4.2 Climatic Data

The average climatic data during the experimental period is presented in Table 4.2. Average wind speed decreased from November to December and then increased from January to March, but remained constant between December and January. The average temperature dropped from November to December and rise from December to February. However, from February to March there was a fall in temperatures. The maximum and minimum temperatures were both observed in the month of January with the maximum temperature being 36.0 °C and the minimum temperature being 21.2 °C. Total rainfall recorded for each month decreased from November to January and increased from February to March. November recorded the highest rainfall amount of 136.85 mm while January recorded the lowest of 1.27 mm.

Table 4.2 Climatic data during the experiment

Month	Wind speed	Temp. (°C)		Relative humidity (%)		Solar radiation	Rainfall	ETo
	(ms^{-1})	Max.	Min.	Max.	Min.	(MJ m^{-2} day^{-1})	(mm)	(mm day-1)
Nov.	4.4	32.7	21.7	100.0	58.6	13.7	136.85	4.38
Dec.	3.5	32.3	21.5	99.8	53.5	13.2	37.59	4.23
Jan.	3.5	36.0	21.2	100.6	44.3	12.4	1.27	5.59
Feb.	4.7	35.5	23.2	99.4	43.0	14.8	46.23	6.08
Mar.	4.9	34.9	22.3	100.0	49.4	17.2	105.66	5.80

4.3 Moisture Characteristics

A graph of moisture content plotted against time showed the soil moisture content trend for full irrigation (FI) treatment during the experimental period (Figure 4.1). The trend showed that mulch treatment (FI M) conserved moisture from the beginning of the experiment to the end as compared to no mulch treatment (FI NM). The trend also showed that mulch affected the rate at with moisture was lost through evaporation. Similar trends observed for deficit irrigation treatment and no irrigation treatment are presented in Appendix B.

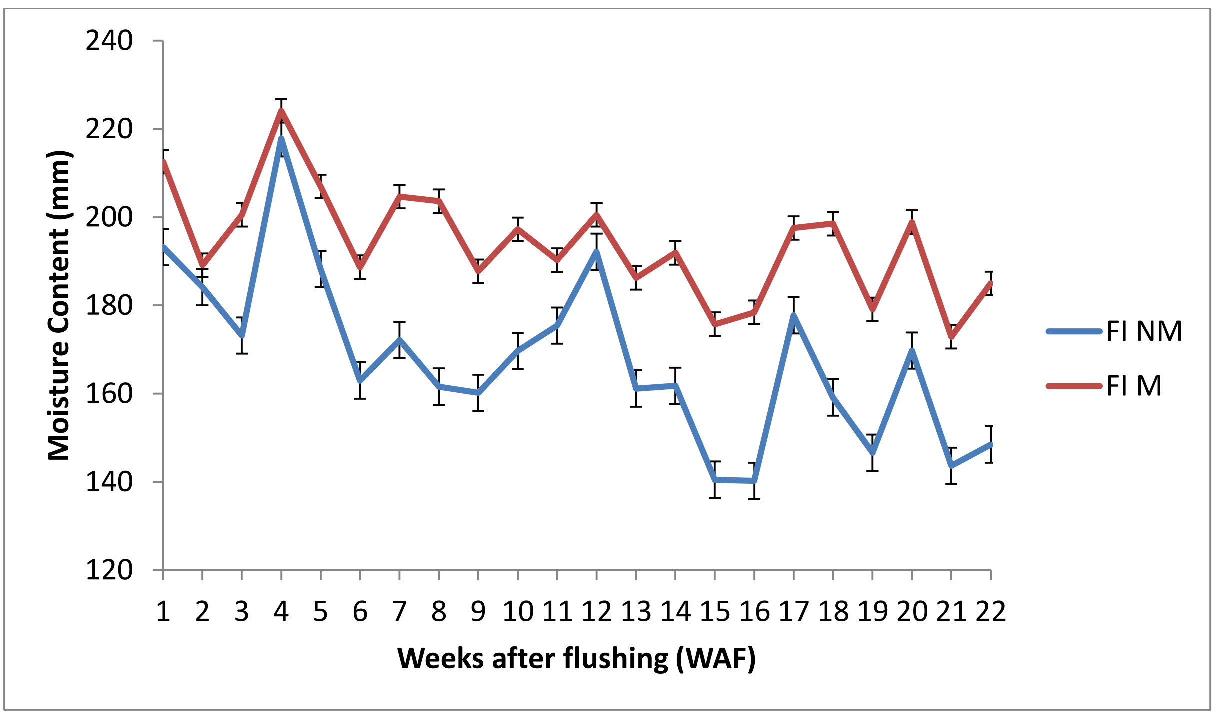


Figure 4.1 Moisture content for FI treatment

4.4 Effect of Irrigation and Mulch on NDVI

The NDVI measurement of transplanted cocoa canopy began at the start of the initial flushing after transplanting. Figure 4.2 shows the measured NDVI of transplanted cocoa canopy for all treatments under mulch for the various irrigation levels during the experiment period.

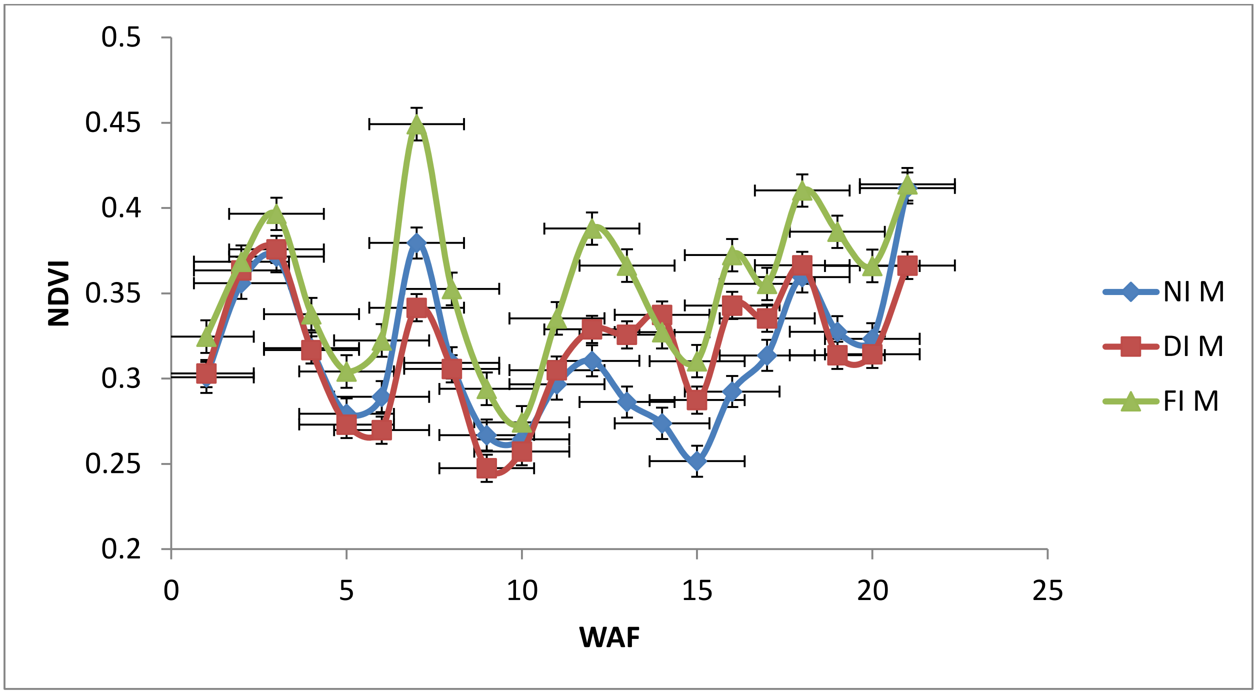


Figure 4.2 Measured NDVI of transplanted cocoa for NI, FI and DI under mulch

Figure 4.2 shows the measured NDVI values for transplanted cocoa canopy for NI, DI and FI under mulch. The initial NDVI value coincided with the beginning of the flush cycle of the transplanted cocoa for all treatments. The NDVI values for all treatment under mulch showed an increase and a decrease over time and this can be attributed to the flush cycle of the cocoa. Wood & Lass (2008) reported that the flush leaves might vary from pale green to different shades of red in colour before turning green during hardening. The flushing occurred at regular intervals of 5 weeks, which was less than the range of 6.5 to 8.5 weeks as reported by Smith (1964). The high NDVI values recorded in the irrigated plots (FI and DI) as compared to NI can be attributed to the availability of Nitrogen to the seedlings through irrigation (Birch, 1964), which affects plant growth (Tissue & Wright, 1995). In addition, treatments with higher NDVI values (Figure 4.2) had higher establishment percentage (Figure 4.10). A similar trend observed for all treatments under no mulch is presented in APPENDIX B.

4.5 Effect of Irrigation and Mulch type on ET_c

Figure 4.3 & Figure 4.4 show the cumulative ET_c for the various irrigation levels under mulch and no mulch during the experiment respectively.

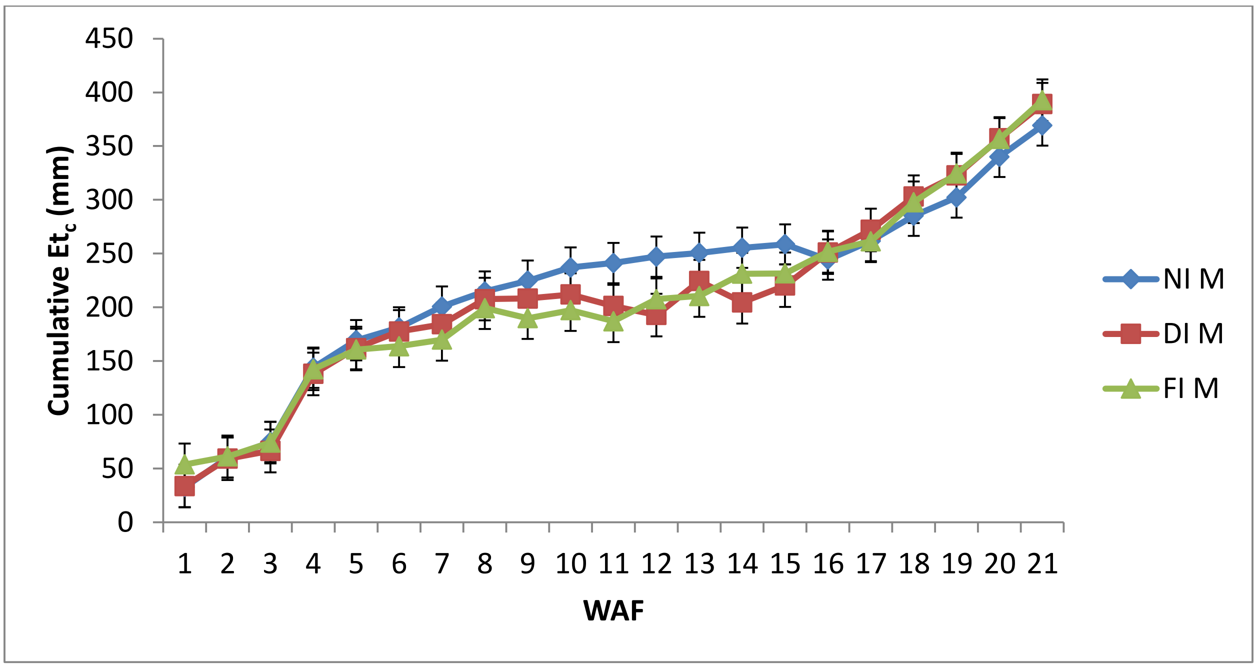


Figure 4.3 Cumulative ET_c for NI, DI and FI under mulch

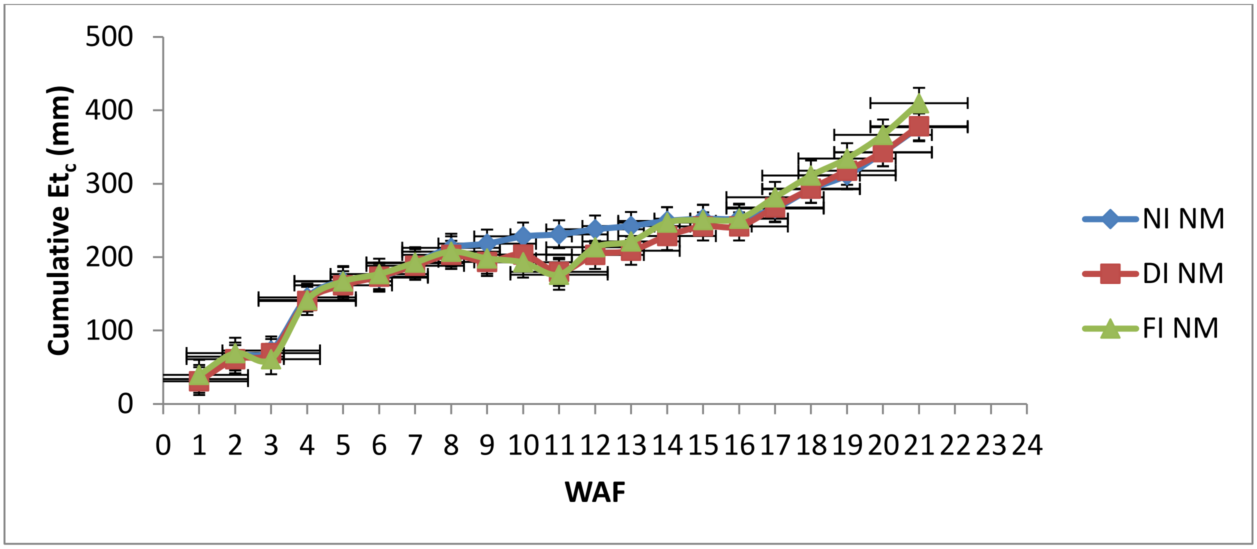


Figure 4.4 Cumulative ET_c for NI, DI and FI under no mulch treatment

Figure 4.3 shows the weekly cumulative ET_c for NI, DI and FI under mulch treatment. Differences were observed from 5 weeks after initial flush to the end of the experiment. The cumulative ET_c for NI M was higher than DI M and FI M from 5 WAF to 16 WAF which can be attributed to the reduced surface evapotranspiration from using drip irrigation. Danso *et al*. (2015) reported a similar finding for okra. The NI M treatment recorded a lower cumulative ET_c value at the end of the experiment. The cumulative ET_c for NI M, DI M and FI M at the end of the experiment were 369.16 mm, 389.06 mm and 392.62 mm respectively which gives an estimate of the water used by cocoa seedlings during establishment on the field.

Figure 4.4 shows the monthly cumulative ET_c for NI, DI and FI under no mulch treatment. There was no much difference in the cumulative monthly ET_c from the beginning to 8 WAF. This was because natural rainfall met the irrigation needs for all the treatments before the start of the dry season. A difference was observed after 8 WAF with the start of the dry season and the application of irrigation in treatments DI NM and FI NM. The cumulative ET_c for NI NM, DI NM and FI NM at the end of the experiment was 376.77 mm, 378.29 mm and 409.83 mm respectively.

4.6 Effect of Irrigation and Mulch Type on K_c

Figure 4.5 & Figure 4.6 show the crop coefficient curve for NI, DI and FI under mulch and no mulch.

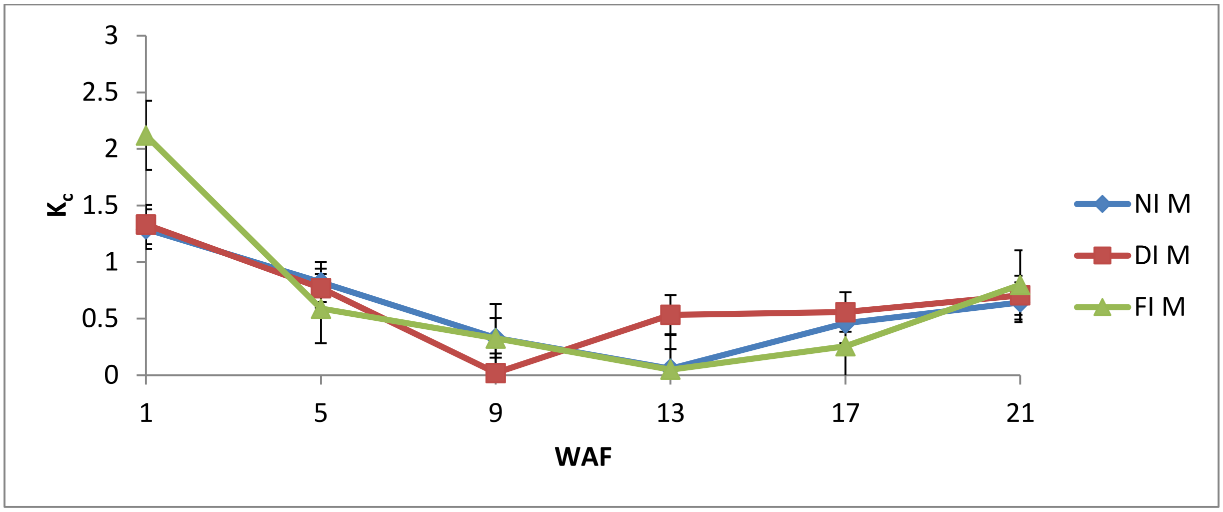


Figure 4.5 Crop Coefficient (K_c) measured for NI, DI and FI under mulch

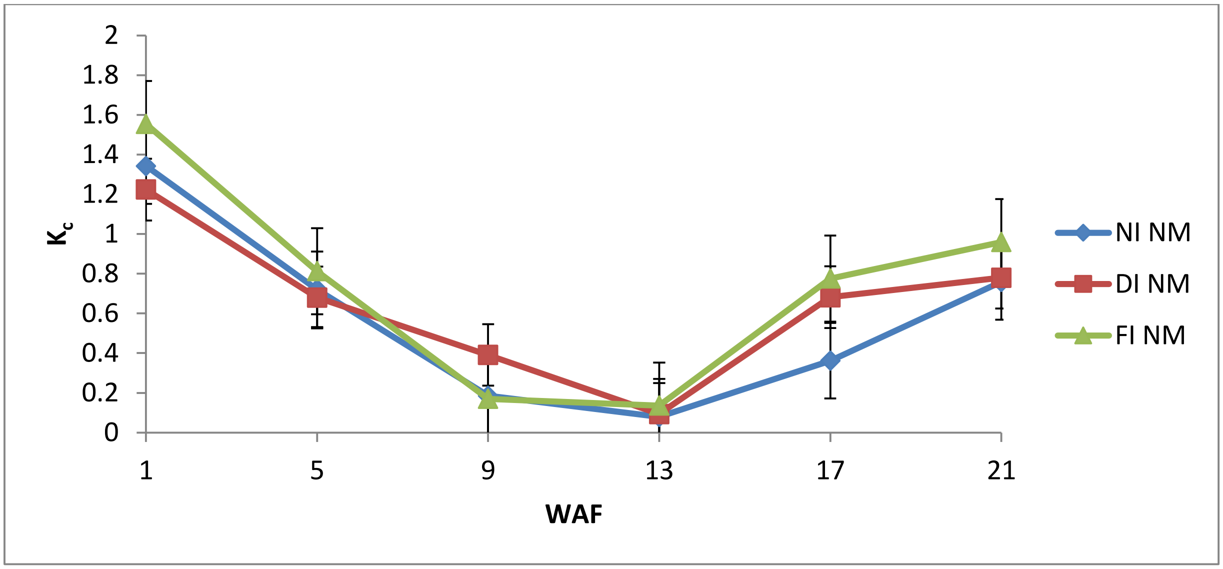


Figure 4.6 Crop Coefficient (K_c) measured for NI, FI and DI under no mulch

Figure 4.5 shows the crop coefficient for NI, DI and FI under mulch treatment. The K_c values decreased from 1 WAF to 9 WAF for DI M and 13 WAF for both FI M and NI M as rainfall decreased leading to the onset of the dry season and began to increase as rainfall increased. The initial K_c values for NI, DI and FI under mulch were 1.29, 1.33 and 2.12, which was above the initial K_c range for cocoa given by Allen *et al*. (1998). This can be attributed to the high rainfall amount (Table 4.2) which is known to increase K_c (Allen *et al*., 1998). At the end of the experiment, the K_c values for NI, DI and FI under mulch were 0.64, 0.71 and 0.80 respectively. Allen *et al*. (1998) recommended a K_c value of 1.0 at the initial stage, which is higher than the K_c values found in this research. A similar observation was noted by Carr & Lockwood (2011) for cocoa with a complete canopy.

Figure 4.6 shows the measured crop coefficient for NI, DI and FI under no mulch treatment. The K_c graph for NI, DI and FI under no mulch showed a similar pattern to that of K_c graph for mulch The K_c values under no mulch at the end of the study were 0.76, 0.78 and 0.96 for NI, DI and FI respectively. The irrigation treatments under no mulch had higher K_c values at the end of the experiment as compared to those under mulch. This means that mulching was able to decrease soil evapotranspiration leading to moisture conservation in the soil.

4.7 Plant Growth Response

4.7.1 Effect of Irrigation and Mulch on Stem Girth

Figure 4.7 shows the stem girth for all the treatments at the end of each month.

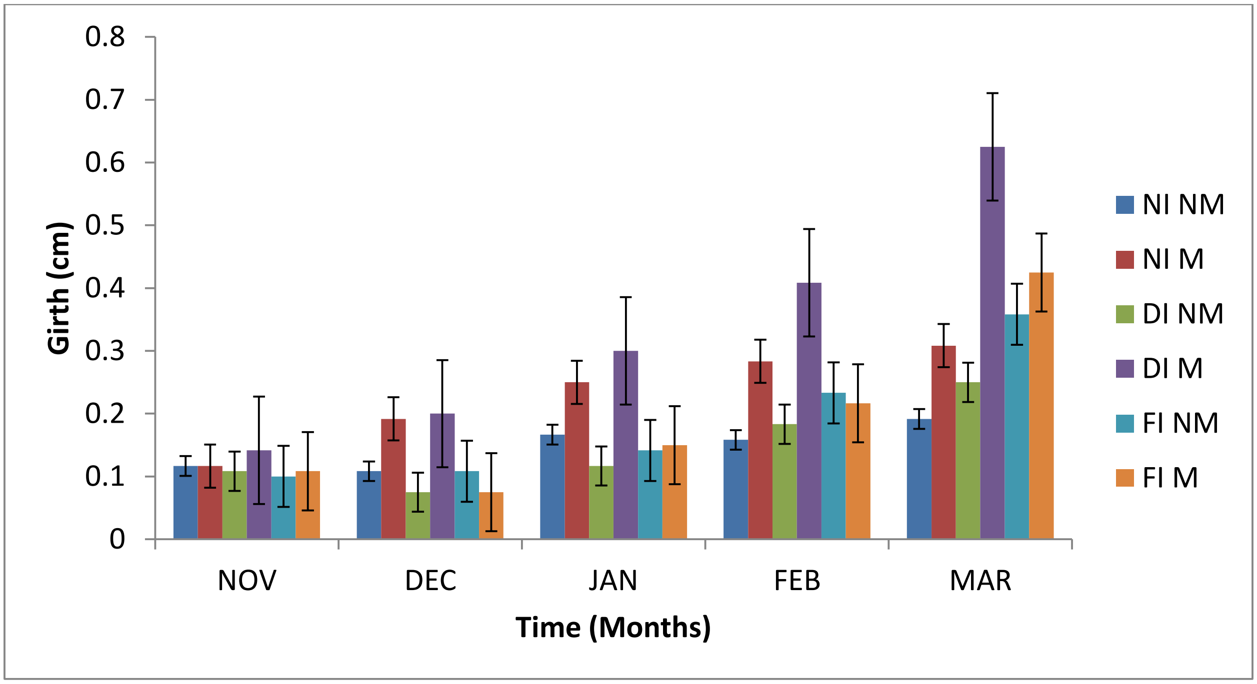


Figure 4.7 Stem girth at the end of each month for the various treatments

Figure 4.7 shows the stem girth for all the treatments at the end of each month. Generally, there was increase in the mean stem girth difference during the entire experiment with clear differences showing at the end of December between the treatments. The first mean stem girth difference measured for all treatments was almost the same with values ranging from 0.1 cm to 0.14 cm. The largest mean stem girth difference at the end of the experiment was 0.63 cm in treatment DI M while the smallest stem girth was 0.19 cm in treatment NI NM.

Table 4.3 presents the analysis of variance (ANOVA) for stem girth at the end of the experiment. The analysis showed that irrigation and mulch had significant difference on the stem girth at

P=0.05. However, the interaction between irrigation and mulch did not have any significant difference on the stem girth. This means that the combined effect of irrigation and mulch did not affect the growth of the seedlings.

Table 4.3 ANOVA table for stem girth at the end of the experiment

Source	**Df**	**SS**	**MS**	**vr**	**F pr**
Irrigation	2	0.11465	0.05733	9.12	0.032
Mulch	1	0.15587	0.15587	9.20	0.023
Interaction	2	0.08215	0.04108	2.42	0.169
Error	12	0.14125	0.03044		
Total	17	0.49392			

Table 4.4 shows the difference in means of stem girth between the different irrigation levels. The result shows that at P=0.05 the difference was significant in the means between NI and DI and between NI and FI. However, there was no significant difference between DI and FI at P=0.05.

The no significant difference between DI and FI could have been as a result of using the length of the TDR probes as the rooting depth (Zr). Wood & Lass (2008) reported that most of the lateral feeder roots can be found in the top 20 cm of the soil and can stretch to 40 – 50 cm when the humic layer of the soil is deep. The probe length used in this experiment was 65 cm which suggests that both DI and FI treatment plots might have been over irrigated.

The significant difference observed in the means of the stem girth between NI and DI and between NI and FI was because of the application of irrigation. This means that irrigation had effect on the stem girth of the cocoa seedlings.

Table 4.4 Difference in means of stem girth between irrigation levels

Irrigation Level (X)	Irrigation Level (Y)	Mean Difference (X-Y)	Significance
NI	DI	-0.188*	0.1271
	FI	-0.142*	0.1271
DI	NI	0.188*	0.1271
	FI	0.046	0.1271
FI	NI	0.142*	0.1271
	DI	-0.046	0.1271

* The mean difference is significant at P ≤ 0.05 from LSD test.

Table 4.5 shows the difference in means of stem girth at different ground cover. The result shows that there was significant difference in the means between M and NM at P=0.05. The significant difference observed in the means of the stem girth was because of the mulch (M) treatment which helped conserve moisture in the soil as compared to the no mulch (NM) treatments which did not.

Table 4.5 Difference in means of stem girth between ground cover

Ground Cover (X)	Ground Cover (Y)	Mean Difference(X-Y)	Significance
M	NM	0.186*	0.1501
NM	M	-0.186*	0.1501

*The mean difference is significant at P ≤ 0.05 from LSD test.

4.7.2 Effect of Irrigation and Mulch on Plant Height

Figure 4.8 shows the plant height at the end of each month.

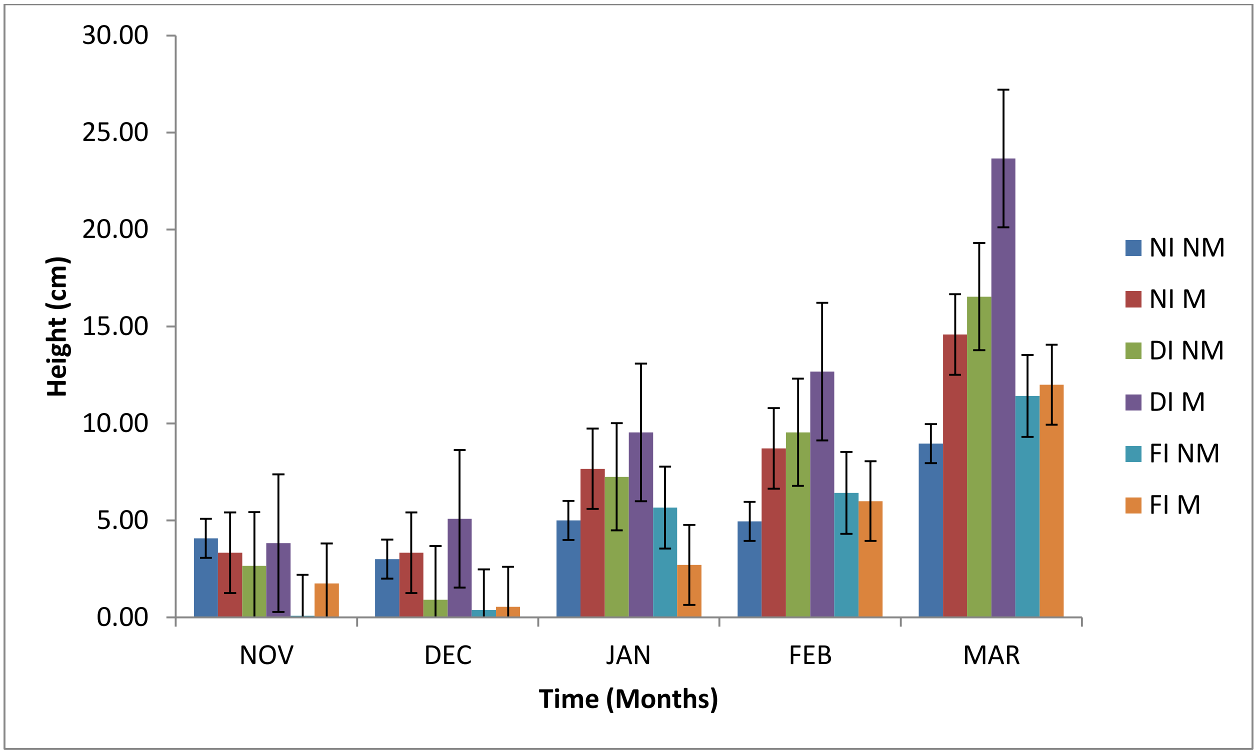


Figure 4.8 Plant height at the end of each month for the various treatments

Figure 4.8 shows the plant height for at the treatments at the end of each month. Generally, the mean plant height increased throughout the experiment period. All treatments showed significant increase from January to March with the highest mean plant height increase of 23.67 cm recorded in DI M treatment and the lowest mean plant height increase of 8.96 cm recorded in NI NM treatment at the end of the experiment.

Table 4.6 shows the ANOVA table for the plant height at the end of the experiment. The various treatments (Irrigation and ground cover) and their interaction were found not to have any significant difference at P=0.05.

Table 4.6 ANOVA table for plant height at the end of the experiment

Source	Df	SS	MS	vr	F pr
Irrigation	2	281.11	140.55	2.77	0.176
Mulch	1	70.01	70.01	1.18	0.319
Interaction	2	44.87	22.43	0.38	0.700
Error	12	596.29	128.76		
Total	17	992.28			

4.8 Effect of Irrigation and Mulch on Plant Vigour

Figure 4.9 shows the vigour of cocoa seedlings under the various treatments during the study period. The graph shows a general decrease in the vigour over time for all treatments. When cocoa seedlings are transplanted it takes time for the roots to get established in the new environment and this can be attributed to the decline in vigour as seen in Figure 4.9. The various treatments showed vigour score above 5 during the experiment.

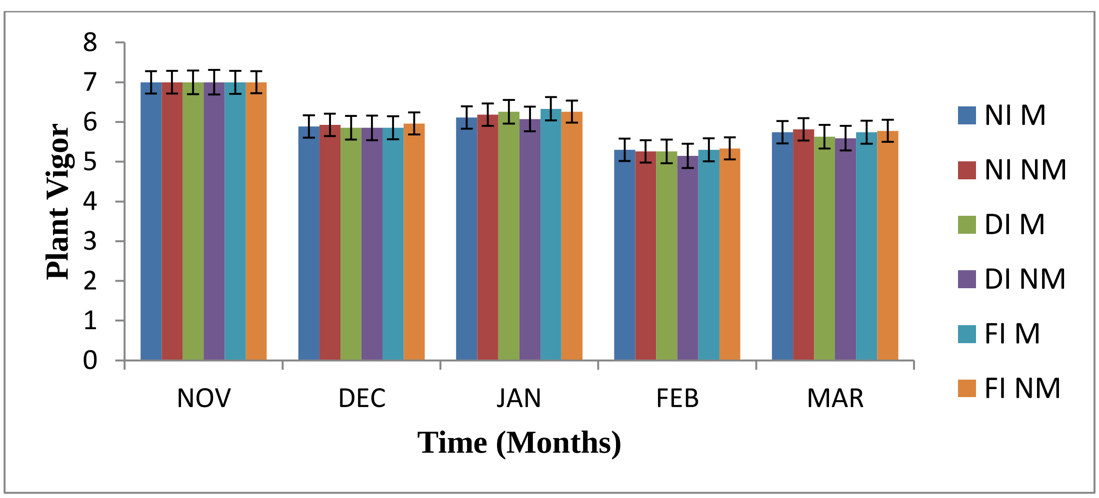


Figure 4.9 Plant vigour for the various treatments

Table 4.7 shows the results of ANOVA analysis for plant vigour at the end of the experiment. The various treatments and their interaction were found not to have any significant difference at P=0.05.

Table 4.7 ANOVA table for plant vigour at the end of the experiment

Source	**d.f.**	**SS**	**MS**	**v.r.**	**F pr.**
Irrigation	2	0.100137	0.038752	1.29	0.369
Ground cover	1	0.002743	0.002743	0.33	0.585
Interaction	2	0.009602	0.004801	0.58	0.587
Error	12	0.781893	0.335734		
Total	17	0.894376			

4.9 Effect of Irrigation and Mulch on Plant Survival

Figure 4.10 shows the plant survival of each treatment from the beginning to the end of the experiment.

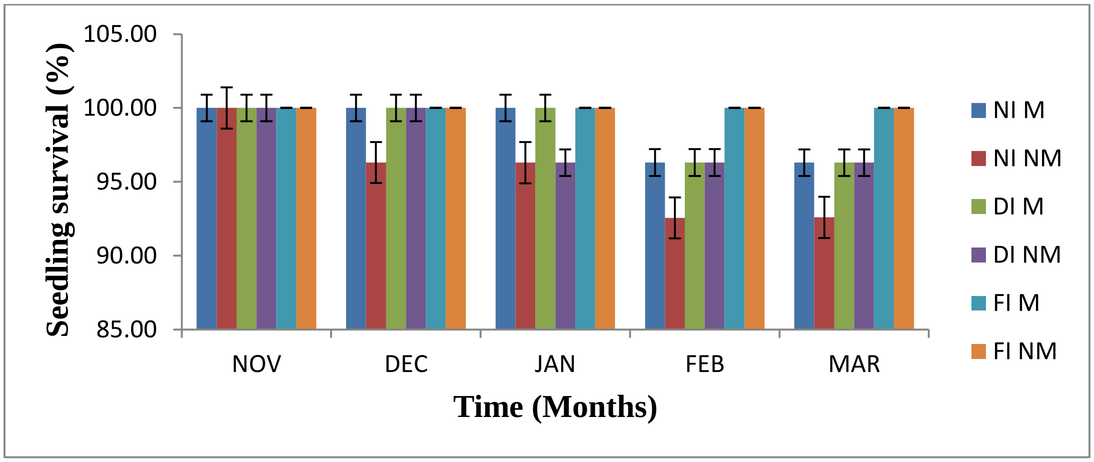


Figure 4.10 Plant survival for the various treatments

From Figure 4.10 it is observed that over the period from November to March, plant mortality was recorded in most of the treatments. Treatment NI NM was first to record some plant mortality in December followed by treatments DI NM, NI M and DI M.

At the end of the experiment all the treatments had some plants dying with the exception of the FI M and FI NM treatments which had all plants surviving. The treatment that gave the lowest survival percentage was NI NM. The high establishment percentage that was above 90% for all the treatments can be attributed to the high rainfall amount recorded throughout the experiment (Table 4.2) as compared to rainfall amount recorded by Padi *et al*. (2013) during their experiment. Also, the late onset of the dry season in December during the experiment period could have influenced the high establishment rate in contrast to the early start of the dry season observed by Padi *et al*. (2013). In addition, the high visual plant vigour scores for all the treatments related to their high seedling establishment, which is in line with observations made by Padi *et al*. (2013).

Table 4.8 shows the results of ANOVA analysis for plant survival at the end of the experiment. There was no significant difference between the various treatments and their interaction at P=0.05.

Table 4.8 ANOVA table for plant survival at the end of the experiment

Source	**d.f.**	**SS**	**MS**	**v.r.**	**F pr.**
Irrigation	1	6.86	6.86	0.14	0.742
Ground cover	2	96.02	48.01	1.00	0.410
Interaction	2	13.72	6.86	0.14	0.869
Error	12	576.13	144.03		
Total	17	692.73			

CHAPTER FIVE

5 CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

The following conclusions were made based on the results obtained from the experiment:

i. The cumulative crop water requirement for transplanted cocoa at the end of the experiment period were 376.77 mm, 369.16 mm, 378.29 mm, 289.06 mm, 409.83 mm and 392.62 mm for NI NM, NI M, DI NM, DI M, FI NM and FI M respectively.

ii. The K_c values determined in this experiment were found to be lower than the suggested K_c value of 1.0 for cocoa at the initial stage by Allen *et al*. (1998) with the exception of FI NM, which had its K_c value closer to the suggested value.

iii. Irrigation and mulch had significant difference on the stem girth of transplanted cocoa.

iv. The high vigour of transplanted cocoa played a role in the observed high cocoa seedling establishment on the field.

v. The cocoa seedling establishment on the field at the end of the experiment was 92%, 96%, 96%, 96%, 100% and 100% for NI NM, NI M, DI NM, DI M, FI NM and FI M respectively.

5.2 RECOMMENDATION

i. Further studies should be carried out using different mulching materials at different application rates to help ascertain the level that conserves soil moisture content and gives a higher establishment rate on the field.

6 REFERENCES

Acheampong, K., Hadley, P., Daymond, A. J., & Adu-Yeboah, P. (2015). The Influence of Shade and Organic Fertilizer Treatments on the Physiology and Establishment of Theobroma cacao Clones. *American Journal of Experimental Agriculture*, *6(6)*, 247-360.

Adu-Ampomah, Y. (1994). The Cocoa Breeding Programme in Ghana Achievements and Prospects for the Future. *Proceedings of the International Workshop on Cocoa Breeding Strategies* (pp. 30-32). Kuala Lumpur, Malaysia: INGENIC.

Afoakwa, E. O. (2014). *Cocoa Production and Processing Technology*. CRC Press.

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper., *56*. Rome, Italy.

Amoakwah, E., Frimpong, K. A., Okae-Anti, D., & Arthur, E. (2017). Soil water retention, air flow and pore structure characteristics after corn cob biochar application to a tropical sandy loam. *Geoderma, 307*, 189-197.

Anim-Kwapong, G. J., & Frimpong, E. B. (2006). Vulnerability of agriculture to climate change- impact of climate change on cocoa production. In: Report on vulnerability and adaptation assessment under the Netherlands climate change studies assistance programme phase 2 (NCCSAP 2). *Cocoa Research Institute of Ghana*, *2*, 1-44.

Asare, R., Afari-Sefa, V., & Muilerman, S. (2016). Access to improved hybrid seeds in Ghana: Implications for establishment and rehablitation of cocoa farms. *Experimental Agriculture, 54*(2), 273-285.

Ayeni, L. S., Adetunji, M. T., Ojeniyi, S. O., Ewulo, B. S., & Adeyemo, A. J. (2008). Comparative and cumulative effect of cocoa pod husk ash and poultry manure on soil and maize nutrient contents and yield. *American-Eurasian Journal of Sustainable Agriculture*, *2*(1), 92-97.

Barry Callebaut Group. (2018). *The three grand cocoa varieties*. Retrieved June 11, 2018, from Barry Callebaut Website: https://www.barry-callebaut.com/about-us/media/press-kit/history-chocolate/theobroma-cacao-food-gods

Bart-Plange, A., & Baryeh, E. A. (2003). The physical properties of Category B cocoa beans. *Journal of Food Engineering*, *60*(3), 219-227.

Bausch, W. C. (1995). Remote sensing of crop coefficient to improve the irrigation schedule of corn. *Agricultural Water Management*, *27*(1), 55-68.

Birch, H. F. (1964). Mineralisation of plant nitrogen following alternate wet and dry conditions. *Plant and Soil*, *20*(1), 43-49.

Boadu, V. (2001). *Evaluation of Cocoa Types for Resistance to Capsids.* (Doctoral dissertation, University of Ghana).

Bunn, C., Lundy, M., Laderach, P., & Castro, F. (2017). Global climate change impacts on cocoa. *2017 International Symposium on Cocoa Research (ISCR).* Lima, Peru.

Carr, M. K., & Lockwood, G. (2011). The Water Relations and Irrigation Requirements of Cocoa (Theobroma cacao L.): A Review. *Experimental Agriculture*, *47*(4), 653-676.

Chatt, E. M. (1953). *Cocoa: Cultivation Processing Analysis* (Vol. III). London: Interscience Publishers Ltd.; London.

COCOBOD. (2018). *Cocobod, Ghana - Cocoa Production, Processing and Marketing, Ghana Cocoa Board, Ghana Cocoa Exports - The Ghana Cocoa Story*. Retrieved June 04, 2018, from Cocobod: https://cocobod.gh/the_ghana_cocostory.php

Corti, R., Flammer, A. J., Hollenberg, N. K., & Lüscher, T. F. (2009). Cocoa and Cardiovascular Health. *Circulation, 119*(10), 1433-1441.

Cruz, G., Pirilä, M., Huuhtanen, M., Carrión, L., Alvarenga, E., & Keiski, R. (2012). Production of Activated Carbon from Cocoa (Theobroma cacao) Pod Husk. *J Civil Environment Engg, 2*(2), 1-6.

dos Santos, E. A., de Almeida, A.-A. F., Ahnert, D., da Silva Branco, M. C., Valle, R. R., & Baligar, V. C. (2016). Diallel Analysis and Growth Parameters as Selection Tools for Drought Tolerance in Young Theobroma cacao Plants. *Plos one 11(8): e0160647*, 1-22.

El-Shirbeny, M. A., Saleh, N. H., & Ali, A. M. (2014). Estimation of Potential Crop Evapotranspiration Using Remote Sensing Techniques. *Proceedings of the 10th International Conference of AARSE,* (pp. 460-468).

Enriquez, G. A., & Soria, J. V. (1996). Genetic Research on Cocoa Diseases at CATIE (1960-1990). *In Proceedings of the International Workshop on the Contribution of Disease Resistance to Cocoa Variety Improvement*, 33-39.

FAO. (2006). *Guidelines for soil description* (4th ed.). Rome, Italy.

FAO/UNESCO. (1990). FAO/UNESCO Soil map of the world, generalized from the FAO/UNESCO soil map of the world (FA). Kyoto Japan.

FAOSTAT. (2017). *FAOSTAT*. Retrieved MAY 28, 2018, from http://www.fao.org/faostat/en/#data/QC/visualize

Farg, E., Arafat, S. M., El-Wahed, M. S., & El-Gindy, A. M. (2012). Estimation of Evapotranspiration ETc and Crop Coefficient Kc of Wheat, in south Nile Delta of Egypt Using integrated FAO-56 approach and remote sensing data. *The Egyptian Journal of Remote Sensing and Space Science, 15*(1), 83-89.

Gao, Y., Duan, A., Sun, J., Li, F., Liu, Z., Liu, H., & Liu, Z. (2009). Crop coefficient and water-use efficiency of winter wheat/spring maize strip intercropping. *Field Crops Research, 111*(1-2), 65-73.

Hutchins, A., Tamargo, A., Bailey, C., & Kim, Y. (2015). Assessment of Climate Change Impacts on Cocoa Production and Approaches to Adaptation and Mitigation: A Contextual View of Ghana and Costa Rica. *International Development Studies,* 1-22.

Ko, J., Piccinni, G., Marek, T., & Howell, T. (2009). Determination of growth-stage-specific crop coefficients (Kc) of cotton and wheat. *Agricultural Water Management, 96*(12), 1691-1697.

Laven, A., & Boomsma, M. (2012). Incentives for sustainable cocoa production in Ghana. *Royal Tropical Institute, Amsterdam, 49.*

Mawunya, F. D., Adiku, S. G., Laryea, K. B., Yangyuoru, M., & Atika, E. (2011). Characterisation of Seasonal Rainfall for Cropping Schedules. *West African Journal of Applied Ecology, 19*(1), 107-118.

Medina, V., & Laliberte, B. (2017). A review of research on the effects of drought and temperature stress and increased CO_2 on Theobroma cacao L., and the role of genetic diversity to address climate change. *Costa Rica: Bioversity International*, 1-59.

Medina, V., Laliberte, B., Weise, S., & Van Etten, J. (2017). Exploring cacao genetic diversity for resilience to climate change – validating or contradicting current predictive models of production suitability. *2017 International Symposium on Cocoa Research (ISCR)*, (pp. 1-10). Lima, Peru. Retrieved June 13, 2018, from https://www.icco.org/about-us/international-cocoa-agreements/cat_view/68-icco-workshops-and-seminars/352-international-cocoa-research-symposium-lima-peru-2017/438-proceedings-of-the-international-symposium-on-cocoa-research-2017/442-thematic-4.html

Mensah, E., Mensah-Brako, B., Agyare, W. A., & Padi, F. (2013). Water Application Rate Effect on Growth Performance of Hybrid Cocoa Seedlings in the Semi-deciduous Forest Zones of Ghana. *International Journal of Engineering Research & Technology (IJERT), 2*(2), 1-12.

Nair, K. P. (2010). *The agronomy and economy of important tree crops of the developing world.* Elsevier.

Ndubuaku, U. M., & Kassim, A. (2003). Use of organic and inorganic fertilizers to improve the rate of cocoa seedling establishment in the field in Nigeria. *Forests, Trees and Livelihoods, 13:1*, 101-106.

Nkansah, G. O., Ofosu-Budu, K. G., & Ayarna, A. W. (2011). Growth and yield performance of bird eye pepper in the forest ecological zone of Ghana. *Journal of Applied Biosciences, 47*, 3235-3241.

Nyadanu, D., Akromah, R., Adomako, B., Awuah, R. T., Kwoseh, C., Dzahini-Obiatey, H., . . . Assuah, M. K. (2012). Effects of Cocoa Swollen Shoot Virus Infection on Foliar Resistance to P. palmivora and P. megakarya and its Implications in Selection and Breeding Against Black Pod Disease. *International Journal of Plant Pathology, 3*(2), 45-55.

Oddoye, E. O., Rhule, S. W., Agyente-Badu, K., Anchirinah, V., & Ansah, F. O. (2010). Fresh cocoa pod husk as an ingredient in the diets of growing pigs. *Scientific Research and Essays, 5*(10), 1141-1144.

Ofori, A., Konlan, S., Dadzie, A. M., & Amoah, F. M. (2014). Genotypic Performance of Cocoa (Theobroma cacao L.) during Establishment under Natural Drought Stress. *Journal of Crop Improvement, 28(6),* 804-824.

Ofori, A., Padi, F. K., Acheampong, K., & Lowor, S. (2015). Genetic variation and relationship of traits related to drought tolerance in cocoa (Theobroma cacao L.) under shade and no-shade conditions in Ghana. *Euphytica 201*, 411-421.

Ojo, A. D., & Sadiq, I. (2010). Effect of climate change on cocoa yield: A case of cocoa research institute (CRIN) farm, Oluyole Local Government Ibadan Oyo State. *Journal of Sustainable Development in Africa, 12*(1), 350-358.

Onumah, J. A., Onumah, E. E., Al-Hassan, R. M., & Brummer, B. (2013). Meta-frontier analysis of organic and conventional cocoa production in Ghana. *Agricultural Economics/Zemedelska Ekonomika, 59*(6), 271-280.

Oppong Danso, E., Abenney-Mickson, S., Sabi, E. B., Plauborg, F., Abekoe, M., Kugblenu, Y. O., . . . Andersen, M. N. (2015). Effect of different fertilization and irrigation methods on nitrogen uptake, intercepted radiation and yield of okra (Abelmoschus esculentum L.) grown in the Keta Sand Spit of Southeast Ghana. *Agricultural water management, 147*, 34-42.

Padi, F. K., Adu-Gyamfi, P., Akpertey, A., Arthur, A., & Ofori, A. (2013). Differential response of cocoa (Theobroma cacao) families to field establishment stress. *Plant Breeding. 132*, 229-236.

Santos, I. C., Almeida, A.-A. F., Anhert, D., Conceição, A. S., Pirovani, C. P., Pires, J. L., . . . Baligar, V. C. (2014). Molecular, Physiological and Biochemical Responses of Theobroma cacao L. Genotypes to Soil Water Deficit. *PLoS ONE, 9*(12), 1-17.

Savva, A. P., & Frenken, K. (2002). Crop Water Requirements and Irrigation Scheduling., (p. 132). Harare.

Sivakumar, M. V., & Hinsman, D. E. (2004, July 7-11). Satellite remote sensing and GIS applications in agricultural meteorology and WMO satellite activities. *Proceedings of the Training Workshop in Dehradun, India, 1182*, pp. 1-21. Dehradun, India.

Smith, R. W. (1964). The Establishment of Cocoa Under Different Soil-Moisture Regimes. *Empire Journ. of Exper. Agric., 32*(127), 249-256.

Tissue, D. T., & Wright, S. J. (1995). Effect of seasonal water availability on phenology and the annual shoot carbohydrate cycle of tropical forest shrubs. *Functional Ecology*, 518-527.

van der Vossen, H. A. (1997). Strategies of Variety Improvement in Cocoa with Emphasis on Durable Disease Resistance. *International Group for Genetic Improvement of Cocoa*, 23-31.

Wood, G. A., & Lass, R. A. (2008). *Cocoa*. John Wiley & Sons.

7 APPENDICES

APPENDIX A: Spread sheet for calculating ET_o and Water Deficit

Table A1Sample spread sheet for computing ET_o

Date	T_{min}	T_{max}	RH_{min}	RH_{max}	U_2	R_s	dr	δ	ω_s	R_a	T_m	Δ	γ	$e^o(T_{min})$	$e^o(T_{max})$	e_s	e_a	e_s-e_a	R_{so}	R_{ns}	R_{nl}	R_n	Eto
01-11-17	22.15	32.66	57.88	100	4.02	11.98	1.03	-0.40	1.53	33.10	27.41	0.21	0.07	2.67	4.94	3.80	2.76	1.04	24.83	9.23	1.30	7.93	4.11
02-11-17	22.18	32.45	59.33	100	3.01	11.09	1.03	-0.40	1.53	33.08	27.32	0.21	0.07	2.67	4.88	3.78	2.78	0.99	24.82	8.54	1.08	7.46	3.58
03-11-17	20.98	33.03	60.24	100	3.00	10.32	1.03	-0.40	1.53	33.06	27.01	0.21	0.07	2.48	5.04	3.76	2.76	1.00	24.80	7.95	0.91	7.04	3.50
04-11-17	20.33	33.13	60.23	100	4.10	11.05	1.03	-0.41	1.53	33.05	26.73	0.21	0.07	2.39	5.07	3.73	2.72	1.01	24.79	8.51	1.09	7.42	3.97
05-11-17	22.14	32.65	61.17	100	3.04	10.90	1.03	-0.41	1.53	33.04	27.40	0.21	0.07	2.67	4.93	3.80	2.84	0.96	24.78	8.39	1.02	7.38	3.51
06-11-17	22.07	32.28	60.33	100	7.06	11.62	1.03	-0.41	1.53	33.03	27.18	0.21	0.07	2.66	4.83	3.74	2.78	0.96	24.78	8.95	1.20	7.74	4.62
07-11-17	20.21	32.51	58.81	100	6.17	9.93	1.03	-0.41	1.53	33.02	26.36	0.20	0.07	2.37	4.89	3.63	2.62	1.01	24.77	7.64	0.86	6.79	4.43
08-11-17	21.06	33.24	55.95	100	2.65	14.38	1.03	-0.41	1.53	33.01	27.15	0.21	0.07	2.50	5.10	3.80	2.67	1.12	24.77	11.07	1.93	9.15	4.09
09-11-17	22.01	32.78	59.65	100	4.90	11.17	1.03	-0.41	1.53	33.01	27.40	0.21	0.07	2.65	4.97	3.81	2.80	1.00	24.76	8.60	1.10	7.51	4.18
10-11-17	22.38	34.10	54.94	100	3.33	17.33	1.03	-0.41	1.53	33.01	28.24	0.22	0.07	2.71	5.35	4.03	2.82	1.21	24.76	13.35	2.53	10.82	4.89
11-11-17	21.26	32.88	57.70	100	6.47	16.60	1.03	-0.41	1.53	33.01	27.07	0.21	0.07	2.53	5.00	3.76	2.70	1.06	24.76	12.78	2.43	10.35	5.33
12-11-17	20.52	33.15	55.28	100	3.33	16.37	1.03	-0.41	1.53	33.01	26.84	0.21	0.07	2.41	5.07	3.74	2.61	1.13	24.77	12.61	2.46	10.15	4.62
13-11-17	22.34	33.02	56.76	100	5.78	15.34	1.03	-0.41	1.53	33.02	27.68	0.22	0.07	2.70	5.04	3.87	2.78	1.09	24.77	11.81	2.08	9.73	5.11
14-11-17	21.74	33.29	55.07	100	4.70	15.02	1.03	-0.41	1.53	33.03	27.52	0.21	0.07	2.60	5.11	3.86	2.71	1.15	24.78	11.57	2.06	9.51	4.93
15-11-17	22.34	32.98	58.31	100	7.94	14.35	1.03	-0.41	1.53	33.04	27.66	0.22	0.07	2.70	5.02	3.86	2.81	1.05	24.78	11.05	1.83	9.23	5.35
16-11-17	21.60	32.45	63.02	100	3.63	14.01	1.03	-0.41	1.53	33.05	27.03	0.21	0.07	2.58	4.88	3.73	2.83	0.90	24.79	10.79	1.72	9.06	3.99
17-11-17	22.50	32.58	63.09	100	4.41	13.37	1.03	-0.41	1.53	33.06	27.54	0.21	0.07	2.73	4.91	3.82	2.91	0.91	24.80	10.29	1.53	8.76	4.11
18-11-17	22.40	32.28	61.40	100	2.94	14.98	1.03	-0.41	1.53	33.08	27.34	0.21	0.07	2.71	4.83	3.77	2.84	0.93	24.82	11.53	1.94	9.59	3.99
19-11-17	21.87	32.69	58.62	100	8.92	14.37	1.03	-0.41	1.53	33.10	27.28	0.21	0.07	2.62	4.94	3.78	2.76	1.02	24.83	11.06	1.85	9.21	5.45
20-11-17	21.13	33.05	59.05	100	6.08	15.15	1.03	-0.40	1.53	33.12	27.09	0.21	0.07	2.51	5.04	3.78	2.74	1.03	24.85	11.67	2.04	9.62	5.02
21-11-17	22.01	32.04	60.29	100	2.55	12.61	1.03	-0.40	1.53	33.14	27.03	0.21	0.07	2.65	4.77	3.71	2.76	0.95	24.86	9.71	1.43	8.28	3.56
22-11-17	21.85	32.45	59.79	100	3.43	13.77	1.03	-0.40	1.53	33.17	27.15	0.21	0.07	2.62	4.88	3.75	2.77	0.98	24.88	10.60	1.70	8.90	4.05
23-11-17	21.80	31.53	63.65	100	3.23	13.62	1.03	-0.40	1.53	33.19	26.67	0.21	0.07	2.61	4.63	3.62	2.78	0.84	24.90	10.49	1.64	8.85	3.72
24-11-17	21.47	31.12	67.08	100	7.15	9.54	1.03	-0.40	1.53	33.22	26.30	0.20	0.07	2.56	4.52	3.54	2.80	0.74	24.92	7.34	0.70	6.65	3.76
25-11-17	21.26	31.44	64.03	100	3.43	12.46	1.03	-0.40	1.53	33.26	26.35	0.20	0.07	2.53	4.61	3.57	2.74	0.83	24.95	9.59	1.39	8.21	3.60
26-11-17	21.80	33.59	53.32	100	5.39	14.75	1.03	-0.40	1.53	33.29	27.70	0.22	0.07	2.61	5.20	3.91	2.69	1.21	24.97	11.36	1.99	9.37	5.27
27-11-17	20.99	33.99	53.26	100	2.84	16.35	1.03	-0.39	1.53	33.32	27.49	0.21	0.07	2.49	5.32	3.90	2.66	1.24	25.00	12.59	2.39	10.20	4.62
28-11-17	22.17	33.19	50.29	100	2.84	16.81	1.03	-0.39	1.53	33.36	27.68	0.22	0.07	2.67	5.08	3.88	2.61	1.26	25.03	12.94	2.55	10.40	4.71
29-11-17	21.13	32.45	55.34	100	3.43	16.51	1.03	-0.39	1.53	33.40	26.79	0.21	0.07	2.51	4.88	3.69	2.60	1.09	25.06	12.72	2.45	10.27	4.60
30-11-17	22.34	32.72	55.28	100	3.53	16.20	1.03	-0.39	1.53	33.44	27.53	0.21	0.07	2.70	4.95	3.83	2.72	1.11	25.09	12.47	2.29	10.19	4.63

APPENDIX B. Soil moisture for NI and DI

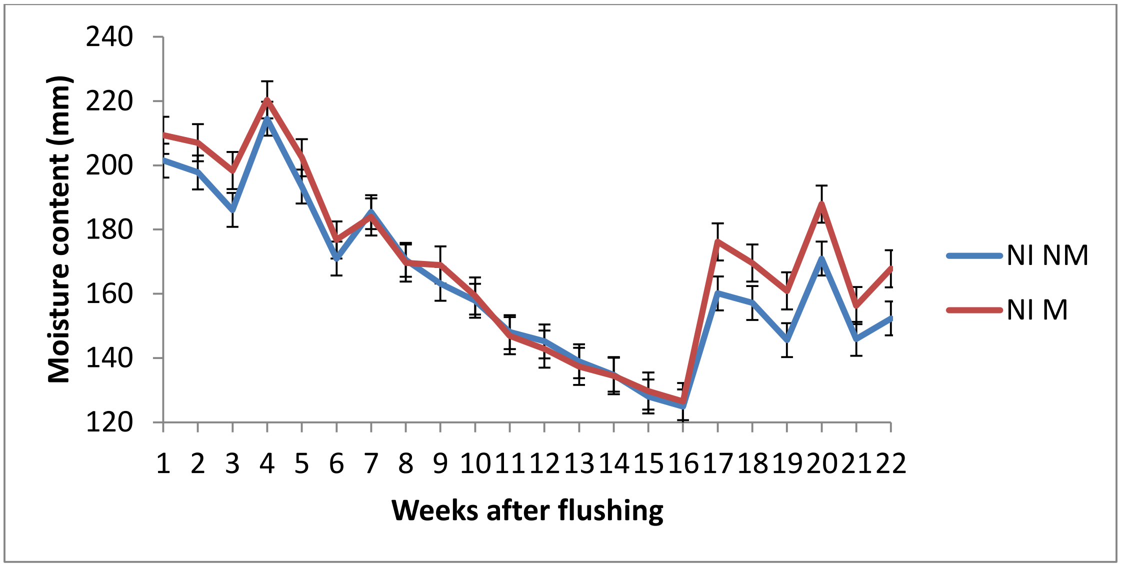


Figure B1 Moisture content for NI treatment

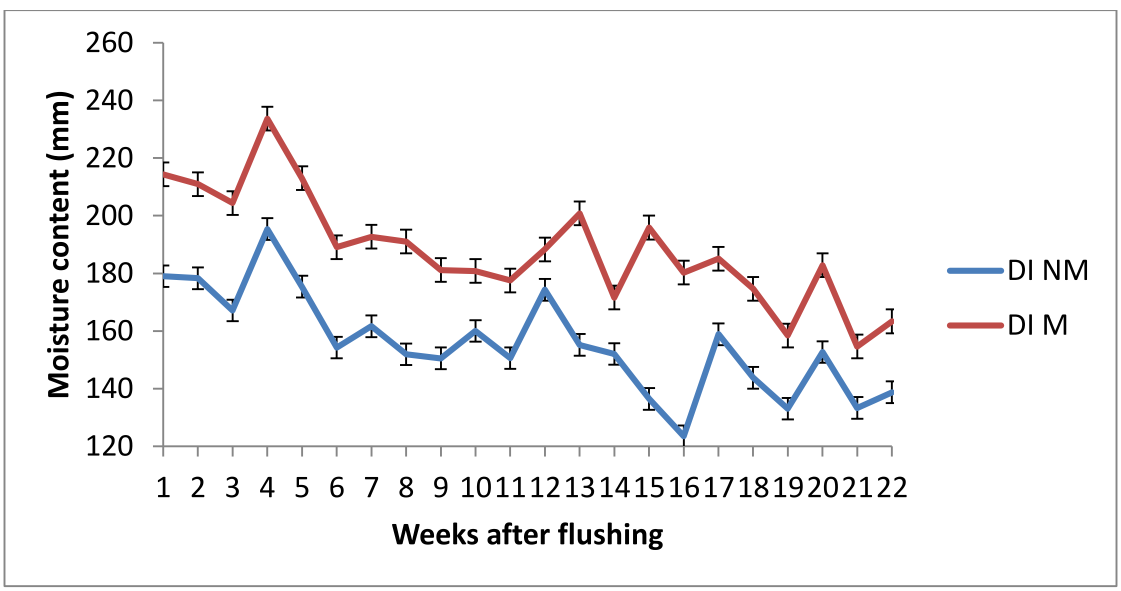


Figure B2 Moisture content for DI treatment

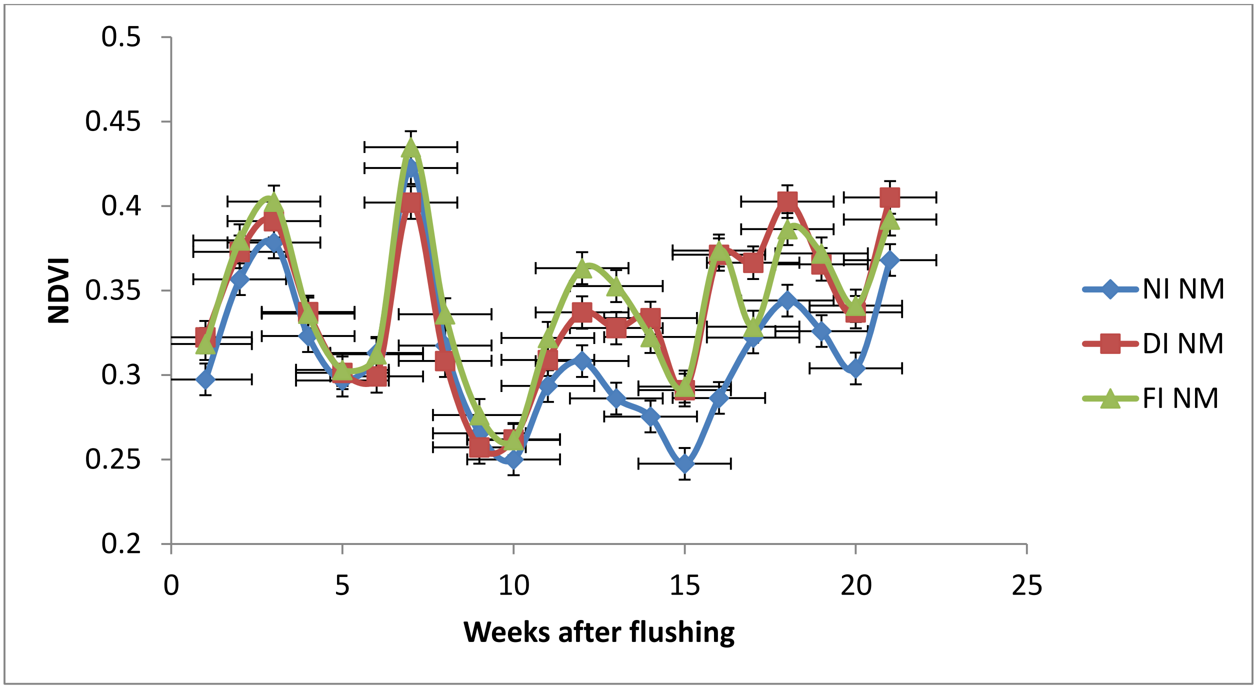
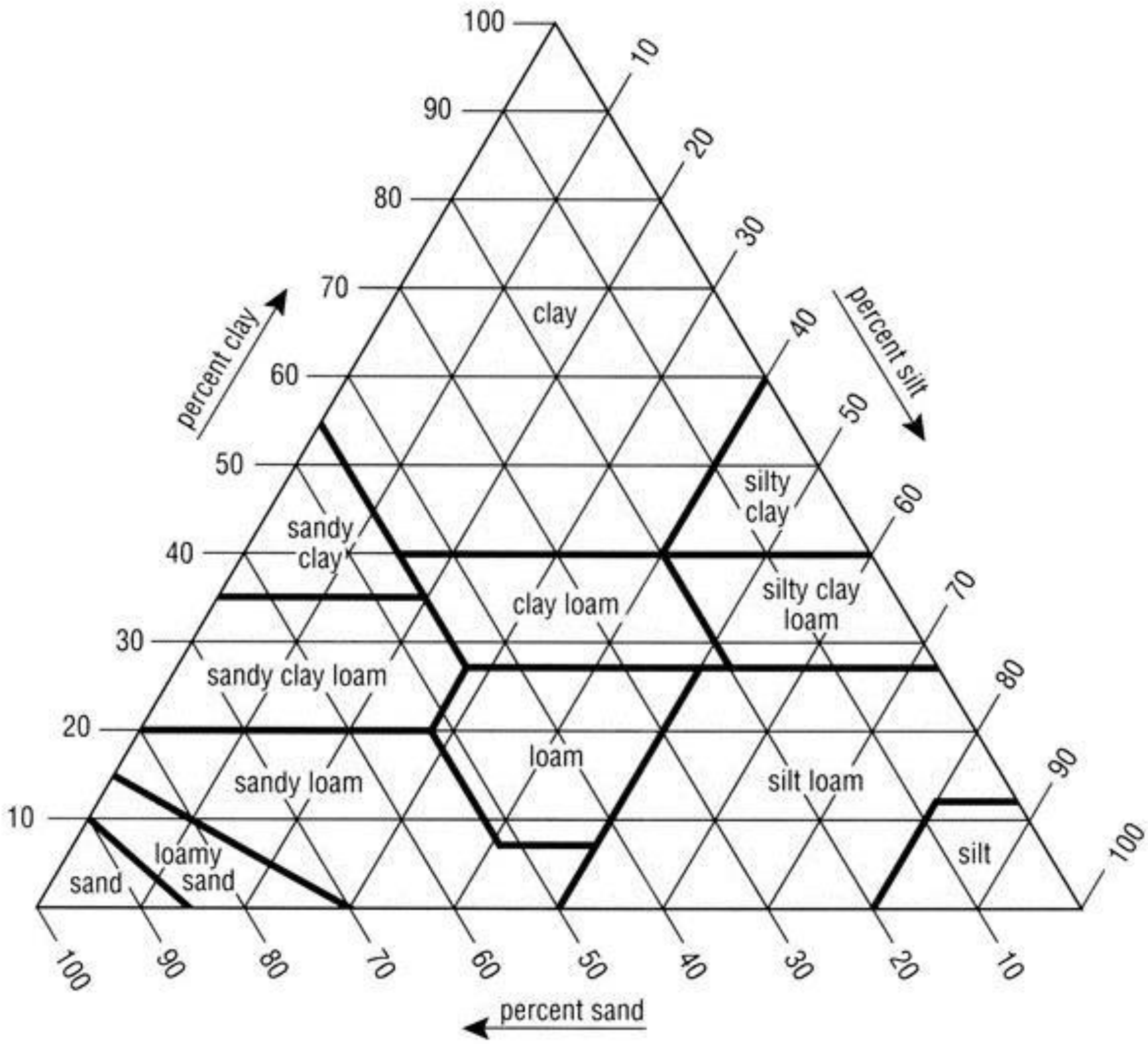


Figure B3 Measured NDVI values for NI, FI and DI under no mulch

APPENDIX C



(Source: FAO, 2006)

Figure C1: USDA soil textural triangle.