A GREENHOUSE INVESTIGATION AND MODELLING THE EFFECTS OF EXTREME TEMPERATURE AND MOISTURE STRESS ON GROWTH, DEVELOPMENT AND YIELD OF SOYBEAN (*Glycine max* (L.) Merrill).

BY

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DECLARATION

I hereby declare that this thesis has been written by me and it is solely based on my own investigations. All references to other researchers' works have been duly acknowledged and cited.

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DEDICATION

This work is dedicated to the Alpha and Omega, the Almighty God for seeing me through from the beginning to the completion of this work. I am eternally grateful for His grace and mercies that endures forever.

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ABSTRACT

Climate change is a major stressor that would adversely affect tropical agriculture, which is largely rainfed. Available evidence shows that associated with climate change is an increasing trend in temperature and in some locations, decline in rainfall leading to repeated droughts during the growing season. In this study, the effects of increased temperature and drought on soybean, a C_3 plant, was investigated under greenhouse conditions. An understanding of how soybean would respond to climate change effect is a major key to improving food security for the global population and continues to be of research interest.

This research was conducted in a greenhouse in the year 2018 with the purpose of determining the effect of climate variables such as temperature, relative humidity (RH), vapour pressure deficit (VPD) and soil water (W) on the phenology, biomass and grain yield of the plant. The research also aimed at developing and testing a simple temperature and water stress model for simulating the effect of these climate variables on the growth and yield of soybean. The experiment was set in a Split Plot Design with three average environmental conditions as main plots: E1 (36 ^{o}C, RH = 55 %), E2 (34 ^{o}C, RH = 57 %) and E3 (33 ^{o}C, RH = 44 %) resulting in VPD values of 2.7, 2.5 and 3.0 kPa for E1, E2 and E3, respectively. Additionally, there were three water treatments: W1 (near saturation), W2 (Field capacity) and W3 (Drought) and two soybean varieties (Afayak and Jenguma) were used in the study. These treatments were replicated nine times.

The results showed that high temperature environment (E1) accelerated soybean development particularly towards flowering. The days from emergence to flowering were 37, 38 and 40 for Afayak (V1) for environments E1, E2, and E3, respectively. In the case of Jenguma (V2), the days from emergence to flowering were 39, 40 and 41 for E1, E2 and E3, respectively. The cumulative evapotranspiration (ET) were 224, 208 and 185 mm for the environments E1, E2 and E3, respectively. Biomass and yield were drastically reduced under the combined effect of high temperature (E1) and drought (W3) compared to combined ambient temperature (E3) and well-watered condition (W1).

The water treatment W3 (drought) had the lowest mean pod weights of 1.29, 1.54 and 3.35 g/plant for E1, E2 and E3 respectively, while W1 (near saturation) had the highest mean pod weight. The interactive effect of environment and drought treatment (W3) was most severe under E1 and E2 giving relatively lower grain yield of 0.45 and 0.53 g/plant compared to the ambient environment E3 which had mean weight of 1.54 g/plant.

The varieties differed statistically in their responses to drought in both E1 and E2 environments with Jenguma significantly having higher yields than Afayak.

The model developed performed quite well, correctly predicting the time-course of the total dry weight (TDW) of both soybean varieties under the range of temperature and soil water conditions. The final seed weights were also well predicted. In general, the agreement between the predicted and observed TDW was good, with R^2= 0.74 and Willmott d -index =0.9.

It was concluded that increasing environmental stresses associated with climate change would adversely affect the productivity of soybean in general, but some varieties may be more resilient. Breeding efforts should be directed to improving not only drought but also temperature tolerance.

CHAPTER ONE

1 INTRODUCTION

1.1 Background

Tropical agriculture depends largely on weather and is expected to remain so for many years, because irrigation development rate continues to be slow. Therefore, climate change, defined as persistent changes in climate variables (IPCC, 2014), is likely to affect crop growth and productivity. The available evidence shows that the average air temperatures have increased all over the world with the mean ambient temperature universally projected to rise between 1.4 and 5.8 ^{o}C in the 21st century (United Nations Environmental Programme, 2006). This may have the potential to negatively impact important agronomic crops, including soybeans (Hatfield *et al*., 2011). It is expected that climate change would also lead to the reduction in mean rainfall as well as increased frequency of droughts in many locations (IPCC, 2014), which together with increasing temperatures would have large negative effects on crops (Schlenker and Lobell, 2010; Roudier *et al*., 2011). When temperature increases beyond the optimum for crop growth and development leading to negative effects on crops, the phenomenon is referred to as heat stress (Zrobek-Sokolnik, 2012), which in combination with other factors would alter crop's lifecycle and impact on growth and development. The negative impact of increase in temperature on plant development and growth can be attributed to several reasons. First, the development rate is accelerated, reducing the overall life cycle of the plants leading to reduction in size, shorter reproductive duration and reduced yield (Hatfield & Prueger, 2015). Second, plant respiration rate increases with temperature **(**Paembonan *et al*., 1992**)** and would lead to the reduction of net assimilate accumulation. The combination of these two effects, even when other factors are non-limiting would decrease the overall growth of plants.

Furthermore, if rainfall reduces under climate change, soil water replenishment and availability is also reduced. This would negatively impact crop growth because the increased vapour pressure deficit and evapotranspiration demand associated with increased temperature cannot be met under low soil water availability. The plant will hence be water stressed.

The simultaneous occurrence of reduced precipitation and increased temperature has been speculated to be more extensive in the future leading to lengthened drought periods (Field *et al*., 2014).

Since crop yields are particularly sensitive to water availability at the reproductive growth stage (Merah, 2001; Kato *et al*., 2008), the occurrence of extreme droughts at this critical development period would be detrimental to crop growth and food security worldwide (Adams *et al*., 1998; Olesen and Bindi, 2002). The understanding of plants response to changes in climate is, therefore, vital for improving food availability to the global population and this continues to be of research interest.

1.2 Problem statement

Soybean (*Glycine max L*.) is ranked as the sixth widely cultivated agricultural crop globally (FAOSTAT, 2016). Soybean is grown in 102 countries all over the world, with an approximated total area of land of over 92.5 million hectares and more than 217.6 million metric tonnes of production (FAOSTAT, 2010). In Ghana, soybean is grown predominantly in the northern region with an average farm size of 1.4 hectares (Plahar, 2006) and is intended to be exported as a cash crop and at the same time to supplement farmers' food needs (Aoyagi, 2007). Soybean is universally recognised as a legume and oil seed crop, it is also a quality source of protein for human consumption and also used as biofuel and livestock feeding (Masuda and Goldsmith, 2009). According to El Agroudy, *et al*. (2011), soybeans contain 30 % oil which is cholesterol free, 40 % protein and also contain most essential vitamins required by human beings. Goldsmith *et al*. (2008) also reported that only 2 percent of the protein found in soybean is consumed by humans in the form of food products. Soybean crop has the potential of improving three important sectors of Ghana's economy, viz; agriculture, health, and industry (Plahar, 2006).

Temperature is a key environmental factor that affects soybean development and growth. The intensity (temperature in ^{o}C), duration, and the rate at which temperature increases determines the severity of heat stress (Sung *et al*., 2003; Wahid *et al*., 2007), and also the stage of crop development (Prasad *et al*., 2008) with the reproductive stage being more prone to heat stress effect than the vegetative stage. Studies have shown that flowering and seed filling periods which represent the reproductive phase of crop development are the most sensitive growth stage of crops to heat stress (Singh *et al*., 2010; Teixeira *et al*., 2013). Research has also shown that there may be varietal differences in the tolerance to heat stress.

With respect to water availability, both greenhouse experiment and field studies have shown that water stress leads to a notable reduction (24 %–50 %) in soybean seed yield (Frederick *et al*., 2001; Sadeghipour and Abbasi, 2012). Considerable efforts have been made to enhance drought tolerance in soybean, with the primary goal being to enhance yield under drought conditions.

The combined effect of high temperature and drought has more detrimental effects on yield and grain number as compared to their individual effects (Prasad *et al*., 2011). Understanding the combined effects of heat and drought stress on plants is paramount since the future climate is projected to be characterized by frequent incidence of increased temperatures and reduced precipitation (Hartfield *et al*., 2011).

Associated with temperature and soil water variation is the changes in relative humidity. Under high soil water conditions, the relative humidity of the air is likely to rise, reducing transpiration rates and overall growth. On the other hand, dry spells would also reduce the relative humidity and increase the potential evapotranspiration rate, aggravating drought effects. The way the soybean crop would respond to such climate change induced environmental conditions remains largely unknown. Furthermore, possible differences in varietal response is not well documented.

Crop models offer opportunities for predicting the impacts of varying weather conditions on plant growth. Examples include DSSAT-Legume models (Jones *et al*., 2003), APSIM (McCowan *et al*., 1996), among others. Though these models have been validated under ambient temperature and rainfall conditions in Ghana (MacCarthy *et al*., 2017), the performance of these models under extreme temperature and rainfall conditions has not been investigated in Ghana. This study therefore seeks to derive temperature and water stress functions that can be included in crop models to improve their efficiency in modelling crop growth under such extreme weather conditions.

Given the paucity of information on the possible climate change effects on soybean production in Ghana, this study is designed to shed further light on the climate change-soybean productivity nexus, especially under extreme conditions.

1.3 Objectives

The purpose of this study is to evaluate the response of two soybean varieties to varying temperatures and soil moisture regimes. This study is designed to:

(i) determine the effect of increased temperature, relative humidity and reduced soil water on the phenological development of the crop,

(ii) determine how temperature, relative humidity and soil water affect the biomass and grain yield of the crop, and

(iii) develop a simple temperature and water stress model for simulating the effect of extreme weather conditions on the growth and yield of soybean.

CHAPTER TWO

2 LITERATURE REVIEW

2.1 Global soybean production trends

Soybean (*Glycine max* L.) Merrill is a highly nutritious and globally important crop. Soybean production is one of the important among the oil crops and is a relevant source of income for producers (FAO, 2016) making it the major source of edible vegetable oils and high protein feed supplements for livestock in the world. In order to continually provide nourishment for human and animal sustenance, there is need to increase soybean production in all areas.

The tropics and semi-arid tropics account for about 90 % of the world's soybean production. Yet, these tropical regions have prevailing high temperatures and low or erratic rainfall (Thuzar *et al.*, 2010). United States of America (USA), Brazil, Argentina, China, and India are the major producing countries of soybean in the world with over 92 % of the world's total production with USA being the leading producer. Brazil and USA account for the largest production and exportation of soybean in the world (Kumudini, 2010). Brazil's soybean production has expanded from 1 million hectare in 1970 to over 33 million hectares in 2016 (Yue *et al.*, 2017).

In USA, soybean production has been at its highest rate of 89,507 million tons on an area of over 33,640 million hectares of cultivated land since 2005 (USDA, 2014). The annual increasing rate of soybean from 1961 to 2007 was at 4.6 %, with the average annual production of 217.6 million tons in 2005 to 2007 (Masuda and Goldsmith, 2009). In the 2009/2010 harvest, soybean grain production in the world was estimated to be 261.57 million tons on 102.38 million hectares of cultivated land (FAOSTAT, 2012). In 2012/2013 agricultural year, the State of São Paulo, a municipality in

Southeast region of Brazil had an average grain yield of 3,220 kg ha^{-1} and average grain production of 2.15 million tons on harvested area of 637 thousand hectares (CONAB, 2013).

Soybean (*Glycine max*) was newly introduced to Sub-Saharan Africa (SSA) in the 19th century by Chinese traders along the east coast of Africa (Giller and Dashiell, 2006). The first record of cultivation of soybeans in Ghana (formerly known as the Gold Coast) was in 1909. Between 1909 and 1956, 17 annual soybean trials on about 40 different varieties were conducted (Sawer, 1911; Snow, 1961; Mercer-Quarshie, 1975).

The cultivated area for soybean production in SSA has rapidly increased from 20 thousand hectares in the 1970s to 1.5 million hectares in 2016, which has been the primary factor responsible for increase in soybean production from 13,000 tons in the early 1970s to 2.3 million tons in 2016 (US Department of Agriculture, 2017). Between 1987 and 2016, soybean production in South Africa and Nigeria increased from 84,000 tons to 1,320,000 tons and from 40,000 tonnes to 680,000 tonnes respectively (Khojely *et al*., 2018).

Nigeria, South Africa, and Uganda are the top soybean-producing countries in the SSA region with other countries such as Zimbabwe, Malawi, Ghana, Sudan, and Ethiopia also experiencing a reasonable increase in soybean production.

In the Upper West Region of Ghana, soybean productivity was 1.20 t/ha, 1.42 t/ha and 1.13 t/ha on a cultivated area of 14,370 ha, 14,970 ha and 15,630 ha in the years 2009, 2010 and 2011 respectively (SRID-MoFA, 2011). Soybean in Ghana is grown on different types of soils. Even though most soils of the northern Ghana are light textured, soybean is also grown on a limited scale on some heavier clayey soils in the coastal savanna of Ghana (MacCarthy *et al*., 2017).

Sapra and Anaele (1991) reported that different cultivars of soybean differ in their response to increasing temperatures. In SSA, soybean improvement is still a major activity in breeding and management practices. Between 1970 and 2011, 195 soybean varieties were released of which (119) were by private breeders, (71) from IITA and (5) from National Research Programs (Alene *et al*., 2015).

The USAID Soybean Innovation Lab (SIL) are involved in collaborative work with research scientists from the University of Illinois and the national soybean improvement program in Ghana investigated how maturity duration, long juvenile period could affect the adaptation of soybean in particularly in the northern regions of Ghana.

In the Upper West Region, soybean is relatively new and grown as a cash crop by smallholder farmers in the region predominantly under rain-fed agriculture (Salifu, 2003).

Despite the potential of soybean to become a cash crop, average soybean productivity in northern Ghana is still relatively low with yields of about 1 t/ha which is far below the yields of about 3 t/ha which can be achieved under optimised growing conditions. Average yield of soybean is 1.65 t/ha (SRID-MoFA, 2011).

2.2 Soybean use / utilization

Soybean (*Glycine max* (L.) Merr. originated from China and is a major source of protein for humans and livestock animals (FAO, 2003). Soybean seeds can be processed into oil, being one of the largest sources of vegetable oil and it is a good source of animal protein feed in the world (Sugiyama *et al*., 2015), which makes it a rich source of nutrients in human food, animal feed, and valuable raw material for industries. Soybean has a high protein content greater than 40 % and has recently been used in meal formulations in the poultry industry in SSA (Joubert and Jooste, 2013).

In Nigeria, many delicacies prepared using soybean has been found to be highly acceptable and incorporated into traditional local dishes (Osho and Dashiell 1998). Food products such as *nshima* (Zambia & Malawi), *dawadawa* (Nigeria), *mahewu*, *tuubani* (Ghana), *soy-ogi*, *soy kebab* (spicy tofu), biscuits, soy flour, soy yogurt, and soymilk is a common relish by local people in many SSA countries (Shannan and Kalala, 1994; Kolapo, 2011; Dlamini *et al*., 2014).

In order to ensure food sufficiency in Sub-Saharan Africa, especially protein, the introduction of soybean as a tropical crop provides a possible solution to food supply (Kolapo, 2011; Masuda and Goldsmith, 2009; Hartman *et al*., 2011; Sinclair *et al*., 2014).

The inclusion of soybean (*Glycine max* L.) Merrill in cropping systems is advantageous (Sinclair and Vadez, 2012), as its potential to fix atmospheric nitrogen through symbiotic nitrogen fixation can substitute for the huge amounts of nitrogen fertilizer usually used in crop production in Africa.

The demand for soybean is expected to rise by almost 140 % in the year 2050 (Bruinsma, 2009), which makes soybean a potential source of income and revenue to the economy of most African countries.

2.3 Soybean varieties in Ghana

The Savanna Agricultural Research Institute of Ghana (SARI) in 2003 released Jenguma soybean variety to increase soybean production in the northern region of

Ghana. SARI is located in Nyankpala, Ghana and is part of the Council for Scientific and Industrial Research (CSIR) Program in Ghana.

The variety name ‘Jenguma’, is from a local Lobi dialect which literally means "stay and wait for me". The formal name is Tax 1445-2E and is the most widely cultivated soybean variety in Ghana (Salifu, 2003). It was developed to withstand the climatic conditions of the region.

Jenguma has an attractive grain colour, high oil content, is resistant to pod shattering in the field and also effective in control of *Striga hermonthica*, a weed that hinders crop performance and yield in Ghana (Fosu *et al.*, 2012). It has a high nutritional and economic value of 40 % protein content and 20 % oil content and is also relevant for industrial purposes.

Other common soybean varieties in Ghana include,” Salintuya-1”, “Anidaso” and “Quarshie” which are medium maturing (101-110 days). Nangbaar variety is early maturing usually less than 100 days while “Jenguma: is late maturing (110-115 days). Grain yield of the varieties are 1.2 -1.8 t/ha (12 – 18 bags/ha) for Salintuya-1 and Anidaso, Nangbaar is 1.5 – 2.5 t/ha (15-25 bags/ha) while Jenguma has a grain yield of 1.7 – 2.8 t/ha (17-28 bags/ha) (Asafo-Adjei *et al.*, 2005). Afayak variety with a formal name of TGX 1834-5E has a maturity period of 110-115 days with a potential yield of 2.0-2.2 t/ha and is also excellent for striga control. Denwar and Mohammed (2008) reported that Jenguma has an average plant height of 65 cm and it takes on an average of 45 days to 50 % flowering.

2.4 Constraints of Soybean production in SSA

The SSA comprises 48 countries and has a total area of 21.2 million square kilometres and 600 million hectares (Khojely *et al*., 2018) of arable land, of which only less than

10% is currently cultivated (Khojely *et al*., 2018). Soybean is a short day plant (Garner & Allard, 1920), which is sensitive to photoperiod (Wu C. *et al*., 2006; Jiang *et al*., 2013; Wu T. *et al*., 2015) and as such most of the improved varieties introduced from temperate regions often reach anthesis quickly resulting in poor yield due to insufficient accumulation of vegetative biomass before the onset of the reproductive phase of the crop. Therefore, in SSA regions, soybean varieties that are highly insensitive to photoperiod are preferred.

Also, the low soybean yields associated with the sub Saharan Africa countries may be as a result of poor-performing varieties and lack of sustained rhizobial inoculant use and insufficient fertilizer application (Woomer *et al*., 2012). Poor performing varieties is due to little involvement of National Soybean Research Programs in developing improved varieties of which most improved varieties in SSA have been developed by either private breeders or International Research Institutions such as IITA.

Decreasing soil fertility has long been a major hindrance to boosting agricultural production in SSA (Matusso *et al*., 2014; Raimi *et al*, 2017; Vanlauwe *et al*., 2017). Agricultural Research (EIAR) in Ethiopia have been working on developing low-phosphorus-tolerant soybean varieties.

Erratic and inconsistent rainfall distribution which are characteristics of climate change impact has prompted some research on the response of soybean production to rainfall variability (Ibrahim, 2012). In Sudan, the National Soybean Breeding program of the Agricultural Research Corporation (ARC), Wad Medani, has been conducting research over a decade on adaptation of soybean to irrigated and rain-fed cropping systems in Sudan (Ibrahim, 2012).

Another major constraint of soybean expansion in Ghana is the poor development of diverse soy-based food products thus resulting in limited land put to soybean cultivation. Human resource is also another factor impeding soybean improvement research across Sub Saharan Africa.

2.5 Environmental factors influencing soybean production in the tropics

The major environmental factors namely: (i) temperature (ii) relative humidity (iii) solar radiation and (iv) soil water availability that affect soybean growth and productivity is the same as for most crops. Though the factors act in combination, their individual effects can be studied and discussed as follows.

Literature sources indicate that high relative humidity and temperature during soybean seed production are not conducive for good seed production which is required for establishment of healthy plant stands (Tekrony *et al.*, 1980). It is also known that hot dry weather during the seed maturation process adversely affect seed quality (FAO, 1994). Other factors of importance to seed quality include the incidence of diseases during the reproductive stages. Disease incidence increases with relative humidity. Therefore, the timing of soybean cropping operations is crucial to successful production. The tropical environment is characterized by several agro-ecological zones, namely arid, semi-arid, humid, sub-humid, resulting in diverse weather conditions that may constrain or support soybean production. The soybean production belt falls within the humid and sub-humid zones. The humid zone is characterized by high humidity and rainfall usually rainfall for at least 270 days or more in a year (Wohl *et al.*, 2012), whereas the sub-humid zone has high and low humidity seasons alternating within the year.

The starting point of a successful soybean production begins with good seed production. Given a good seed, soybean research has focused on the aspects of breeding (Sadok and Sinclair, 2009), varietal trials (Fletcher *et al*., 2007; Seversike *et al*., 2013) and the analysis of yield components. Few studies have investigated the effect of fertilizer phosphorous on soybean yields (Mabapa *et al*., 2010; Ahiabor *et al*., 2014). Though multi-location trials may capture temperature effects and soil moisture variations on soybean yield, targeted studies on temperature and soil water effect are still lacking.

2.5.1 *Effects of temperature on growth, development and yield of soybean*

Gibson and Mullen (1996) reported that high temperatures occurring just before the beginning of seed filling period caused a decrease in the number of fertile pods and the number of seeds per plant in soybean. Growing plants at mean temperature of 27.5 ^{o}C led to reduced seed production unlike plants grown at mean temperature of 17.5 ^{o}C (Heinemann *et al*., 2006). Even though heat stress due to high temperatures is known to affect yields, it particularly influences seed filling period leading to small seed size and reduced yields (Prasad *et al*., 2008).

Increase in temperature above 28 ^{o}C during the day and 18 ^{o}C at night with a mean temperature of 23 ^{o}C delays post-anthesis reproductive development and seed development leading to a reduction in soybean seed size (Sinclair *et al*., 2010). According to (Tacarindua, 2013), increase in temperature mostly affect soybean seed yield causing seed yield reduction by up to 16 % to 40 %. The reduced seed yield resulting from increase in temperatures was caused by the reduction of some yield components such as fertile pods, seed size and number, and the poor pod formation which may likely delay the onset of seed growth.

Heinemann *et al*. (2006) also reported decreased soybean seed yields resulting from temperatures greater than 30 °C. Obviously, the impacts of climate change which results in temperature change are particularly visible on crop production when high temperatures occur after flowering in soybeans (Hatfield *et al*., 2011), which will significantly affect seed yields.

Temperature generally promotes plant development through stimulation of enzyme activities and processes (Horie, 1994). Plant physiology indicates that plants will not initiate development when sown until a minimum temperature, called the base temperature (Tb °C) is attained. The Tb varies for crops and is about 10 °C for soybean (Hundal *et al*., 2003). Beyond this Tb, development rate increases reaching a maximum rate of 39 °C for soybean (Boote *et al*., 2005). Further rise in temperature leads to the retardation of development rate.

The temperature effect on plant development is often expressed in terms of thermal time or Growing Degree Days (GDD °Cd), given by:

$$GDD = \sum (Tav - Tb) \times t \qquad [2.1]$$

Where Tav is the average ambient temperature °C and Tb is the base temperature, and t is time.

For a determinate plant such as soybean, several development stages can be distinguished, namely (i) emergence VE, (ii) vegetative (V1-Vn): node formation, (iii) flowering (R1-R2) (iv) podding(R3-R4) (v) Seed filling (R5-R6) (vi) maturity(R7-R8) (Fehr and Caviness, 1977). The chronological duration of each stage may vary with ambient temperature, but this is to satisfy the genetically fixed thermal time for the variety in question. For soybean cultivar, BRS Tracaja cultivated in the northeast region of Para state of Brazil requires between 1,685 and 1,770 ^{o}Cd for flowering. (de Souza *et al*., 2013).

Plant growth also responds to temperature in a similar manner as development. Even though both photosynthesis and respiration increase with temperature rise, the former is initially higher so that the net photosynthesis is positive until compensation point temperature is reached.

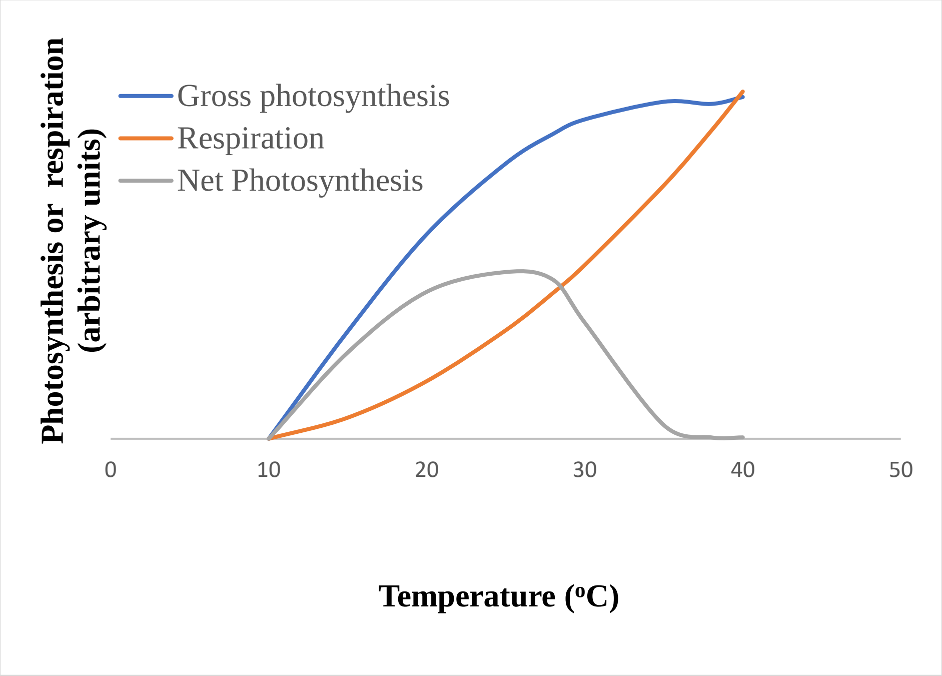


Fig. 2.1: A diagrammatic representation of the response of photosynthesis and respiration to temperature rise.

Beyond the compensation point, further increase in temperature results in negative net photosynthesis. For many plants, the response of growth to temperature follows the pattern shown in Fig. 2.1. Note in Fig. 2.1 that the net photosynthesis or growth rate reduces after the optimum temperature is more rapid. The optimum temperature (Topt) for soybean growth is given generally as 30 ^{o}C (Hoeft *et al*., 2000) while the maximum temperature (Tmax), beyond which growth ceases is 39 ^{o}C (Boote *et al*., 2005).

Due to non- symmetrical response below and above Topt, the two arms of the curve are often described separately.

$$GR = GR_{max}\,(a+bT+cT^2) \qquad Tb \leq T \leq Topt \qquad [2.2a]$$

$$GR = GR_{max}\,(e+fT+gT^2) \qquad Topt < T \leq max \qquad [2.2b]$$

Where GR= the actual growth rate kg/d, GR_{max}= maximum growth rate kg/d, T= temperature ^{o}C and a, b, c, d, e, f, g are constants.

Although, several studies have been carried out to understand and investigate the response of physiological processes to increased temperature due to climate change effect, further studies are required to better quantify the impacts involved in the temperature response of biomass production and seed yield of soybean. At the critical stages of plant development, increases in daily or seasonal temperatures beyond the optimum will be a major limitation in crop production (Thuzar *et al*., 2010).

Under typical field conditions, the effects of high temperature on the physiology of many crop species is more obvious at reproductive stage as compared to vegetative stage (Hall, 1992). In soybeans, floral initiation occurring after six or more trifoliate leaves have emerged (Martin *et al*., 2006), which marks the onset of the reproductive stage, is largely dependent on temperature. A deviation in temperature from the optimal can seriously impede the growth and development and even total loss of plants (Kotak *et al*., 2007). The day and night temperature cycles are also known to significantly affect flowering, pod formation and seed yields in soybean. For example, the effect of soil and air temperature during the day of 28 °C and 38 °C respectively, from the onset of flowering to maturity was investigated, revealing that at high temperatures there was a 50 % reduction in pod yield (Prasad *et al*., 2000) while, day and night temperatures as high as 30 °C and 20 °C respectively during flowering and pod set favoured more pod formation, (Lawn and Hume, 1985), but temperatures above 40 °C drastically hindered pod formation (Mann and Jaworski, 1970).

High temperature enhances rapid vegetative growth in soybean but negatively affects yield at the reproductive stage. Gibson and Mullen (1996) measured about 27 % yield reductions in soybean when the plants were exposed to temperature of 35 °C for about 10 hours at daytime. The R1-R7 stage which is the reproductive growth stage of soybean crop is more sensitive to high temperatures than vegetative growth stage (Reddy and Kakani, 2007). Puteh *et al*. (2013) showed that, with regard to seed production, yield components such as number of pods per plant, seeds per pod, seeds per plant and seed yield decreased with increasing air temperature. The highest seed yield was recorded at the lowest temperature while the lowest seed yield was recorded at the highest temperature. It has also been reported that high temperature of 32- 38 ^{o}C during reproductive periods reduce seed yield components of soybean (Huxley *et al*., 1976; Dornbos and Mullen, 1991; Gibson and Mullen, 1996). This indicates that high temperatures during flowering and pod set are detrimental to soybean seed yield.

Harel *et al*. (2014) found that fruit number, the percentage of fruit set and fruit weight per plant decreased as air temperature increases from 25 to 29 °C. Thus, in general, the situation whereby ambient temperatures are rising globally would likely be detrimental to soybean productivity.

2.5.2 *Relative humidity (RH) and vapour pressure deficit (VPD)*

Humidity is an expression of the amount of water vapour in air. Water vapour is an invisible gas that accounts for 1 % to 4 % by volume of the atmosphere. Relative humidity (RH) is a measure, in percentage, of the water vapour in the air compared to the maximum amount of water vapour that the air can hold at a given temperature. This implies that as the air temperature rises, the ability of the air to hold water vapour also increases and as the air becomes warmer, more moisture must be added to the air to maintain the same relative humidity. At high humidity levels, the water vapour in the air is high hence it prevents plants from transpiring water into the air and causes low transpiration which limits the transport of mineral nutrients, CO_2 uptake, and O_2 exchange.

Grange and Hand (1987), reported that the effect of very low humidity on crops grown in the open air was to induce leaf water stress due to inadequate uptake of water through the root system to meet the high transpiration demand. Studies have shown that when relative humidity was low, soybean showed no effect on the rate of reproductive development. It however, resulted in reduced seed yield through reduction in number of pods per plant due to floret abortion, possibly as a consequence of reduced photosynthate supply (Woodward and Begg, 1976). On the contrary, high RH was found to increase Soil Plant Analyses Development (SPAD) values, plant height, root length, leaf area and plant dry weight of soybean (Roriz *et al*., 2014).

Vapour Pressure Deficit (VPD) is the difference (deficit) between the current amount of moisture in the air and how much moisture the air can hold when it is saturated. In other words, the VPD simply measures the drying power of the air. The units of VPD are usually expressed in standard pressure units such as millibars, kilopascals, pascals. The VPD is a very important climatic variable that affects the plant via transpiration which increases with increase in temperature but decreases with increase in relative humidity.

The drier the atmospheric air, the larger the VPD value which indicates a higher potential the air has for extracting moisture out of the plants, on the other hand, a low

VPD value represents more moisture in the air and the plants are unable to transpire any water into the air which causes a build-up of pressure within the plant.

The VPD adequately reflects stress effect in plants due to either high transpiration (high VPD values) or failure to transpire adequately (low VPD values). According to Zolnier *et al.* (2000), VPD reflects more accurately the environmental situation of the plant by taking into consideration both of temperature and relative humidity. Atmospheric VPD and transpiration rates follow a day-to-day pattern, being lowest at dawn and reaching maximum around 3 pm (Hirasawa and Hsiao, 1999). A glasshouse experiment conducted on tomato under two vapour pressure deficits (VPD) showed that under low VPD, there was an increase in fruit relative growth rate whereas under high VPD, there was a wide variation in relative fruit growth. An increase of VPD from 1.6 to 2.2 kPa caused an approximately 10 % reduction in fruit fresh weight (Leonardi *et al*., 2000). Vapor Pressure Deficit (VPD) above 2 kPa approximately have been shown to result in increased rates of transpiration and reduced leaf water potential even in situations where water is not limiting in the root zone (El-Sharkawy *et al*., 1986).

According to Rylski and Spigelman (1986), both high VPD (2 kPa) and low VPD (0.2 kPa) may lead to injury as a result of heat stress as leaf temperatures increase. In soybean, a lower stomatal conductance occurred at a VPD of 3.0 kPa as compared with 1.0 kPa and it has also been observed that the response of stomatal conductance to VPD differs with genotypes (Bunce, 1984). Low VPD limits transpiration rates and significantly alter the energy balance of the crop. Low VPD values (less than 0.3 kPa) in tomato caused guttation and soft growth, while high VPD values (greater than 1.5 kPa) resulted in wilting, leaf roll, stunted plants, dried and crispy leaves (Shamshiri *et al*., 2016).

The simultaneous increase in temperature and vapour pressure deficit aggravates the atmospheric dryness which affects soybean growth and yield leading to reductions in fertile pods, seed number and seed size (Tacarindua *et al*., 2013). Also, high VPD as a result of high temperatures might have been responsible for reduced photosynthesis in soybean due to stomatal closure for a period of time (Tacarindua *et al*., 2013).

In an experiment to estimate whether increasing temperatures modified VPD responses of two genotypes of soybean, it was observed that at a temperature of 25 ^{o}C, VPD did not restrict transpiration rate but as temperature was increased to 30 ^{o}C, there was an obvious limitation in transpiration rate as VPD also increased beyond approximately 1.9 kPa (Seversike *et al*., 2013).

Genotypic characteristics of soybean cultivars influence response to VPD. Some cultivars, such as the slow-wilting genotype, reached a maximum transpiration rate at a VPD of approximately 2 kPa and as VPD increases. In other words, for most commercial cultivars, a continued increase in transpiration rate was observed as VPD increases (Fletcher *et al*., 2007; Sadok and Sinclair 2009).

2.5.3 *Water availability effect on soybean growth*

Apart from temperature, soil water availability is a major determinant of plant growth. Plants require water as a means of nutrient uptake, but also to meet the transpiration demand of the atmosphere. Water restrictions caused by insufficient soil moisture and high atmospheric water demand might lead to plants closing their stomata to conserve moisture in order to limit water loss from transpiration which may reduce the absorption of CO_2 which is essential for photosynthesis (Kaiser, 1987; Flexas *et al*., 2009; Pinheiro and Chaves, 2011), due to stomatal closure.

Excessive soil water also affects growth because of poor aeration to roots. Several descriptions of water stress effect on plant growth have been published, including the measurement of stomatal conductance and relative water content (Hossain *et al*., 2014), the leaf water potential (Tanguilig *et al*., 1987, Allen *et al*., 1998), among others.

Indeed, it has been shown that most legumes tolerated water stress much more effectively than the cereals (Sohrawardy and Hossain, 2014). For practical purposes, Feddes *et al* (1978) provided a simple but effective concept for quantifying the effect of soil water stress on plant growth. Their concept is shown in Fig. 2.2. In this a water stress factor (α) is defined to vary between 0 and 1. Below some critical soil water (ϴc), α reduces reaching 0 at the permanent wilting point (PWP). Between ϴc and field capacity ϴFc, α = 1. Beyond ϴFc, α reduces reaching 0 at saturation ϴs.

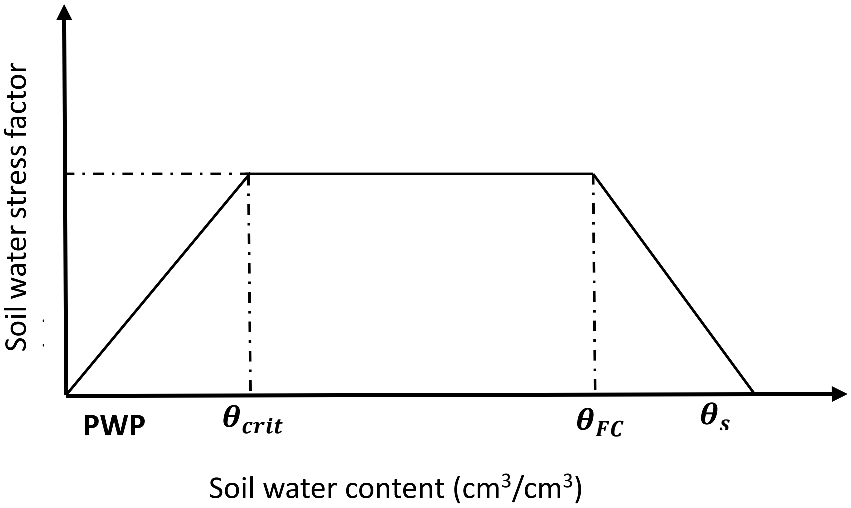


Fig. 2.2: Relationship between soil water content and soil water stress factor on plant growth. (Θ_{crit} is critical soil water content, Θ_{PWP} is water content at permanent wilting point, Θ_{FC} water content at field capacity and Θ_{S} is water content at saturation).

These conditions can be expressed mathematically

(i) When $\theta_{pwp} \leq \theta \leq \theta_{crit}$,

$$\propto \;=\; \frac{\theta-\theta_{pwp}}{\theta_{crit}-\theta_{pwp}} \qquad [2.3a]$$

(ii) When $\theta_{crit} \leq \theta < \theta_{FC}$,

$$\alpha = 1 \qquad [2.3b]$$

(iii) When $\theta_{FC} < \theta < \theta_{s}$,

$$\propto \;=\; \frac{\theta_s-\theta}{\theta_s-\theta_{FC}} \qquad [2.3c]$$

For a given variety, Θ_{crit} and Θ_{z} must be determined to estimate α. In many works, Θ_{c} is taken as the field capacity (Θ_{FC}), but this can differ for a water loving crop. Some studies have suggested that Θ_{crit} for legumes, including soybeans is about 30.5 % moisture content (Rosadi *et al*., 2005) but the exact value for the upper limit Θ_{c} seems to be in contention.

2.6 Climate Change impact on soybean productivity

Agriculture is one of the sectors mostly affected by climate change (Ramirez and Challinor, 2012; Beck, 2013). Climate which is a limiting factor and very difficult to control is largely responsible for hindering soybeans from attaining its maximum yield potential. The impacts of climate change are closely associated with the decrease in the growth and flowering seasons, along with reduction of the number and size of grains, as well as the total yield (Craufurd and Wheeler, 2009; Rose *et al.*, 2016).

Thanacharoenchanaphas and Rugchati (2011) found in their study that unfavourable environmental conditions (variations in temperature and rainfall) during the reproductive growth stage of soybean can reduce seed yield. As discussed earlier, higher temperatures can negatively impact on plant production as a result of rapid phenological development (Menzel *et al.,* 2006; Lobell *et al*., 2012) resulting in shorter time for accumulation of biomass (Menzel *et al*., 2006). According to Sinclair (2000), changes in climatic patterns led to changes in potential evapotranspiration and also a shortened growing season in wheat. Rising global temperature has resulted in more severe dry and wet rainy seasons and, and eventually aggravated the risks of more incessant floods and drought (Schewe *et al*., 2014).

Since agriculture is largely dependent on climate, its contribution to national economies of Ghana and many other countries of Sub-Saharan Africa can be impaired by climate change. (Mawunya and Adiku, 2013). Climate change as noted is associated with changes in both temperature and rainfall patterns, leading to adverse effects on crop yields and food production (Hall *et al*., 2017). Climate change, therefore, has and continues to receive research attention in many tropical countries including Ghana.

Stanturf *et al*. (2011) predicted climate change and climate variability scenarios in various zones of Ghana. The predictions for the coastal savannah showed a decrease in rainfall from 52 % to 44 % by 2080 while rainfall have remained unchanged at other forested and interior savannah locations of Ghana (Adiku *et al*., 2007). It is clear however, that the rainfall distribution within the year has changed significantly. In northern locations, early rainfall (beginning April/May) has diminished whereas late rainfall (August/ September) has increased (Adiku, 2019).

Soybean grown in early season would experience drought and if planted late would experience flooding conditions. Both of these conditions, as discussed are detrimental to growth. In the coastal savannah zone where rainfall is declining, drought conditions could handicap successful soybean production. Further projections of rainfall for the West African region continues to be uncertain. Sylla *et al.* (2015) projected a more evident increase in the intensity of the rainfall events by the end of the 21st century. The Intergovernmental Panel on Climate Change (IPCC) projected that the global average surface temperature would increase by a value between 1.4 and 5.8 °C this century (United Nations Environmental Programme, 2006), which according to (Fedoroff *et al.*, 2010; Hatfield *et al*., 2011) could possibly have negative effects on crops that are of agronomic importance of which soybean is included.

It is more certain that global temperatures have continued to rise over the past 100 years by 0.74 °C. (Stocker *et al*., 2013). Climate change scenarios in Ghana carried out by World bank (2010) predicted increase in temperatures in the North by 2.1-2.5 °C, while the Western, Eastern, Ashanti, Central and Volta regions will rise by 1.7–2.0 °C by 2050. Works by Adiku (2019) show a clear increasing trend in the maximum daily temperature at several locations in Ghana. For some time period, maximum temperature attained exceeded 40 °C. The heat load on plants on the field could be enormous.

Changes in temperature affect evapotranspiration. Thus, the increasing temperature trends will increase the atmospheric demand for water. If drought frequency increases (which is often associated with climate) then the combination of high temperatures and drought can be detrimental to plant growth and productivity. Precipitation, solar radiation, winds, and other indicators which could also lead to extreme events contribute largely to climate change and may occur for short periods, longer periods or even be permanent. Therefore, these changes have the ability to alter the geographical distribution pattern and production of many crop species.

There are other elements such as evaporative demand (ETo), vapour pressure deficit (VPD) and wind that are important in agriculture but are often not considered in climate change impact studies, though their effects could diminish some of the assumptions about crop system responses to the environment.

2.6.1 *Water Effects*

Water stress, which is categorized as either drought or flooding can occur independently or at different times during the growing season and is largely responsible for limiting growth and yield of plants (Boyer, 1982; Thomas *et al.*, 2004). Drought is caused by insufficient supply of water either by rainfall or irrigation resulting in soil drying, whereas, in flooding, the water table is very high (Jackson and Colmer, 2005), or the soil is saturated with water which could lead to water logging or total submergence of plants. In soybean crop production, 40–60 % yield losses were recorded in response to drought and flooding stress (Ahmed *et al.*, 2011; Valliyodan and Nguyen, 2006).

2.6.1.1 Effects of drought on soybean growth and yield

Two-thirds of food produced in the world through cultivation occurs under water stress conditions (Gerten and Rost, 2010). Thus, climate change would impact negatively on plant productivity by about 50 % in most parts of the world (Lisar *et al.*, 2012).

Soybean plant growth requires daily transpiration, reaching 7-8 mm day^{-1} with peaks at the flowering to grain filling stages and decreasing thereafter. In order to attain maximum productivity, total water requirement of soybean varies between 450 and 800 mm, this depends largely on atmospheric weather conditions, management practices and timing of crop’s cycle (Embrapa, 2011; Farias *et al*, 2007). Earlier studies have shown that the reduced productivity under drought conditions depends on the phenological stage of the soybean crop at the time of drought, duration and intensity of water shortages (Doss and Thurlow, 1974).

Drought occurring at the initial growth stages of germination and emergence resulted in reduced plant stand, but at flowering, drought hinders anthesis and can also cause flower abortion while in the seed filling stage, seed weight is affected (Fageria, 1989).

Kron *et al.* (2008) assessed soybean responses to drought induced at various phenological stages and observed that plant subjected to drought at the V4 (fourth trifoliate) stage has a higher tendency to tolerate water deficit in the later stages. This stage was referred to as the "developmental window" in soybean, in which the plant is able to develop resistance to environmental changes in the plants. Desclaux *et al*. (2000) also investigated the effects of drought stress imposed at different stages of development in soybean plants and found that the length of the internode is the most responsive to drought when it occurs at the vegetative stage (V4) and flowering (R1-R3) stage. The number of grains per pod was significantly affected when water shortages occurred at the reproductive stages (R3-R5). Initial studies indicated that seed filling was not the most crucial stage to drought effect but rather at the early flowering stage (R1) which may significantly reduce seed yield (Eck *et al*., 1987, Brown *et al.*, 1985, Hoogenboom *et al*., 1987). In recent studies, however, water deficit at pod initiation (R3-R7) is considered most critical stage that affects soybean productivity (Rosolem, 2005).

2.6.1.2 Effects of flooding on soybean growth and yield

Excessive amount of water due to high rainfall frequencies associated with climate change has resulted in flooding (Bailey-Serres *et al*., 2012; Oh *et al.*, 2014). Flooding is regarded as one of the main environmental factors that has an adverse stress effect on crop growth which eventually causes a reduction in yield (Normile, 2008).

Hou and Thseng (1991) reported that soybean is vulnerable to flooding stress. Yield losses in various crops in flooded situation varies between 15 % and 80 %, depending on the plant species, soil type, and length of the stress period (Patel *et al*., 2014). Flooding results in the quick depletion of oxygen, resulting in a change from aerobic to anaerobic respiration (Voesenek *et al*., 2006). This depleted oxygen causes damage to the plant as the normal metabolism, growth and development of the plant is impaired. Soybean grown in flooded soils show a reduction in photosynthetic activity (Mutava *et al.*, 2015). Waterlogging also decreases nitrogen fixation activity because nodules need adequate oxygen for respiration (Oosterhius *et al*., 1990).

Furthermore, the CO_2 concentration in waterlogged conditions in soil is usually high, and as a result, biomass accumulation and soybean root elongation are impeded (Grable, 1966; Boru *et al*., 2003). About 25 % yield reduction has been estimated in soybean due to injuries associated with flooding in Asia, North America, and other regions of the world (Mustafa and Komatsu, 2014). Oosterhuis *et al*. (1990) observed a decline in soybean yield by 17–43 % and 50–56 % at the vegetative and reproductive stages respectively, due to flooding stress. Flooding from 24 hours to 14 days led to a decline in soybean yield (Scott *et al*.,1989; Singh and Singh, 1995), reduction in branch number, pods per node and seed size after flooding was imposed for 7 days (Linkemer *et al*, 1998). A reduction in pod number was also established by Sullivan *et al*. (2001). Rhine *et al*. (2010) obtained yield reductions of 20 to 39 % in experiment conducted in flooded soil on the field using different soybean cultivars. According to Jin–Woong and Yamakawa (2006) the first parts of the soybean plant to respond to flooding stress are the leaves and the branches.

Flooding for six days may reduce yields significantly, and longer periods water stress due to flooding may destroy the entire plant population (Naeve, 2002).

Flooding is an abiotic stress which accounts for about 16 % loss in soybean productivity globally and billions of dollars are being lost by farmers (Ahmad *et al.,* 2011).

2.6.1.3 Combined effects of high temperature and drought stress on Soybean

Water availability as well as temperature are crucial environmental factors which influence crop growth, development, biomass accumulation and yield processes. Drought and heat stress are environmental stress which plants are generally exposed to and sometimes occur simultaneously in the field (Mittler, 2006). When high temperature coincides with drought, it leads to further losses on grain production (Farias *et al.*, 2007). It was observed in the southeast region of Brazil that in soybean production, losses occur due to droughts and temperature effects. The losses could be estimated to be more than $18 billion (Farias *et al.*, 2006).

The knowledge of the combined effects of heat and drought stress on plants is vital for future climate projections characterized by repeated series of increased temperature and decrease in rainfall (Hartfield *et al.*, 2011). The combined effect of high temperature and drought stress has been reported to cause detrimental effect on yield, grain size, grain number and above ground biomass. There have been observations that the effect of increasing temperature on plant biomass may be aggravated by water deficit (Mittler, 2006; Prasad *et al.*, 2011).

In sum, the literature review has shown that though considerable research work has been conducted and reported in the literature regarding environmental impact on crop growth, there are gaps in knowledge, especially with regard to the Ghanaian situation. In particular, how different varieties of soybean would respond to a combination of increased temperature and drought in Ghana is poorly documented. Given that climate projections for Ghana predict both increasing temperature and increased frequency of droughts, further research is necessary. Such research must also be modelling oriented, given that the field experimentation approach to represent the various possible climate scenario would be virtually impossible. Yet, to date, detailed modelling studies to understand and quantify these environmental effects continues to be slow in Ghana.

CHAPTER THREE

3 MATERIALS AND METHODS

3.1 Description of the Experimental Area

This study was carried out at the University of Ghana, Soil and Irrigation Research Centre (SIREC) –Kpong which is located within the lower Volta basin at latitude of 6^{o} 09$^{'}$ N and longitude 00^{o} 04$^{'}$ E with an altitude of 22 m above sea level. The Research Centre is located within the Coastal Savannah agro-ecological zone of Ghana.

The soil used was from the centre and is an alluvial material derived from the weathering of garnetiferous hornblende gneiss (Brammer, 1955) which is classified as Typic Calciustert (Amatekpor *et al*., 1993). It is locally known as Amo series which is a modification of the Tropical Black Clay called Akuse series (Adu, 1985; Amatekpor and Dowuona, 1995). These soils are generally deep black which contain more than 30 % clay, having a shrink-swell characteristic, also characterized with deep cracks in the absence of rainfall. The dominant clay mineral is montmorillonite.

The study area has an average maximum temperature of 33 °C and minimum temperature of 22.1 °C respectively, with an average air temperature of 27.2 ^{o}C. The relative humidity ranges between 70 to 100 % at night and 20 to 65 % during the day throughout the year.

The choice of the study area is to also explore soybean production in the coastal savannah zone apart from the northern interior savanna zone, where it is largely promoted.

3.2 Description of the Experimental Procedure

3.2.1 *Experimental set up*

As the study sought to investigate the effect of varying ambient temperatures and soil water on the growth of soybean, three growth chambers were constructed to create different temperature regimes. Each chamber comprised a wooden frame of dimensions 3 m (length), 0.8 m (width) and 1m (height) covered with transparent polythene sheets.

The differences in temperature regimes in the chambers were effected by constructing different number of windows in the polythene sheets. A trial prior to the experiment was initially conducted where it was observed that lesser openings trapped a lot of heat and drastically affected plant growth due to the extreme high temperature that was created. While at 35 cm by 35 cm the heat trap was minimal and it did not lead to loss of seedlings and the temperature was maintained at the intended temperature range for the experiment. The hottest chamber had 2 window openings each of size 35 cm by 35 cm. The next hottest had 4 window openings. The control had half of the polythene sheet removed from all sides to allow free wind circulation. It was not possible to maintain the temperature of each chamber at a constant value. The day-to-day variations reflect the atmospheric conditions.

Superimposed on the three environments were three water treatments, namely (i) post-flowering near saturation, (ii) field capacity (iii) post-flowering drying cycle.

Climate change and climate variability scenarios has been predicted in various zones of Ghana. It is also evident that rainfall distribution has changed significantly, hence, soybean sown in early season will experience drought and if planted late would experience flooding. These conditions are what were intended to be replicated in the experiment, hence, the reason for the post flowering near saturation and drying cycle which represent flooding and drought respectively while field capacity is to represent the ideal condition under which moisture is not limiting.

Two soybean varieties were obtained from the Savannah Agricultural Research Institute (SARI of the CSIR), Nyankpala for the study, namely (i) Afayak and (ii) Jenguma. The maturity period for both varieties are 110 – 115 days. The reason for selecting these two varieties is that Jenguma is most cultivated in Ghana and also both varieties are able to withstand hot climatic condition (high temperature) as imposed in the treatment.

A total of 18 treatments in all three chambers and 6 treatments in each chamber. Each treatment was replicated 9 times to give a total of 54 pots in each chamber and 162 pots in all the three chambers combined.

The experiment was laid out in a Split-plot design with the temperature chambers being the main plots. The other factors (water and varieties) were randomized as sub-plots within each main plot (Chamber). Treatment details are shown in Table 3.1.

3.2.2 *Soil sampling and pot experiments*

The soil used for the experiment was collected at the depth of 0-15 cm. The soils were bulked together, air dried and sieved through a 2 mm sieve to remove debris, large clods and stones in order to obtain the fine soil fraction. Pots of 15 cm diameter and 14 cm width were filled with the soil to a bulk density of 1.34 g/cm^3. Since bulk density is calculated as mass of dry soil divided by the volume. Therefore, I determined the volume of the pot used (1500 cm^3), knowing the desired bulk density, the mass of soil required to achieve that bulk density was calculated (mass of soil = volume x bulk density).

After potting, each pot held 2 kg of sieved soil which was saturated with water and allowed to drain for 2 days before sowing. Soybean (*Glycine max. L*) seeds were sown in each pot and were initially nursed in a larger screen house for 14 days. Emerged seeds were thinned to 1 plant / pot and transferred to the growth chambers at 14 days after emergence (DAE). All the transferred pots continued to receive watering to maintain the soil water at or near field capacity until flowering time.

Thereafter the pots were weighed every other day and topped up to the intended water treatment. For W1, water was applied to saturate the pots with a ponded head of 2 cm which was allowed to drain, transpire or evaporate before the re-watering to saturation. This was achieved by weighing the pots to know the amount of water still present before topping up and this procedure also applies to the drought cycle. For W2, soil continued to be maintained at field capacity with no ponding. In the case of W3, watering was reduced with a longer drying cycle until maturity. The water content in the pots for W1 and W2 were between 0.35-0.4 gg^{-1}, 0.25-0.3 gg^{-1}. For W3, the water content declined from 0.3 gg^{-1} at the onset of water stress imposition to about 0.1 gg^{-1} at maturity.

Plate 3. 1: Growth chamber used for the experiment

Plate 3. 2: Experimental set-up

Table 3. 1: Treatment description

Environment	Variety	Water	Treatment
E1 (T:36 °C, RH:55 %)	Afayak	W1=intermittent saturation (post flowering)	T1(E1V1W1)
		W2= field capacity	T2(E1V1W2)
		W3= post flowering drought	T3(E1V1W3)
E2 (T:34°C, RH:57 %)	Afayak	W1=intermittent saturation (post flowering)	T4 (E2V1W1)
		W2= field capacity	T5(E2V1W2)
		W3= post flowering drought	T6(E2V1W3)
E3 (T:33 °C, RH:44 %)	Afayak	W1=intermittent saturation (post flowering)	T7 (E3V1W1)
		W2= field capacity	T8(E3V1W2)
		W3= post flowering drought	T9(E3V1W3)
E1 (T:36 °C, RH:55 %)	Jenguma	W1=intermittent saturation (post flowering)	T10(E1V2W1)
		W2= field capacity	T11(E1V2W2)
		W3= post flowering drought	T12(E1V2W3)
E2 (T:34 °C, RH:57 %)	Jenguma	W1=intermittent saturation (post flowering)	T13(E2V2W1)
		W2= field capacity	T14(E2V2W2)
		W3= post flowering drought	T15(E2V2W3)
E3 (T:33 °C, RH:44 %)	Jenguma	W1=intermittent saturation (post flowering)	T16(E3V2W1)
		W2= field capacity	T17(E3V2W2)
		W3= post flowering drought	T18(E3V2W3)

3.3 Measurements and Data Collection

3.3.1 *Weather variables and soil water in growth chambers*

Weather data (temperature in ^{o}C and relative humidity in %) were measured in each of the growth chambers daily throughout the growth period using a combined temperature and humidity meter (BioTemp 1× 1.5 V AAA). The measurements were taken 5 times in a day (6 am, 9 am, 12 noon, 3 pm and 6 pm) and averaged to estimate minimum, maximum and mean temperatures and relative humidity.

The average temperatures and relative humidity in each of the growth chambers were used to estimate the vapour pressure deficit (VPD) as proposed by Berry *et al*. (1945):

$$VPD = \frac{100-RH}{100} \times SVP \qquad [3.1]$$

$$SVP = 610.7 \times 10 \frac{7.5T}{237+T} \qquad [3.2]$$

Soil water content was determined from the additions and intermittent weights of the pots. The water content values were converted to water stress factor, α, using equation (2.3).

3.3.2 *Determination of physical and chemical properties of soil*

Soils were collected from the field at 0-15 cm depths at random for physical and chemical characterization. Prior to their use for the study, their properties were determined.

3.3.2.1 Particle size distribution

The particle size distribution of the soil used was determined by Day's modified Bouyoucous hydrometer method. Forty grams (40 g) of air-dried sampled soil was sieved through a 2 mm sieve and weighed into a beaker to be analysed for clay, sand and silt content. The soil was transferred into dispersing bottle and 100 ml of 5 %

sodium hexametaphosphate (calgon) solution was added ensure dispersion. The suspension was shaken in a horizontal reciprocating shaker for 30 minutes.

After shaking, the suspension was transferred into a graduated sedimentation cylinder and made up to 1 Litre mark with distilled water. The suspension was allowed to equilibrate to room temperature for two hours.

A plunger was inserted into the sedimentation cylinder to thoroughly mix the contents and dislodge the particles at the bottom of the cylinder. A hydrometer was then inserted carefully into suspension and the first hydrometer reading was taken for (silt + clay fraction) after 5 minutes. After 5 hours, the second hydrometer reading was taken for only clay particles. To determine sand content, the suspension was then poured directly onto a 0.5 mm sieve and the residue retained on the sieve was washed thoroughly with water to remove remnants of silt or clay particles. The residue was transferred into a moisture can of known weight and dried in an oven at 105 ^{o}C for 24 hours. The dried residue was then weighed, and it represented the sand fraction of the sampled soil.

The particle size distribution for the sampled soil were then estimated using the following formulae;

$$\%\ \text{Clay} = \frac{\text{hydrometer reading at 5 hours}}{\text{Weight of soil(g)}} \times 100 \qquad [3.3a]$$

$$\%\ (\text{Silt}) = \frac{\text{hydrometer reading at 5 min} - \text{hydrometer reading at 5 hours}}{\text{Weight of soil(g)}} \times 100 \qquad [3.3b]$$

$$\%\ (\text{Silt \& Clay}) = \frac{\text{hydrometer reading at 5 min}}{\text{Weight of soil(g)}} \times 100 \qquad [3.3c]$$

$$\% \text{ (Sand)} = \frac{\text{Weight of oven−dried soil}}{\text{Weight of soil(g)}} \times 100 \qquad [3.3d]$$

Weight of soil= 40 g

Textural class was determined using the textural triangle as sandy clay.

3.3.2.2 Determination of bulk density

Three cylindrical cores (3 replicates) were inserted into the soil at a depth of 0-15 cm to sample undisturbed cores. The cores were weighed and dried in an oven at 105 °C for 24 hours. The oven dried mass (Ms) of the samples were also taken. The volume (Vt) of soil was determined by the product of the internal cross-sectional area and height (h) of soil cores. The bulk density was determined as:

$$\rho b = \frac{Ms}{Vt} \qquad [3.4]$$

3.3.2.3 Water relations

A large funnel was placed into a conical flask, and a No. 42 Whatman filter paper was folded into the funnels. Twenty-five (25 g) of soil sieved through 2 mm sieve was weighed and poured into the folded filter paper. One hundred ml of water was added to the soil in the filter paper and allowed to drain for about 20 mins. The water drained into the beaker was collected and subtracted from the water initially added. This was replicated three times and the average estimated. The water retained in the soil was taken as field capacity water. The experiment was repeated with no drainage allowed to estimate the saturated water content. For the permanent wilting point (PWP), the lowest water content determined at the end of the greenhouse experiment was taken as PWP.

3.3.2.4 Soil pH

Twenty grams (20 g) of the sampled soil (2 mm sieved) were weighed into a 50 mL beaker in three replications and 20 mL distilled water was added to make soil : water ratio of 1:1. The soil suspension was then stirred for 30 minutes and allowed to stand for one hour in order to allow the entire suspended particles to settle and also for the suspension to equilibrate with ambient temperature.

A glass electrode pH meter was standardized using two aqueous solutions of pH 4 and 10. The glass electrode was thoroughly rinsed with distilled water and then carefully immersed into the prepared suspension to measure the pH. The procedure was repeated for KCl extracted soil to determine potential acidity.

3.3.2.5 Soil Organic carbon

Organic carbon was determined by the wet combustion method of Walkley and Black (1934). Soil sample was sieved through a 0.5 mm sieve and 0.5 g of soil was weighed into a 500 mL conical flask.10 ml of 1M potassium dichromate ($K_2Cr_2O_7$) solution and 20 mL of concentrated sulphuric acid (H_2SO_4) were added to 0.5 g of soil in a conical flask and swirled 3 times before digesting for 30 minutes in a fume cupboard for oxidation reaction to be completed. Two hundred millilitres (200 mL) of distilled water was added to the conical flask after digestion to dilute the suspension.10 mL of orthophosphoric acid was added and 1 mL barium diphenylamine sulphonate was used as the indicator to a green end point. The solution after the digestion was titrated against 0.2 M ferrous ammonium sulphate which was acidified with 20 mL of sulphuric acid. Blank titration was also carried out in a similar manner.

The titre values were used to calculate the % C from:

$$\%\mathrm{C} = \frac{0.3[10-(\mathrm{XN})]\times 1.33}{\mathrm{W}} \times 100 \qquad [3.5]$$

where,

X = titre value of ferrous ammonium sulphate (mL),

N = Normality of ferrous ammonium sulphate of Fe $(NH_4)_2(SO_4)_2$,

W = weight of soil sample (g),

0.003= Milliequivalent weight of carbon (g),

0.3= 0.003 x 100 and,

1.33= the correction factor.

3.3.2.6 Exchangeable bases.

Five grams (5 g) of the soil samples (2 mm sieved) were weighed into 200 mL extraction bottles. 50 mL of 1N ammonium acetate (NH_4OAc) solution buffered at pH 7.0 was added. The bottles placed on a reciprocating shaker and shaken for 1 hour at 250 rpm. The soil suspension was then filtered through a No. 42 Whatman filter paper. The filtrates were used for the determination of Ca, Mg, K and Na.

A 5 ml aliquot of the filtrates was pipetted into 50 mL volumetric flask and made up to the mark with deionized water. The Perkin Elmer atomic absorption spectrometer (A Analyst 800) was calibrated with the appropriate standards for Ca, Mg and Na respectively and the absorbance for each element in the filtrate determined. Exchangeable bases were calculated as:

$$\text{Ca}\ (\text{cmol}_c\text{kg}^{-1}) = \frac{\text{R} \times \text{Vol.of extract} \times 10^3\ (\text{g}) \times 10^2 (\text{cmol}) \times \text{E}}{\text{Weight of soil} \times 10^6\ (\mu\text{g}) \times 40} \qquad [3.6]$$

where 40 = Atomic mass of Ca and

R = AAS (Atomic absorption spectroscopy) reading in mg L^{-1}

E = Charge of Ca

$$\mathrm{Mg}\ (\mathrm{cmol_c kg^{-1}}) = \frac{\mathrm{R} \times \mathrm{Vol.of\ extract} \times 10^{3}(\mathrm{g}) \times 10^{2}(\mathrm{cmol}) \times \mathrm{E}}{\mathrm{Weight\ of\ soil} \times 10^{6}(\mu\mathrm{g}) \times 24} \qquad [3.7]$$

where 24 = Atomic mass of Mg

R = AAS (Atomic absorption spectroscopy) reading in mg L^{-1}

E = Charge of Mg

$$\mathrm{Na}\ (\mathrm{cmol_c kg^{-1}}) = \frac{\mathrm{R} \times \mathrm{Vol.of\ extract} \times 10^{3}(\mathrm{g}) \times 10^{2}(\mathrm{cmol}) \times \mathrm{E}}{\mathrm{Weight\ of\ soil} \times 10^{6}(\mu\mathrm{g}) \times 23} \qquad [3.8]$$

where,

R = AAS (Atomic absorption spectroscopy) reading on mg L^{-1}

23 = atomic weight of Na

E = Charge of Na

The K content in the diluted soil extracts were measured with the standardized flame photometer. The flame photometer was standardized to give a 100 full scale deflection at 10 mg/kg of K. The values obtained were then used to calculate the amount of potassium contained in the soils as shown in the formula below:

$$\mathrm{K}\ (\mathrm{cmol_c kg^{-1}}) = \frac{\mathrm{R} \times \mathrm{Vol.of\ extract} \times 10^{3}(\mathrm{g}) \times 10^{2}(\mathrm{cmol}) \times \mathrm{E}}{\mathrm{Weight\ of\ soil} \times 10^{6}(\mu\mathrm{g}) \times 39.1} \qquad [3.9]$$

where,

R is the flame photometer reading (ppm)

39.1 = Atomic weight of K

E = Charge of K

3.3.2.7 Determination of Cation Exchange Capacity (CEC)

The soil residues after filtration in section 3.4.4.7 were immediately leached two times with 25 mL portions of methanol to wash off the excess ammonium into empty plastic bottles. The soils were leached again two times with 25 mL portions of acidified 1M KCl through a No. 42 Whatman filter paper into different plastic bottles. Each portion was added at a time and allowed to pass through, before adding the next portion. Five millilitres (5 mL) of the leachates were then pipetted and transferred into a Kjeldahl flask and 5 mL of 40 % NaOH was added and distilled. Five (5 mL) of 2 % boric acid to which about 2 drops of methyl red and methylene blue indicator had been added was added to the distillate in a conical flask. The distillates were then back titrated against 0.01 M HCl and the ammonium ion concentration in the filtrate was determined and the CEC of the soil in $\mathrm{cmol_c\,kg^{-1}}$ soil estimated.

3.3.3 *Plant data Collection*

3.3.3.1 Plant Development

The plant phenology was determined as the number of days for 50 % of the plants to reach a particular development stage. Observations were made on days to (i) 50 % emergence (ii) 50 % flowering, (iii) 50 % podding and (iv) 50 % physiological maturity.

Furthermore, data were also collected on the appearance rate of nodes and leaves on the plant and plant height. For these determinations, three pots from each treatment (making a total of 18 pots in each chamber) was tagged for data collection.

As indicated in section 2.2.1 (chapter 2), the time to reach each development stage was expressed as the Growing Day Degrees or cumulative thermal time TT, defined as

$$GDD = TT = (T_{av} - T_b)\, t \qquad [3.10]$$

Where Tav (^{o}C) = average daily temperature in a given chamber, Tb (^{o}C) = base temperature and,

t = time.

The value Tb =10 ^{o}C was taken from literature (Hundal *et al*., 2003). Also, because temperature in the chambers varied on daily basis, the cumulative thermal time Cum TT, which is the summation of TT, was accumulated on daily basis until the stage duration was complete.

3.3.3.2 Plant growth

Plants were harvested sequentially during the growth period. A total of 4 dry matter harvests were done at vegetative stage (28 DAE), flowering (35 DAE), pod formation (50 DAE) and at maturity.

For the first harvest, 4 pots per variety were harvested in each environment (growth chambers) at 28 days after planting, weighed to determine the fresh total biomass and thereafter separated into leaves, stems and roots. Dry matter was determined after oven drying for 3 days at 70 ^{o}C.

For the second harvest at flowering, 7 pots per variety were harvested from each growth chamber making a total of 14 pots per environment and 42 pots in all. The plants were separated into leaves, stem and roots (after the total fresh biomass was taken) to determine the fresh weights and the dry weights were determined after oven drying for 3 days at 70 ^{o}C. Following this harvest, the water treatments were imposed on the rest of the pots.

For the third harvest at the onset of podding, 3 plants per variety were harvested from each growth chamber representing 2 plants per each water treatment making a total of 6 plants per environment. The plants were separated into leaves, stem and roots to determine the fresh weights and the dry weights were determined after oven drying for 3 days at 70 °C.

At maturity, all the rest of the pots were harvested. Apart from the fresh and dry matter determination, additional data collected were yield parameters such as pod number, seed number and seed weight. The undamaged pods were detached from the plants and counted, manually threshed and the undamaged seeds counted after which the seeds were oven dried and the seed dry weight estimated.

3.4 Statistical Analysis

Experimental data were analysed with the Analysis of Variance (ANOVA) technique using GenStat statistical software (12th edition, 2009), and means were separated using the Duncan Multiple Range Test and compared at 5 % level of significance. Microsoft Excel (Office 2013) was used for data entry and graphical representation of data were with Sigma Plot (2006 version).

3.5 Modelling the effect of environmental factors on soybean growth and yield.

It is the major task of this study to quantitatively assess the effect of temperature and water variability on soybean growth. This would require, apart from statistical analysis, also a description of the growth dynamics. Several crop models e.g. DSSAT describe the response of crops to these environmental variables. Yet their application to the screen-house study may be limited, especially where data such as radiation were not measured.

Therefore, we employed simple logistics equation to describe the daily growth rate as:

$$\frac{dG}{dt} = k \times G\left(1 - \frac{G}{G_{max}}\right) \qquad [3.11]$$

where *G* (g/plant) is the growth variable, *t* is time (day), *k* is the growth rate constant (g/g/d), G_{max} is the maximum growth rate.

Adiku *et al*. (2001) employed this type of equation to describe the growth of phaseolus beans under salinity stress conditions. For this, they introduced a salinity stress factor similar to water stress. Following this approach, two stress factors are coupled with equation (3.11); one for temperature stress and another for water stress, to give:

$$\frac{dG}{dt} = k \times G\left(1 - \frac{G}{G_{max}}\right) \times \alpha_T \times \alpha_W \qquad [3.12]$$

The formulations of α_T (temperature stress) and α_w (water stress) were given in equation 2.2 and 2.3 respectively. Using literature values for Tb, Topt and Tmax, a quadratic curve for temperature stress was derived. Similarly using the values of field capacity, wilting point and saturation water content, the water stress equations could be parameterized.

Using a simple numerical procedure, the cumulative growth over time could be determined as:

$$G_t = G_{t-1} + \frac{dG}{dt} \times dt \qquad [3.13]$$

where G_{t-1} was the growth at the time t-1 and $\frac{dG}{dt} \times dt$ gives the daily increment in growth after discounting with water and temperature stress effects.

The simulated growth of soybean under the environments and water treatments were compared with the observed. The agreement between the predicted and observed was judged based on the coefficient of determination (R^2) and the Willmott (1981) d – index.

CHAPTER FOUR

4 RESULTS

4.1 Characterization of the soil used

Table 4.1 describes the physical and chemical properties of the soil used for the experiment. The soil was classified as sandy clay with sand, clay and silt composition of 52.77 %, 24.20 % and 23.03 % respectively (Table 4.1). The sand composition of the soil was quite high which is possibly due to the inflow of water depositing sand and silt from the Volta riverbank close to the site and also loss of clay particles into the river due to runoff. The bulk density of the soil in each pot was estimated to be 1.34 Mg/m^3.

The soil had a pH value of 7.33 in water and 6.84 in 0.1 M KCl, which can be described as neutral and near neutral tending towards alkalinity. The organic carbon of the soil was 1.27 g/kg which is relatively low. Exchangeable bases were determined with Mg^{2+} and Ca^{2+} being dominant with values of 18.18 and 14.43 cmol$_c$/kg respectively while Na^+ was 10 cmol$_c$/kg and K^+ being the least with value of 0.19 cmol$_c$/kg. Though N and P were not determined, data by Koomson, (2013) who worked with similar soils reported about 0.06% and 5 Mg/kg of N and P respectively. Though this can be considered relatively low, the crops did not show drastic reduction in growth. Furthermore, as a legume, the soybean plants produced nodules and there were no visible chlorosis or N-deficiency symptoms during the experiment.

Table 4. 1:Physical and chemical properties of the soil used

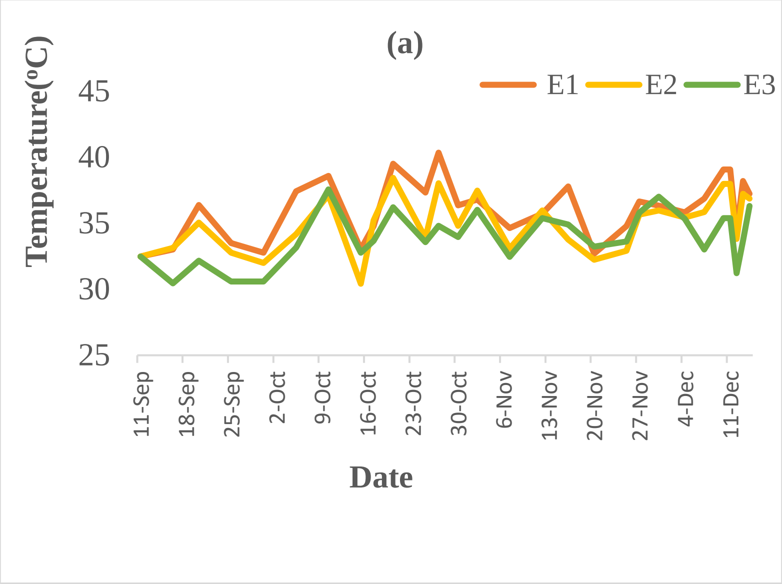
Parameters	Soil properties
pH (H_20)	7.33
pH (KCl)	6.84
Organic Carbon (g/kg)	12.7
Ca^{2+} ($cmol_c$/kg)	14.43
Mg^{2+} ($cmol_c$/kg)	18.18
Na^{+} ($cmol_c$/kg)	10
K^{+} ($cmol_c$/kg)	0.19
CEC ($cmol_c$/kg)	35.1
Bulk density (Mg/m^3)	1.34
Sand (%)	52.77
Clay (%)	24.20
Silt (%)	23.03
Textural Class	Sandy clay

4.2 Environmental Conditions during the Experiment

4.2.1 *Temperature*

The daily temperature patterns throughout the duration of the experiment (September to December 2018) for the three growth chambers are shown in Figure 4.1. The maximum and minimum temperatures were 41 and 29.7 ^oC, 38 and 29.6 ^oC, 37.5 and 29.1 ^oC for E1, E2 and E3 respectively. The average temperatures for each of the environments, E1, E2 and E3 were 36 ^oC, 34 ^oC and 33 ^oC respectively. Environment one (E1) had the highest maximum and mean temperatures followed by E2 and E3 having the least maximum and mean temperatures. The minimum temperatures for all the environments (E1, E2, and E3) were similar.

The highest temperatures coincided with the flowering stage in E1, while E2 and E3 had the highest temperature occurring at maturity as shown in Fig 4.2. E1 had the highest temperature during the various developmental stages of the crop. Throughout the duration of the experiment, the highest temperatures were recorded during flowering (R1) stage and the maturity (R5-R7) stage.



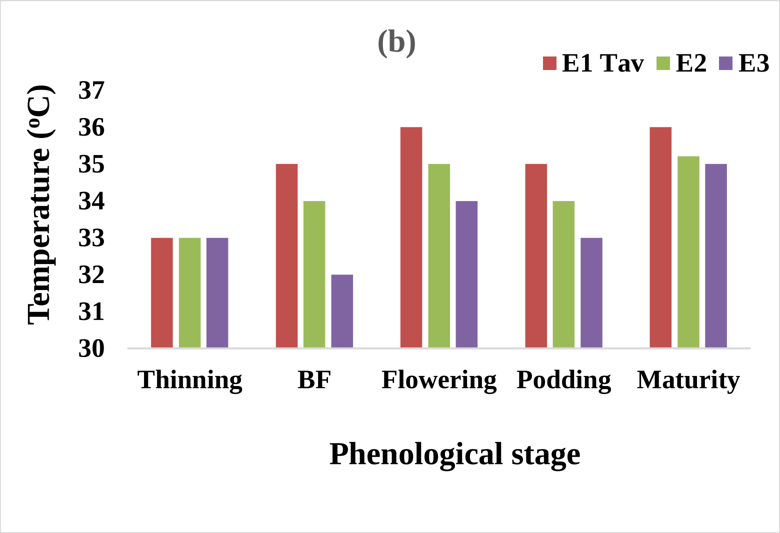


Fig.4. 1 (a) Temperature (ºC) in the growth chambers throughout the duration of the experiment and (b) daily average temperature at each phenological stage

4.2.2 *Relative Humidity (RH)*

Relative humidity is a measure, in percentage, of the water vapour in the air compared to the total amount of water vapour that the air can hold at a given temperature. The patterns of RH varied throughout the duration of the experiment for the three growth chambers (Figure 4.2). There was a general trend of RH decreasing from the beginning of the experiment to the end. The mean relative humidity for the three environments E1, E2 and E3 were 54, 57 and 44 % respectively. E2 had the highest RH value while E3 had the lowest RH value. E1 had an average maximum daily RH of 68 % and an average minimum RH of 34 % which occurred in September and October respectively. E2 had an average maximum daily RH of 70 % and an average minimum daily RH value of 45 % which both occurred in September. E3 had an average daily RH of 57 % and an average minimum daily RH value of 30 % which occurred in September and December respectively.

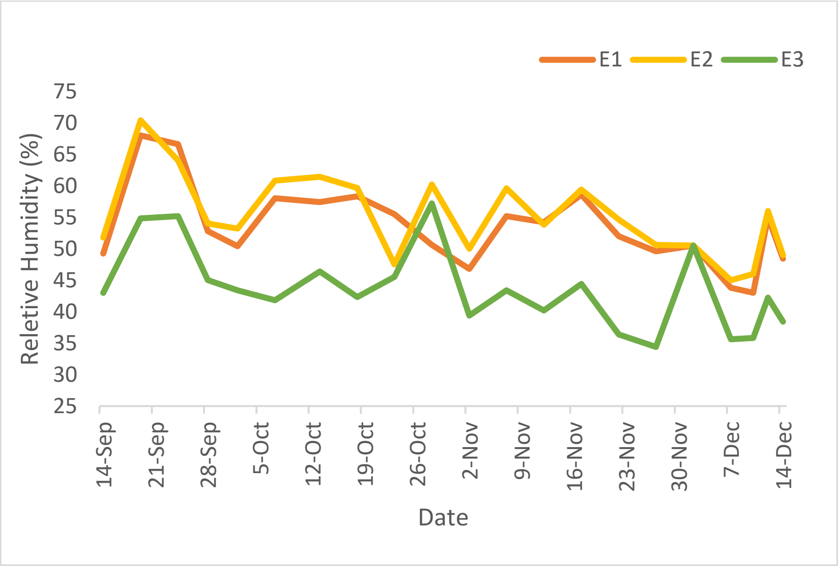


Fig. 4.2: Relative humidity (%) in the growth chambers during the experiment

4.2.3 *Vapour Pressure Deficit (VPD)*

The average Vapour Pressure Deficit (VPD) on a daily basis was 2.7, 2.5 and 3.0 kPa for E1, E2 and E3 respectively. Fig. 4.4 shows that E3 had the highest VPD which is due to the consistently low RH, followed by E1 and E2. For the duration of the experiment, the maximum VPD occurred during the month of December with an average of 3.3, 3.0 and 3.3 kPa while the minimum VPD occurred during the month of September with average VPD of 2.4, 2.3, 2.5 kPa for E1, E2 and E3 respectively. It is worthy of note to mention that temperature and RH significantly influence VPD which is largely responsible for the differences in VPD observed.

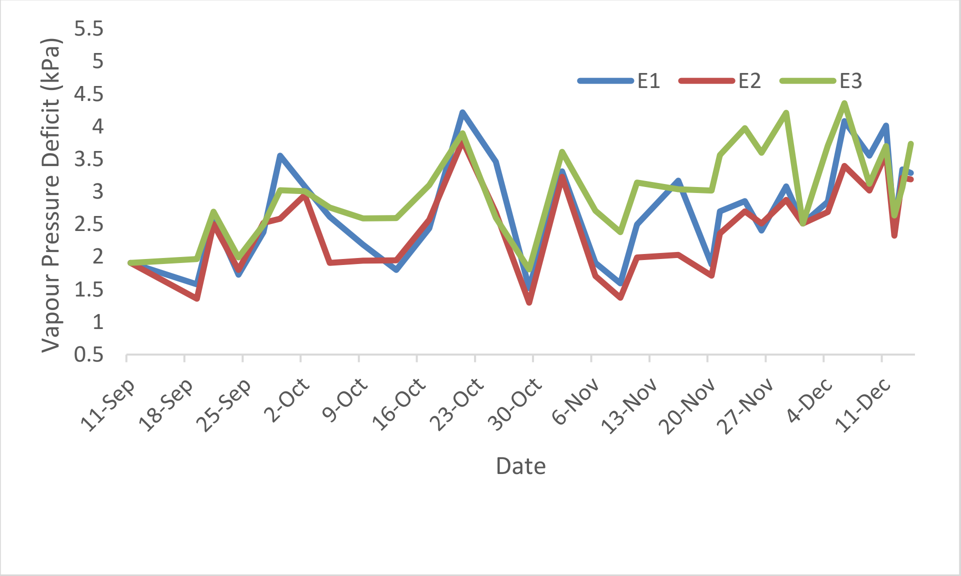


Fig. 4.3: Vapour Pressure Deficit (kPa) in the growth chambers during the experiment

Table 4.2 shows that the air temperatures were generally high in all the growth chambers for the duration of the experiment. Even though there were daily fluctuations, this temperature factor influenced the daily relative humidity which were relatively low during the day in all the growth chambers, particularly between the hours of 9 am -3 pm.

Table 4.2: Temperature, RH and VPD ranges for the duration of the experiment

Environment	Date/ DAE	T (°C)	RH (%)	VPD (kPa)
E1	September (0-32)	32-39	49-68	1.6-3.6
	October (33-63)	30-41	34-67	1.5-4.2
	November (64-93)	30-38	48-63	1.6-3.3
	December (94-110)	33-39	43-52	2.5-4.1
E2	September (0-32)	32-38	45-70	1.4-3.1
	October (33-63)	30-39	47-70	1.7-3.8
	November (64-93)	30-37	48-65	1.4-3.2
	December (94-110)	33-38	46-54	2.5-3.6
E3	September (0-32)	30-35	43-58	1.9-3.3
	October (33-63)	29-38	38-57	2.0-3.9
	November (64-93)	30-38	33-46	2.4-4.2
	December (94-110)	31-37	36-51	2.5-4.4

4.2.4 *Soil water and evapotranspiration*

Water was maintained in the pots of all three growth chambers at field capacity till the onset of flowering when different watering regimes were imposed as shown in Fig.4.4. W1 (intermittent saturation) had the highest water content followed by W2 (field capacity) and W3 (drought). For the three environments, the cumulative evapotranspiration (ET) varied being 224, 208 and 185 mm for E1, E2 and E3, respectively. This implies that despite the higher VPD for E3, E1 (with the highest temperature) still had the highest cumulative ET.

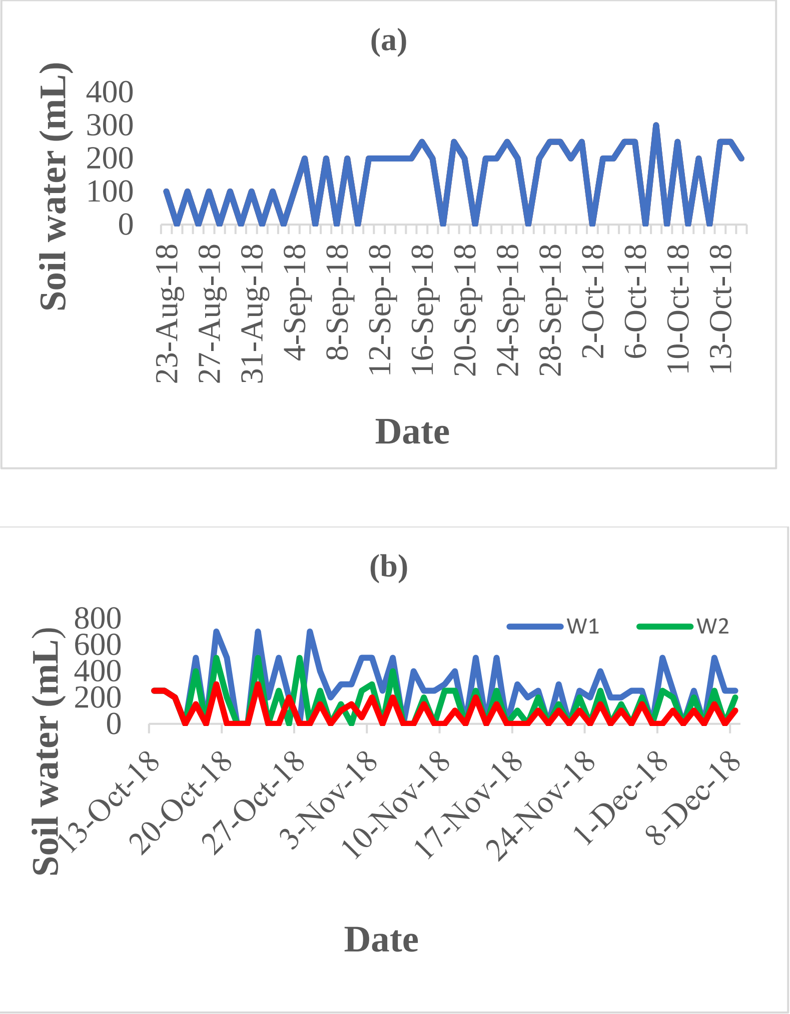


Fig. 4.4: (a) Water application before flowering (b) water treatment application after flowering. W1- near saturation, W2- Field capacity, W3 – drought (water stressed)

4.3 Plant Development

4.3.1 *Phenology*

Plant emergence was observed for both varieties by the second and third day after planting with Jenguma having about 42 pots emerged while Afayak had only about 20 pots emerged out of 84 pots sowed for each variety. Fifty (50) % emergence for the two varieties, Afayak and Jenguma occurred at 4 and 3 Days After planting (DAP) respectively.

In E1, it took Afayak 37 DAE to attain 50 % flowering while Jenguma delayed by 2 days reaching 50 % flowering at 39 DAE (Table 4.3). In E2, it took Afayak and Jenguma, 38 DAE and 40 DAE respectively to attain 50 % flowering, while it took Afayak 40 DAE and Jenguma 41 DAE to attain 50 % flowering in E3. In all the environments, Afayak had a shorter time to flowering as compared to Jenguma variety. This differences in time to attain 50 % flowering between the three environments may be largely due to differences in temperature.

Afayak attained 50 % podding at 48 DAE, 50 DAE & 50 DAE in E1, E2 and E3 respectively, while Jenguma attained 50 % podding at 52 DAE in all three environments. Table 4.3 shows a summary of the plant development. Across the three environments, Afayak had the shortest time to flowering at 37 DAE in E1, 38 DAE in E2 and 40 DAE in E3. Afayak attained podding at 48 DAE in E1 and 50 DAE in both E2 and E3, while there were no differences observed in podding date for Jenguma (52 DAE) in all the three environments.

In terms of thermal time, there were no differences in flowering time. Afayak accumulated a total of 894, 895 and 893 ^{o}Cd respectively, for E1, E2 and E3 (Table 4.3). Similarly, Jenguma accumulated 928, 935 and 913 ^{o}Cd for E1, E2 and E3, respectively. Thus, plants in E1 took less days to attain the same thermal time than the cooler environment E3. In the case of podding and maturity, the imposition of water treatments appeared to distort the trend.

4.3.2 *Plant Height*

Both varieties as expected, showed obvious increase in plant height with time (Days after Emergence) with Afayak (V1) having mean heights of 41, 38, and 36 cm at 48 DAE in E1, E2, and E3 respectively while Jenguma (V2) had mean heights of 40, 37 and 35 cm at 51 DAE in E1, E2, and E3 respectively (Fig. 4.5). Both varieties (Afayak and Jenguma) had the highest mean heights in E1 with Afayak showing a rapid increase in plant height at increased temperature.

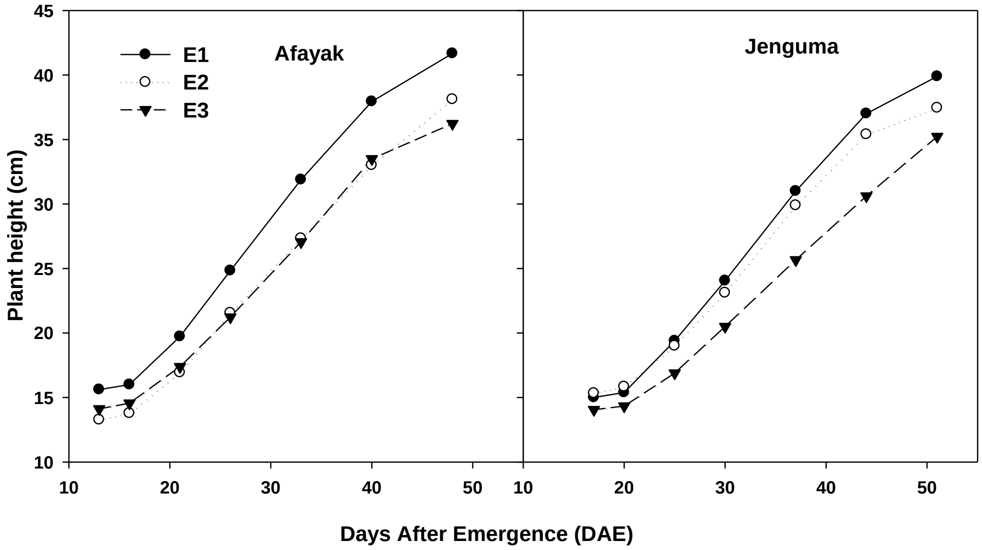


Fig.4.5: Differences in plant height of the two varieties under varying environment. (E1:36°C, RH: 55 %, E2: 34°C, RH: 57 % and E3: 33°C, RH: 44 %)

Table 4.3: Chronological days and thermal time for the developmental stages

		Flowering		Podding		Maturity	
Environment	Variety	CT(DAE)	TT(^{O}Cd)	CT(DAE)	TT(^{O}Cd)	CT(DAE)	TT(^{O}Cd)
E1 (36^{o}C)	Afayak	37	894	48	1176	97	2416
E2 (34^{o}C)	Afayak	38	895	50	1194	104	2530
E3 (33 ^{o}C)	Afayak	40	893	50	1134	97	2271
E1 (36 ^{o}C)	Jenguma	39	928	52	1265	101	2506
E2 (34^{o}C)	Jenguma	40	935	52	1234	101	2429
E3 (33 ^{o}C)	Jenguma	41	913	52	1174	101	2360

CT: Chronological time, TT: Thermal time, DAE: Days after emergence

4.3.3 *Number of Nodes*

Environment E1 had the highest rate of node appearance with about 10 nodes formed by 48 DAE and 50 DAE for Afayak and Jenguma respectively. E1 (highest temperature) showed an initial rapid rate of node appearance as compared to the other environments, E2 and E3 (Fig. 4.5). Soybean variety (Afayak) showed greater sensitivity to increasing air temperature in the chamber (E1) as the rate of node appearance was faster as compared to the other environments, this implies that high temperatures in E1 enhanced faster production of leaves. Jenguma showed little or no difference in the number of nodes formed in all three environments before flowering. Jenguma had a total number of nodes of 10 for all three environments. E1 and E2 which had mean temperatures of 36 °C and 34 °C respectively had higher rates of node appearance while E3, with the least mean temperatures of 33 °C had a lower initial rate of node appearance. Although there was no difference in the total number of nodes formed for both varieties in all three environments, the rate of node appearance differed.

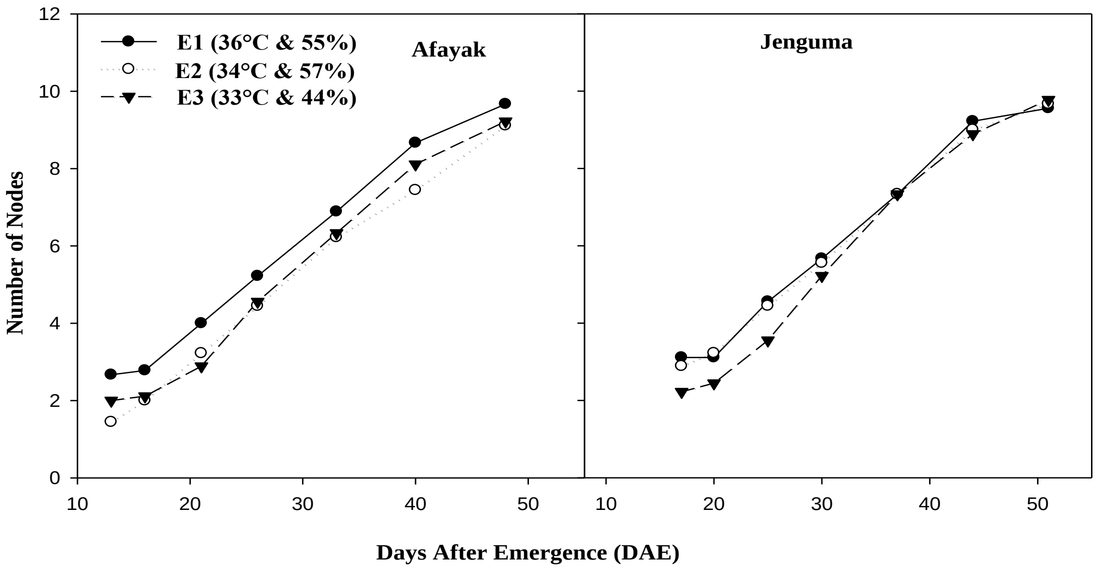


Fig. 4.6: Differences in node appearance of the two varieties under varying environment (E1: 36°C, RH:55 %, E2: 34°C, RH: 57 % and E3: 33°C, RH: 44 %).

4.3.4 *Number of Leaves*

The total number of leaves for Afayak in E1, E2 and E3 were 35, 25 and 32 respectively at 50 DAE, while Jenguma had 37, 35 and 41 for E1, E2 and E3 respectively. E1 had the highest number of leaves for Afayak while E3 had the highest number of leaves for Jenguma. Both Afayak and Jenguma had the lowest number of leaves in E2.

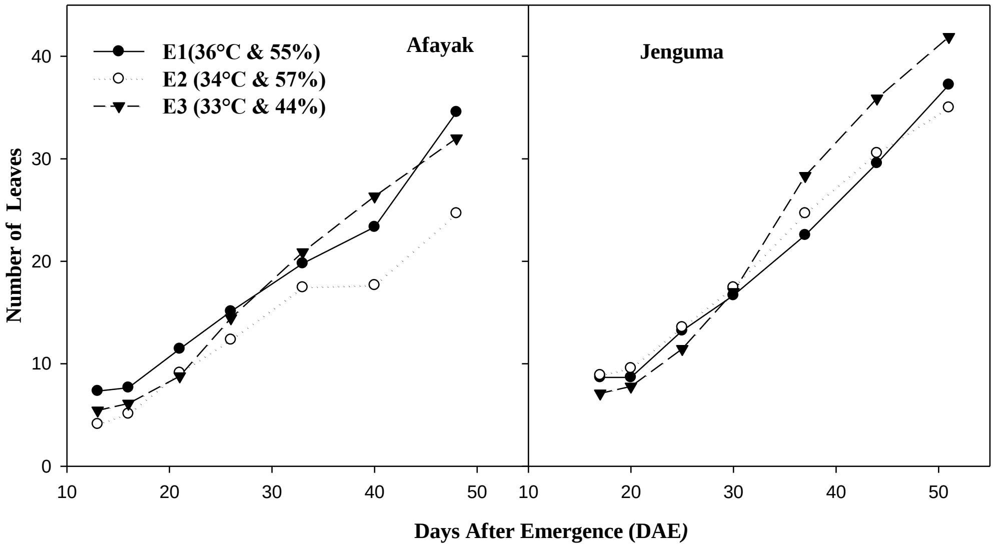


Fig.4.7: Environmental differences in number of leaves of the two varieties

4.4 Plant Growth

4.4.1 *Vegetative Stage*

The mean total dry biomass weight (TDW) at the end of the vegetative stage was highest in E2 with a mean weight value of 2.39 g/plant while E1 had the least mean weight of 1.51 g/plant (Table 4.4). Total dry weight of biomass in E1 was significantly different from those from the other two environments but there was no statistical difference between those from E2 and E3. Both varieties showed different responses to the varied environment treatments with Afayak having its highest total dry biomass weight of 2.18 g/plant in E2 which was significantly different from E1 but not statistically different from E3, while Jenguma had its highest total biomass weight of 2.82 g/plant in E3, however no significant difference exist among the environments. Jenguma generally had higher total dry biomass weight that was significantly different from Afayak in both E1 and E3, but no significant differences existed between the varieties in E2.

Table 4.4: Effect of environment on plant biomass production at the vegetative stage

Environment	Variety	TDW (g/plant)	DLW (g/plant)	DSW (g/plant)	DRW (g/plant)
E1 (36 °C)	Afayak	0.85	0.63	0.30	0.05
E2 (34 °C)	Afayak	2.18	1.20	0.65	0.10
E3 (33 °C)	Afayak	1.83	0.95	0.55	0.08
E1 (36 °C)	Jenguma	2.17	1.38	0.85	0.13
E2 (34 °C)	Jenguma	2.60	1.23	0.90	0.10
E3 (33 °C)	Jenguma	2.82	1.15	0.93	0.13
Lsd (0.05)	Envt	0.67	0.32	0.22	0.06
	Var	0.61	0.40	0.18	0.05
	Envt* Var	0.95	0.55	0.31	0.08

TDW: Total dry weight, DLW: Dry leaf weight, DSW: Dry stem weight, DRW: Dry root weight. Variety 1: Afayak, Variety 2: Jenguma.

4.4.2 *Flowering stage*

The Afayak variety had mean total dry biomass weights of 4.01, 3.52 and 5.22 g/plant in E1, E2 and E3 respectively (Table 4.5). Environment E3 had the highest mean weights which was significantly higher than E1and E2 but no significant differences between E1 and E2. For Jenguma, E3 also had the highest total dry biomass weight of 6.04 g/plant which was significantly higher than E1 but not significantly different from E2. However, there was no significant difference between plant growth in environments E1 and E2.

Table 4.5: Effect of environment on plant biomass weight at flowering

Environment	Variety	TDW (g/plant)	DLW (g/plant)	DSW (g/plant)	DRW (g/plant)
E1 (36 °C)	Afayak	4.01	1.60	1.53	0.49
E2 (34 °C)	Afayak	3.52	1.34	1.45	0.44
E3 (33 °C)	Afayak	5.22	2.12	1.98	0.65
E1 (36 °C)	Jenguma	4.69	2.04	1.88	0.45
E2 (34 °C)	Jenguma	5.06	2.13	2.16	0.58
E3 (33 °C)	Jenguma	6.04	2.29	2.12	0.59
lsd (0.05)	Envt	0.95	0.43	0.49	0.11
	Var	0.65	0.32	0.28	0.10
	Envt* Var	1.18	0.55	0.57	0.16

TDW: Total dry weight, DLW: Dry leaf weight, DSW: Dry stem weight, DRW: Dry root weight.

Variety 1: Afayak, Variety 2: Jenguma.

There were significant differences between the total dry weight, dry leaf weight, dry stem weight and dry root weights of two varieties with Jenguma being significantly higher than Afayak. Total dry biomass weights of the Afayak variety at flowering from E1 and E2 were statistically lower than total dry biomass weight from E3 and the total biomass weight from E3 was significantly higher than E1 and E2. However, there was no significant differences between the means of the total dry biomass weights of E1 and E2.

Environment E2 had the lowest dry leaf weights (DLW) of 1.34 g/plant for Afayak variety while E3 had the highest DLW of 2.12 g/plant. Although E2 had higher mean dry leaf weight than E1, there was no significant differences between both environments. However, DLW under E3 was significantly different from the other environments. For Jenguma variety, E1 had the lowest mean dry leaf weights while E3 had the highest mean dry leaf weights. There were no significant differences among the weights of the three environments. The Jenguma variety had a higher dry leaf weight than Afayak in all three environments. In both E1 and E2, Jenguma was significantly different from Afayak with Jenguma having a higher mean weight whereas in E3, there was no significant difference between both varieties. At the lowest temperature environment, the mean dry leaf weights were statistically higher than those in the higher temperature environments (E1 and E2). Even though, the leaf dry weight of the plants in E1 was higher than that of E2, the difference was not significant.

The dry stem weight was highest at E3 and lowest at E2 with mean dry weights of 1.98 and 1.45 g/plant respectively for Afayak variety. Stem dry weight under E3 was significantly higher than those of E1 and E2. However, there were no significant differences in stem dry weights from E1 and E2. For Jenguma variety, the mean weight was highest at E2 and lowest at E1, but not statistically different mean stem dry weights were measured among the environments. Dry stem weight of Jenguma was statistically higher than Afayak in all the environment treatment except in E3. Even though E3 recorded the highest mean dry stem weight, it was not significantly different from those from the other two environments. This implies that the environment treatment did not have a significant effect on stem weight of Jenguma variety.

The highest root dry weights (RDW) for both varieties were produced under E3. The RDW under E3 were significantly higher than those under E1 for both varieties. For the Afayak variety, RDW were similar under E1 and E2. For the Jenguma variety, RDW were similar under E2 and E3.

4.4.3 *Podding*

For both varieties, the highest total dry biomass during podding was observed in E3 while the lowest for Afayak was observed in E2 as shown in Fig. 4.8. For Jenguma variety, total dry biomass weights increased with reducing temperature but for Afayak variety, total dry biomass was lowest in E2 as compared to the other environments at podding.

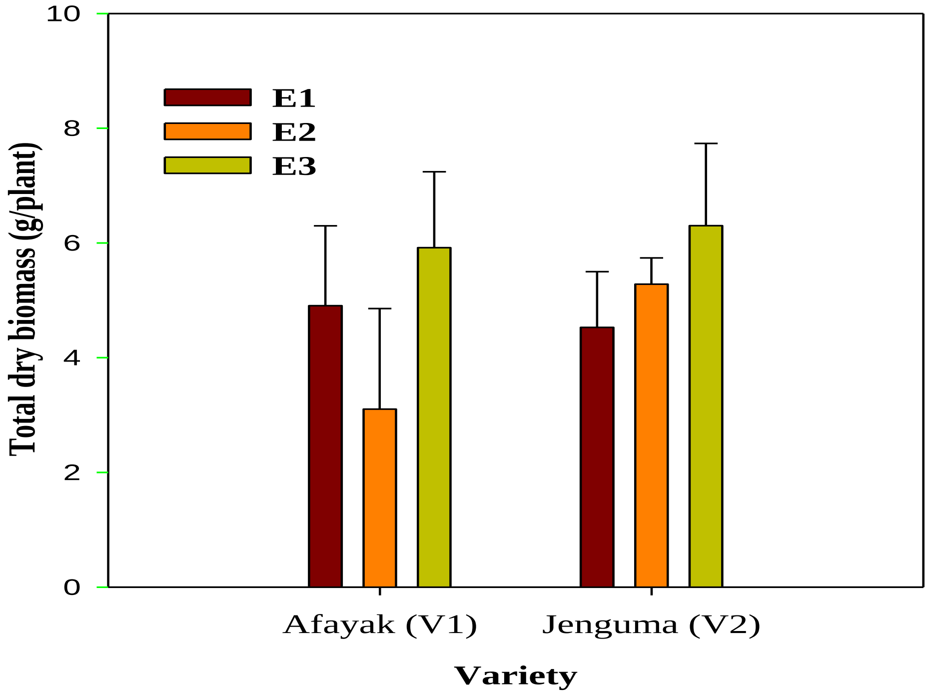


Fig. 4.8: Effect of environment on total dry biomass at podding. The error bars standard errors of the mean

4.4.4 *Biomass accumulation patterns*

Fig 4.9 shows a general increase in biomass accumulation as development stages progressed under each temperature environment for each variety. Environment E3 showed a continuous increase in biomass after flowering for both varieties while Afayak and Jenguma showed a sharp decline in biomass in E2 and E1 respectively. In other words, increasing temperature treatment led to a decline in biomass accumulation for both varieties.

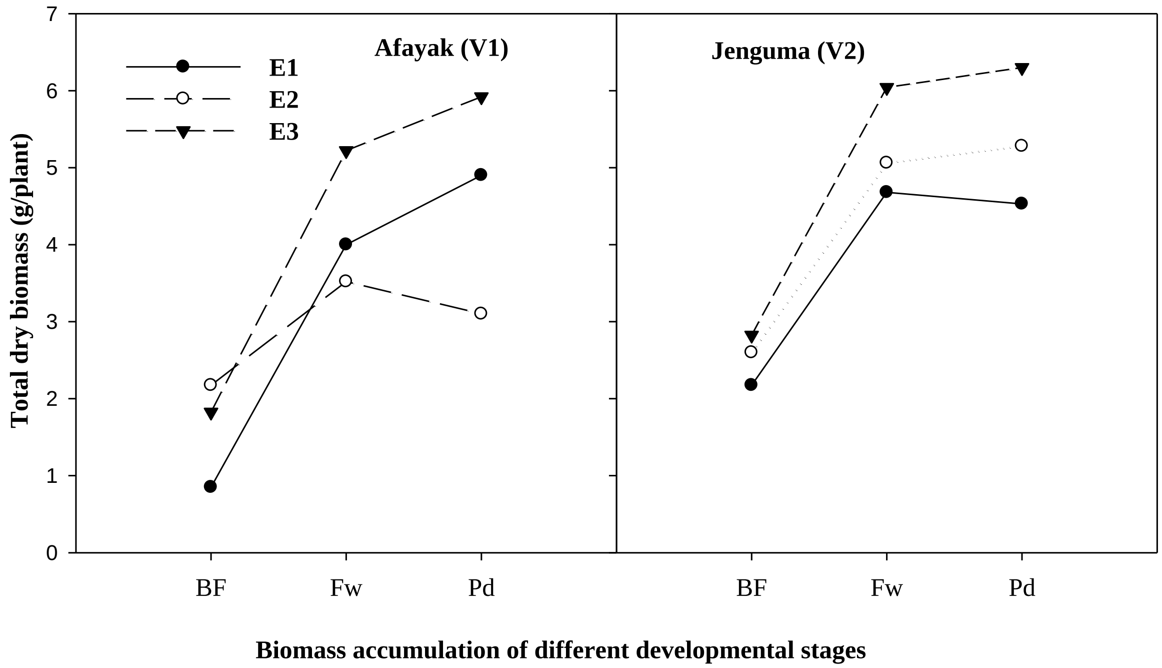


Fig. 4.9: Effect of environment on plant biomass accumulation at different developmental stages (BF; before flowering, Fw; flowering, Pd; podding)

4.5 Plant Yield

4.5.1 *Pod weight*

Figure 4.10a show the effect of water treatments on pod weights under varied temperature environment. The water treatment W3 (drought), had the lowest mean pod weights of 1.29, 1.54 and 3.35 g/plant for E1, E2 and E3 respectively, while W1 (near saturation) had the highest mean pod weight. W1 had the highest mean pod weight in all three environments. Means of the pod weights from treatment W1 were different among the environments with E1 having the lowest mean pod weight which is statistically different from the means of E2 and E3. The combined effect of increased temperature and water deficit had a significant effect on pod weights with W3 in E1 recording the lowest pod weight. Fig.4.10a shows that in all three environments, W3 had the lowest mean pod weight. The drought treatment was most severe on mean pod weight under E1 and least under E3. Pod weight increased as water content increased under reducing temperature.

The mean pod weight of the two varieties increased as temperature declined (Fig. 4.10b). Figure 4.10b shows that for Afayak, pod weight increases from 3.74 g/plant in E1 to 4.34 g/plant in E3 while for Jenguma, there was also a significant increase in pod weights from 3.51 g/plant in E1 to 4.94 g/plant in E3. Although for Afayak, the increase was not significant, for Jenguma, difference in the mean pod weights between E1 and E2 was not significant but that under E3 was significantly higher than the other two environments.

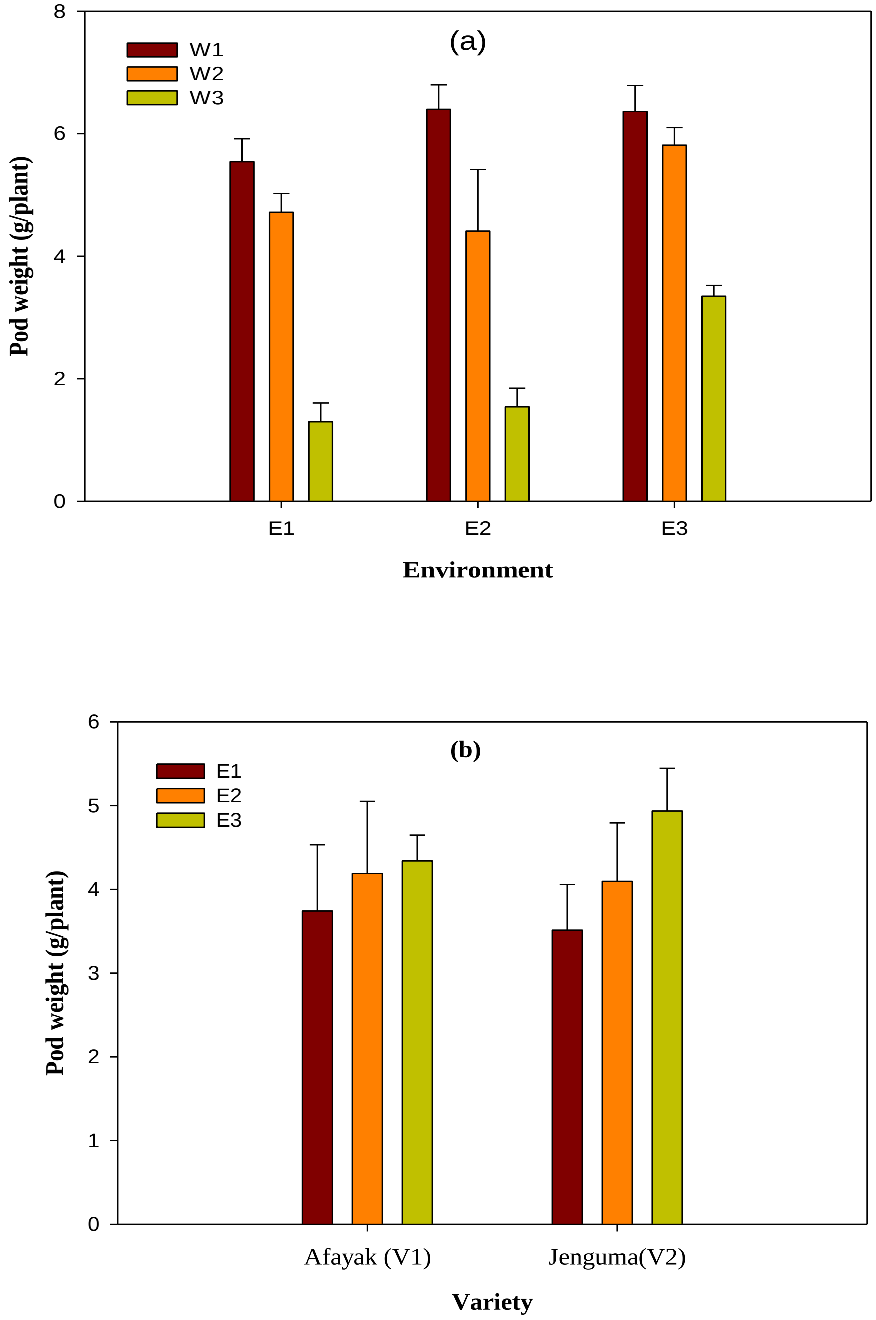


Fig.4.10: (a) Combined effect of environment and different water regimes on pod weight and (b) effect of environment on pod weight of the two varieties (E1: 36°C & RH - 55 %, E2: 34°C & RH - 57 % and E3: 33°C & RH - 44 %. W1, W2, W3 are near saturation, field capacity and drought respectively. The vertical bars are standard errors of the means).

4.5.2 *Seed weight*

The effects of environments (temperature) and water management on dry weight of seed are illustrated in Fig. 4.11. W1 had significantly higher yield than W2 and W3 in all the environment treatments with E3 having the highest dry seed weight as shown in Fig. 4.11a. W3 had the least dry seed weight in all the environment treatments with E1 and E2 being statistically different from E3. However, there was no statistical difference between E1 and E2. Environment had significant effect on dry seed weight of both varieties as shown in Fig.4.11b, with increased dry seed weight with reduced temperature. Although for Afayak, there was no significant difference between E1 and E2, E3 was significantly higher than the other two environment treatments which implies that grain yield is negatively affected by high temperatures. A similar trend was also observed for Jenguma. However, Jenguma had significantly higher yield than Afayak in E3.

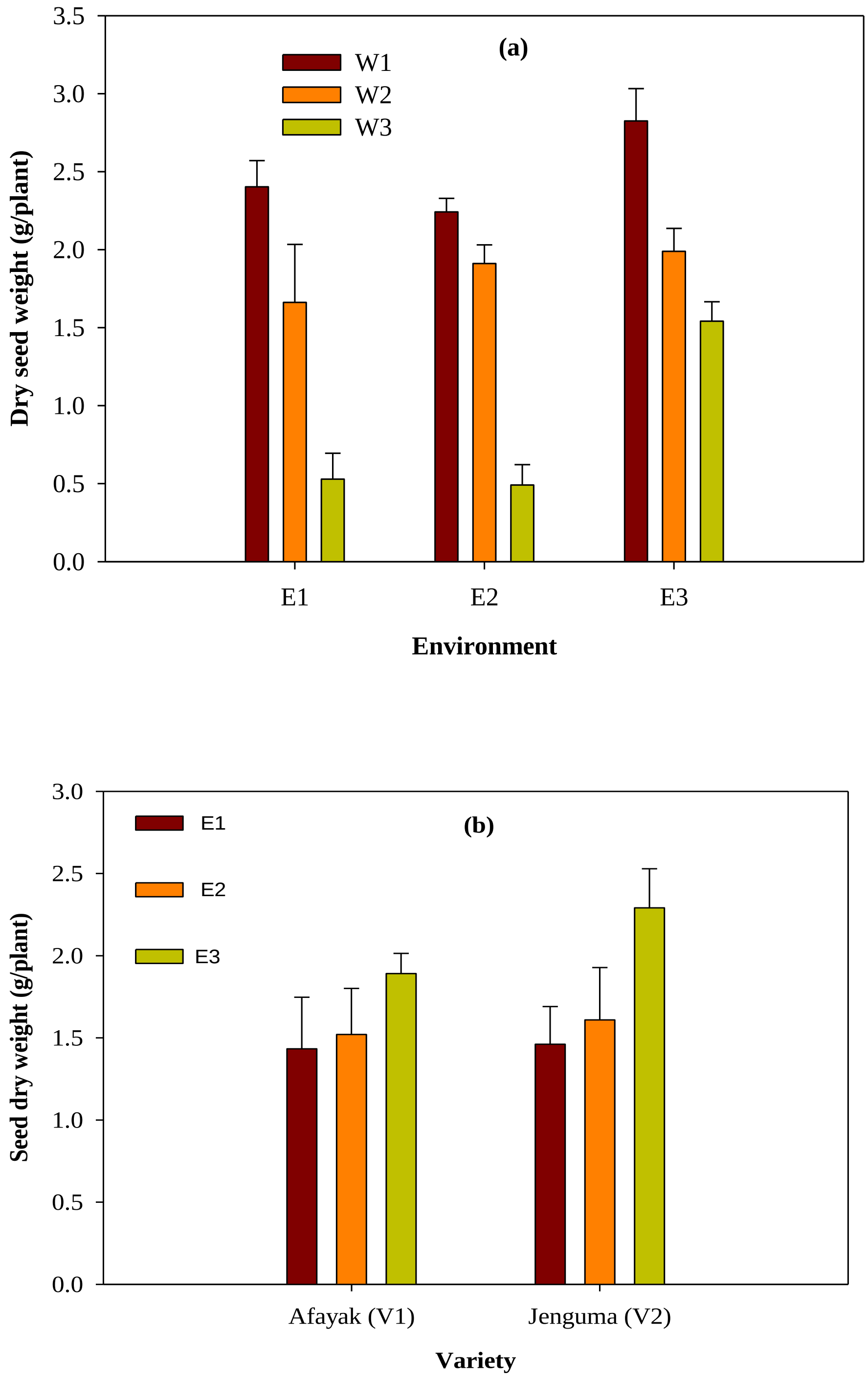


Fig.4.11: (a) Combined effect of environment and water treatments on dry seed weight and (b) effect of environment on dry seed weight of both varieties (W1, W2, W3 are near saturation, field capacity and water stress (drought) respectively).

Table 4.6 shows that among the three environments, W1 had the highest mean dry seed weight of 2.72 g/plant in E3 but it was not statistically different from those obtained from E1 and E2 (2.27 and 2.43 g/plant respectively). A similar trend was observed for W2. In the case of W3 (drought), there was no significance difference between the mean seed weights of E1 and E2 but seed weights under E3 was statistically higher than those under E1 and E2.

The interactive effect of environment and drought treatment (W3) was most severe in E1 and E2 giving relatively lower mean grain yield of 0.45 and 0.53 g/plant within each environment as compared to E3 which had mean weight of 1.54 g/plant. Also, both varieties differed statistically in their responses to drought in both E1 and E2 with Jenguma significantly higher than Afayak in E1, but reverse occurred in E2 while for E3, there was no statistical difference in their response to drought.

In E1, there was no significant difference in the dry seed weights between W1 and W2 but both W1 and W2 was significantly different from mean weights of W3. Similarly, under E3, W1 is statistically different from W3 but not different from W2. However, in E2, there was significant differences among the three water treatments.

The interactive effect of increasing temperature and drought led to significantly low pod weight. W3 (drought) had the lowest pod weights among the water treatments in all three environments with E1and E2 having mean weights of 1.22 and 1.54 g/plant respectively which were significantly lower than pod weights obtained in E3 of 3.34 g/plant.

In E1, there was no significant difference in pod weights between W1 and W2 but W3 was significantly lower than both W1and W2. There were significant differences in pod weights among the water treatments under both E2 and E3.

Table 4.6: Effects of Environment and water as well as their interaction on seed weight and pod weight showing varietal differences

Environment	Water	Variety	Dry Seed weight (g/plant)	Pod weight (g/plant)
E1 (36 °C)	1	1	2.39 cd	6.21 efg
	1	2	2.14 bcd	5.09 defg
	2	1	1.83 bc	4.65 def
	2	2	1.99 bcd	4.78 defg
	3	1	0.27 a	0.88 a
	3	2	0.63 a	1.55 ab
E2(34 °C)	1	1	2.20 bcd	6.22 efg
	1	2	2.66 de	6.62 fg
	2	1	1.51 b	4.61 de
	2	2	1.76 bc	4.29 de
	3	1	0.68 a	1.75 abc
	3	2	0.38 a	1.33 a
E3 (33 °C)	1	1	2.29 bcd	5.71 efg
	1	2	3.15 e	6.76 g
	2	1	1.96 bcd	4.43 de
	2	2	2.03bcd	4.36 de
	3	1	1.59 bc	3.43 cd
	3	2	1.49 b	3.24 bcd
`L.S.D (0.05)	Envt		0.28	0.70
	Water		0.28	0.70
	Variety		0.23	0.57
	Envt*Water		0.48	1.22
	Envt*Variety		0.40	0.99
	Water* Variety		0.40	0.99
	Envt*Water*Variety		0.68	1.72

Common letters are not significantly different ($p<0.05$) according to Duncan multiple range test.

4.6 Modelling Soybean growth under extreme Temperature and Water stress Conditions

4.6.1 *Temperature stress conditions*

Figure 4.12 shows the temperature stress function derived in this study. As explained in Chapter 3 (3.5), the description of temperature effect on plant growth often follows a quadratic function, with zero growth when temperatures are below the base temperature (Tb), maximum growth at optimum temperature (Topt) and zero growth above a maximum temperature (T max). For soybean, the literature indicated that Tb = 10 °C (Hundal *et al.*, 2003), Topt was 25 °C and Tmax = 39 °C (Boote *et al.*, 2005). Using these cardinal temperatures, the temperature stress function gave the relation:

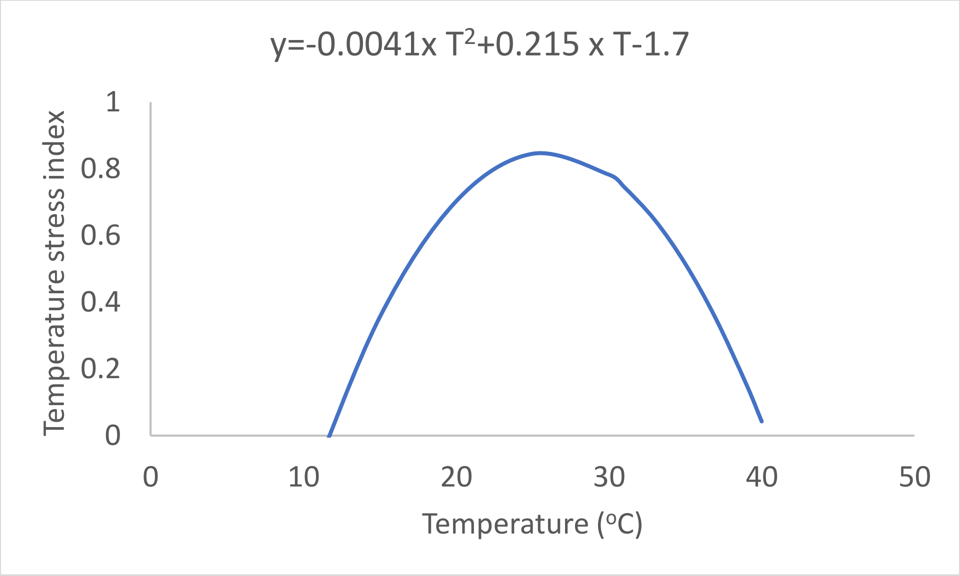


Fig.4.12: Relationship between temperature stress factor and environmental temperature

$$\propto_T = T_{stress} = -0.0041 \times T^2 + 0.215 \times T - 1.7 \qquad [4.1]$$

The stress index yields values between 0 and 1 depending on the prevailing temperature conditions.

A stress index was also derived for soil water availability, such that growth is zero at or below the wilting point and is optimum at or beyond the critical water content or field capacity. The water contents at wilting point and field capacity were determined as 0.1 and 0.2 g/g**,** respectively. These values were used in the water stress function given in Chapter 2 (equation 2.3 a, b and c). It was assumed that the temperature and water stress effects were multiplicative, and the combined stress was used to discount the potential growth rate (equation 3.13) for that day. Table 4.7 gives the input variables and their values for the model.

Model evaluation was based on the coefficient of determination (R^2) and Willmott *d*-statistic given by:

$$d = 1 - \frac{\sum_1^n (P_i - O_i)^2}{\sum_1^n (|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \qquad [4.2]$$

Where d= sums of squares based on measure

P_i= predicted value

O_i= observed value

$\bar{O}$= true mean of observed values

$|P_i - \bar{O}|$ = absolute value

Figure 4.13 shows the time-course of the observed (symbols) and simulated (lines) total dry weight of soybean under non-limiting soil water conditions of (W2) but varying temperature conditions. Despite the large variability in the observed data, the model captured well the temperature effect, with final growth reduced under high temperature (E1) than lower temperature conditions (E3).

Table 4.7: Model input variables

Variety	Input variables	Description	Value	Units	Source
Afayak	Wo	Initial plant dry weight	0.15	g/plant	From study
	Wmax	Maximum dry weight	5.88	g/plant	From study
	K	Growth rate constant	0.15	g/g/d	Charles-Edward *et al*. (1986).
Jenguma	Wo	Initial plant dry weight	0.15	g/plant	From study
	Wmax	Maximum dry weight	6.63	g/plant	From study
	K	Growth rate constant	0.15	g/g/d	Charles-Edwards *et al*. (1986).
Both varieties	Tb	Base temperature	10	^{o}C	Hundal *et al*. (2003)
	Topt	Optimum temperature	30	^{o}C	Hesketh *et al*. (1973)
	Tmax	Maximum temperature	40	^{o}C	Boote *et al*., (2005)
	PWP	Permanent wilting point	0.11	cm^3/cm^3	From study
	Θc	Critical water content	0.22	cm^3/cm^3	From study
	θ_{FC}	Water content at field capacity	0.22	cm^3/cm^3	From study
	Θsat	Saturated water content	0.45	cm^3/cm^3	From study

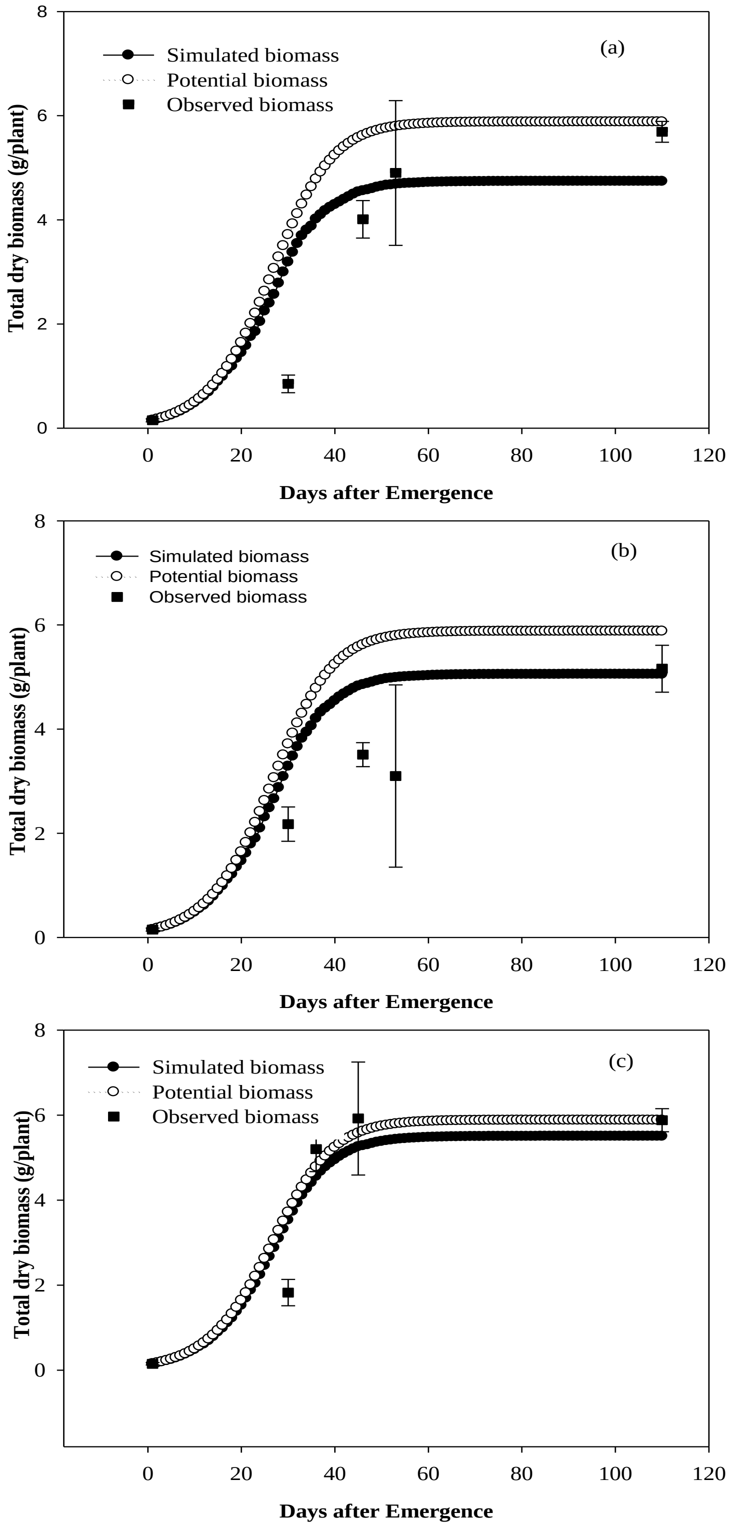


Fig. 4.13: Simulated and observed temperature stress effect for Afayak variety in (a) E1, (b) E2 and (c) E3.

Initially, the model somewhat overpredicted the growth but the agreement improved with time. The model predicted a higher growth rate with temperature stress till about 50 DAE after which the curve flattens which is largely due to reduction in vegetative biomass accumulation as assimilates switched for reproductive growth. Although for E1V1, the model predicted TDB of about 5.0 g/plant, the observed TDB was about 6.0 g/plant. At 20 DAE, the model predicted a biomass weight of about 1.5g/plant while the observed TDB was less than 1g/plant.

Figure. 4.13b compares the predicted temperature stress effect and observed total dry biomass weights for Afayak in E2. The final total dry biomass weight for both the model prediction and the observed were similar but the model predicted a higher total biomass weight between 20-50 DAE, while for E3 in Fig. 4.13c, shows a different trend as the observed was corresponding with simulated potential growth, this is because temperature stress was not imposed on this environment treatment. Although, the observed data was lower at 20-30 DAE but it was able to attain the predicted potential total dry weight.

In the case of Jenguma variety (V2), the model prediction of temperature stress effect and the observed were closely related in E1 and E2 (Fig.4.14a and b), while for E3 (Fig.4.14c), there was a close similarity between the potential total dry biomass and the observed. The model predicted an initial increase higher than the observed at 30 DAE but as time progresses there was an agreement between predicted potential biomass weights and the observed data.

The model was able to predict a total dry biomass weight lower than the potential as a result of the temperature stress imposed on the varying environments. This prediction shows that temperature stress will reduce the biomass weight of plants and this is consistent with both varieties.

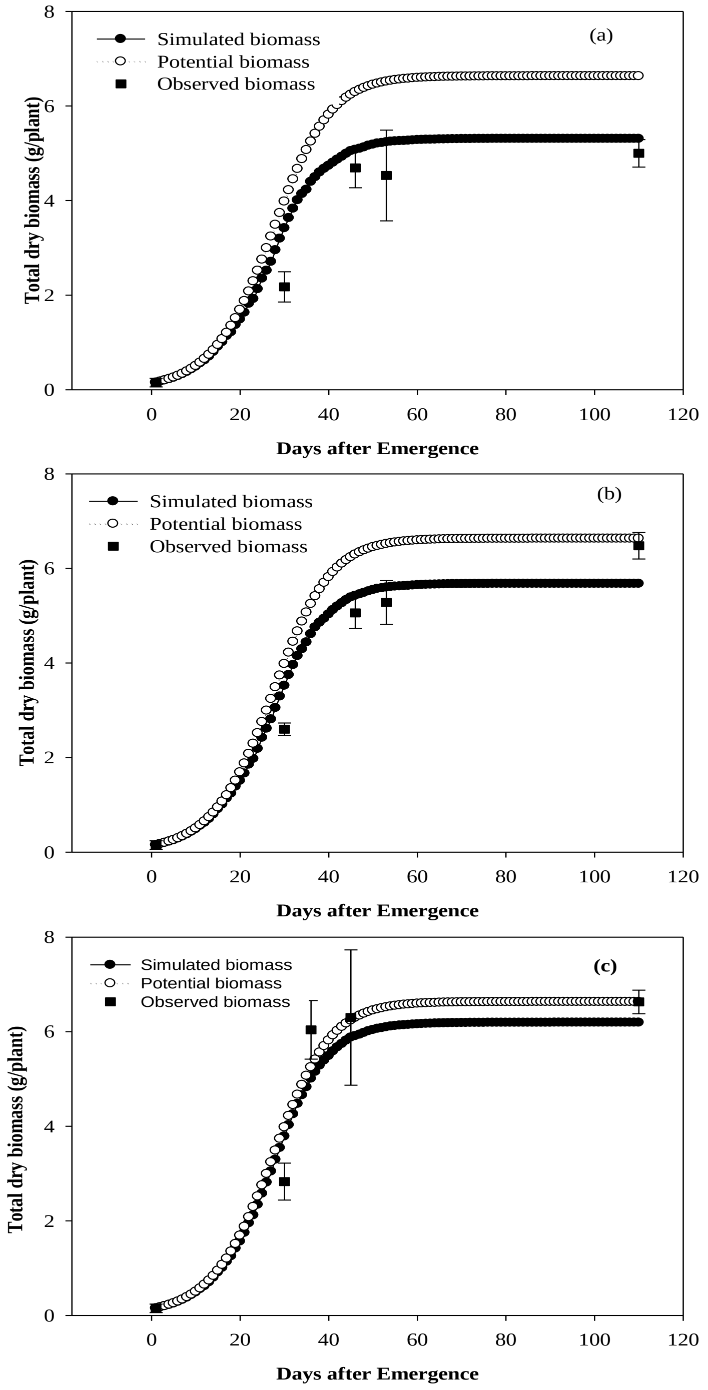


Fig. 4.14: Predicted and observed temperature stress effects on the growth of Jenguma in (a) E1 (b) E2 and (c) E3.

4.7 Combined temperature and water stress conditions

The model prediction of the combined temperature and water stress effects on total dry biomass weights (TDW) is shown in Fig 4.15 and that of seed weight of soybean is shown in Table 4.7. Figure 4.15 shows a combined temperature and water stress effect simulated for both varieties. For Afayak, the model initially underestimated the (TDW) between 25 and 60 DAE after which there was a drop in the observed (TDW) which corresponds with the model predictions, this trend was also similar for Jenguma but it had a relatively lower observed (TDW) compared to the predicted (TDW).

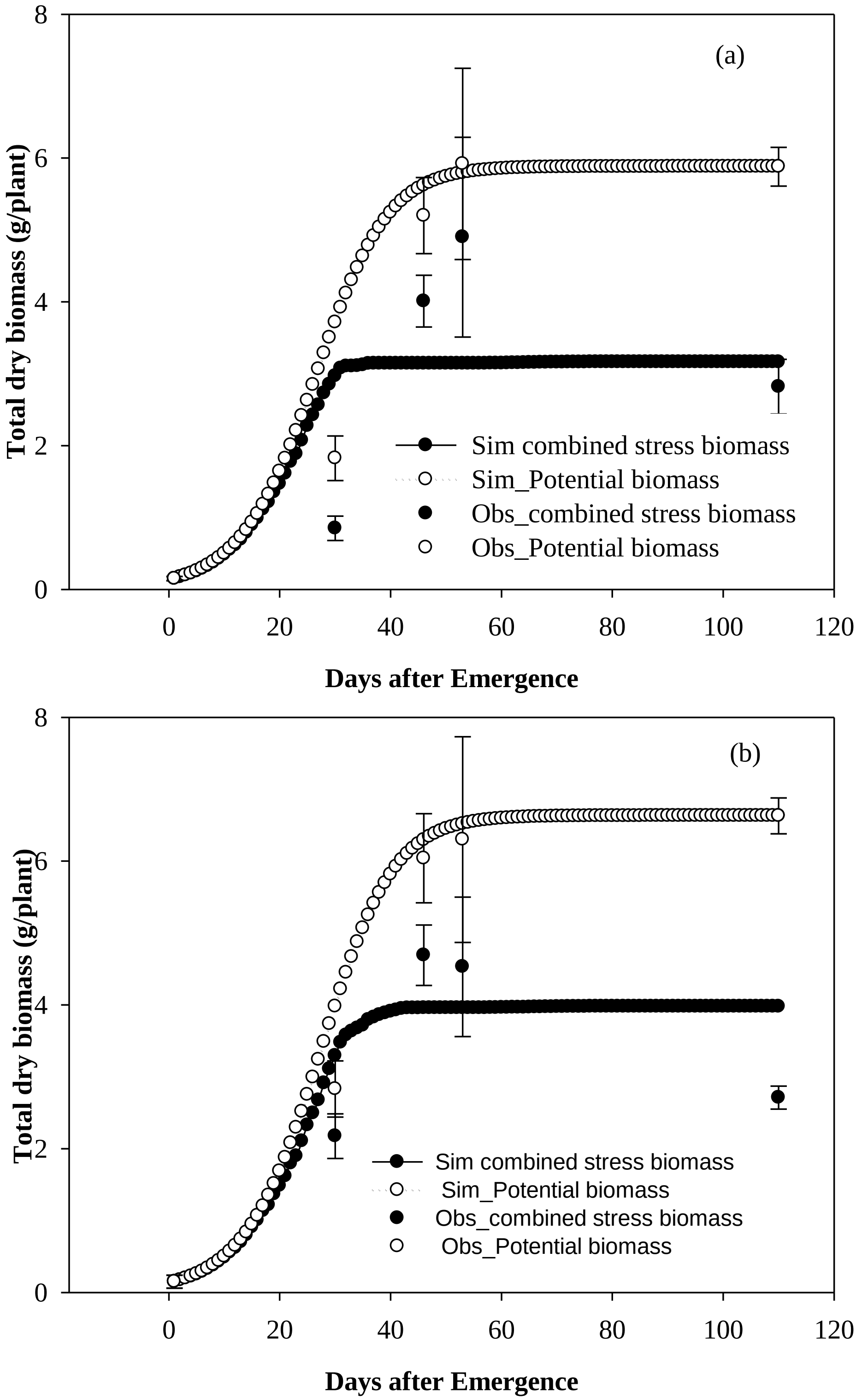


Fig.4.15: Simulated (Sim) and observed (Obs) combined stress effect on the growth of (a) Afayak and (b) Jenguma soybean varieties

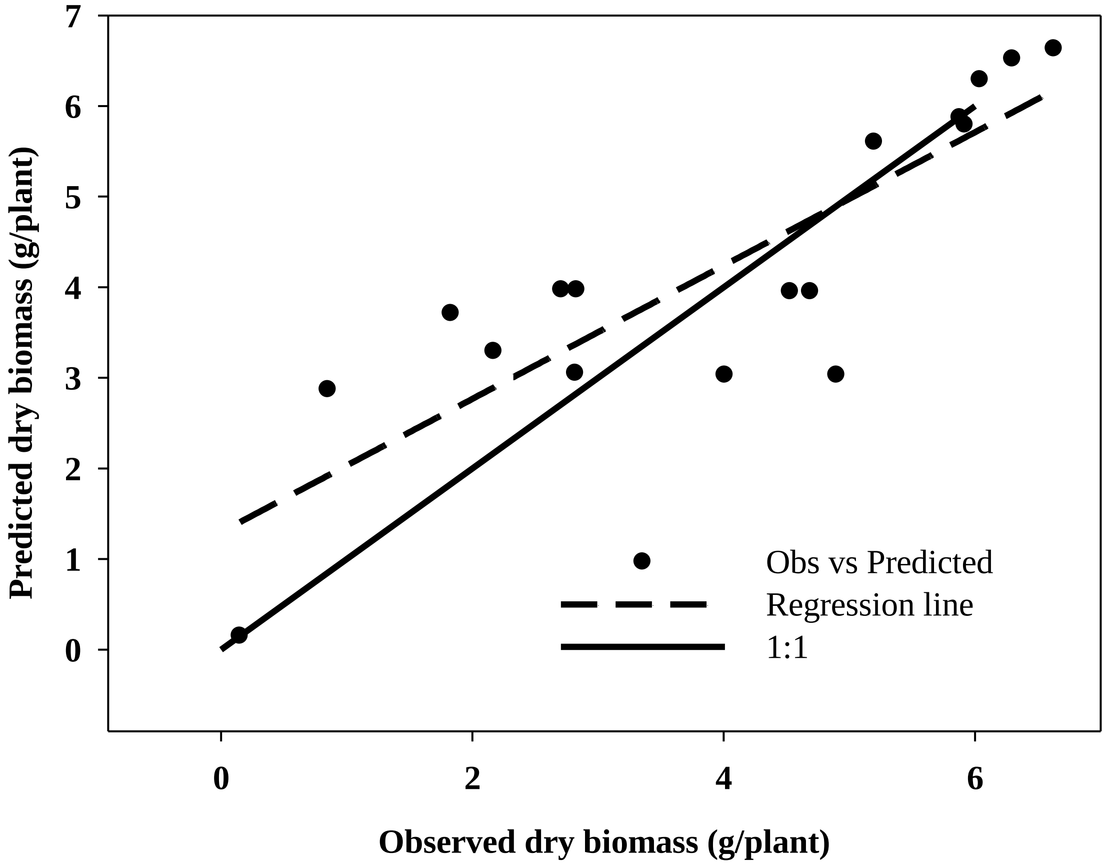


Fig.4.16: Predicted and observed dry biomass showing coefficient of determination

The model over predicted for observed yields less than 3 and under predicts between 3 and 5 g/plant. When water and temperature stress were extreme, the model captures the high ranges quite well. In general, the model agrees well with the observed as shown in Fig.4.16 with R^2 value of 0.74 and Willmott d-statistic value of 0.9.

Table 4.8 shows the comparison between observed and predicted seed weight (g/plant) of the combined temperature and water stress treatment (E1W3) and the no stress treatment (E3W1) for both varieties. The predicted seed yield was calculated as the product of the harvest index and final predicted total biomass. The harvest index (H.I) changes with stress as can be observed shows increasing temperatures (E1) and drought (W3), in particular resulted in drastic reduction in seed yield and this effect was also well captured by the model. The model was able to simulate seed weights that were close to the observed seed weight.

Table 4.8: Observed and predicted seed weight of soybean under combined temperature and water stress conditions in the different environments

				Seed weight (g/plant)	
Variety	Environment	Water treatments	Harvest Index (H. I)	Observed	Predicted
Afayak (V1)	E1 (36 ^oC)	W3 (drought)	0.09	0.27	0.29
Afayak (V1)	E3 (33 ^oC)	W1(field capacity)	0.38	2.29	2.23
Jenguma (V2)	E1 (36 ^oC)	W3 (drought)	0.23	0.63	0.92
Jenguma (V2)	E3 (33 ^oC)	W1(field capacity)	0.47	3.15	3.10

CHAPTER FIVE

5 DISCUSSION

5.1 Climate change impact on plant growth and yield

The introductory chapter (Chapter 1) of this study put into focus the relationship between climate change and plant growth. It was indicated that two variables, namely temperature and water (rainfall) are the major factors that will impact on plant growth. Historical data showed an increasing trend of temperature and many projections show this trend will continue into the future. Adiku (2019) indicated an obvious increasing trend in the daily maximum temperatures at several locations in Ghana. Though the rainfall situation is not consistent for all locations, it is certain that extreme situations (drought or flooding) would become more common.

This study, hence, focused on the impact of increasing temperatures and drought on the growth and yield of two varieties of soybean in the coastal savannah zone of Ghana. The soil used for the experiment belongs to the Amo series which has vertic properties similar to the Akuse series but are not true Vertisols. They were sampled from the proximity to the bank of the Volta Lake at Kpong. The pH of the soil was 7.33 and 6.84 in water and KCl respectively. Previous studies indicated that the organic carbon content of the soil was low (Acquaye and Owusu-Bennoah, 1989), which is characteristic of soils in the savannah as a result of low rates of organic residue addition (Sanchez, 1977). Previous data also indicated that exchangeable bases: magnesium and calcium were the most dominant basic cations with values of 18.18 and 14.43 cmol/kg respectively (Acquaye and Owusu-Bennoah, 1989). Potassium was relatively low with value of 0.19 cmol/kg. Analysis of the soils in this study showed that the Cation Exchange Capacity (CEC) was high (35.1 cmol/kg) probably as a result of the montmorillonitic clay content. Though the drainage was somewhat slow, waterlogging conditions did not prevail for long periods after high irrigation. In general, the soils did not have any physical or biochemical limitations to the growth of soybean.

5.1 Environmental conditions during soybean growth

The experiments conducted were subjected to varying temperature differences in the three growth chambers. The temperatures in the chambers were not held constant but allowed to vary from day to day, but the differences were related to the number and size of windows constructed on each chamber (Chapter 3, section 3.2.1). The hottest environment was E1 with a mean temperature of 36 ^{o}C. The intermediate (E2) and near ambient (E3) had mean temperatures of 34 ^{o}C and 33 ^{o}C, respectively.

The highest temperature recorded in the chambers occurred at mid-afternoon, reaching 41 ^{o}C in environment E1, 39 ^{o}C in E2 and 38 ^{o}C in E3. The lowest temperature values were about 30 ^{o}C for both E1 and E2 and less by 1 ^{o}C in E3. These temperatures are characteristic of temperatures in the tropics and it is set to mimic predicted increasing temperature under climate change. Also, Meehl *et al*. (2007) and IPCC, (2007) have predicted increase in temperature over the years.

The different environments determined the microclimate variables such as the Relative Humidity (RH) and Vapor Pressure Deficit (VPD). The VPD affected the transpiration rates of the plants. Generally, transpiration increases with increases in VPD. The findings in this study indicated that though E3 had the lowest average temperature, the VPD was highest (3.0 kPa) apparently due to consistently low RH as air circulation was enhanced under this environment. This result contradicts that of Tacarindua *et al*. (2013) who indicated in their study on the effects of increased temperature on growth and yield of soybean in temperature gradient chamber in Japan whereby VPD increased with increasing temperature. It could be recalled that E3 was to mimic ambient conditions, so the windows were very large. Despite this, E3 had the lowest cumulative evapotranspiration of 185 mm, compared with 224 and 208 mm for E1 and E2, respectively, apparently due to the lower temperature regime of E3. A VPD above 2 kPa approximately has been reported to cause increased transpiration rates and reduced water potential in leaves of well-watered rooted plants (El-Sharkawy *et al*., 1965). In soybean, a lower stomatal conductance occurred at an atmospheric VPD of 3.0 kPa as compared with 1.0 kPa and it has also been observed that the response of stomatal conductance to VPD differs with genotypes (Bunce, 1984).

Increasing temperature trends will increase the atmospheric demand for water and this was observed for the E1 which had the highest evapotranspiration (224 mm). An increasing water vapor demand will lead to increased leaf transpiration rate by leading to a higher leaf temperature and reduced photosynthetic activity (Hatfield and Prueger, 2015). This reduction in dry matter accumulation was later observed for pod and seed yields of E1 and also E2. At increasing temperature of E1 and E2, evapotranspiration increased, hence water supply became limited and the stomatal conductance would have decreased. Thus, the increasing temperature trends will increase the atmospheric demand for water. If drought frequency increases (which is often associated with climate change) then the combination of high temperatures and drought can be detrimental to plant growth and productivity.

5.2 Effect of temperature on plant development

5.2.1 *Phenology*

Temperature is a major environmental factor that influences the growth, development and yields of crops especially the plant's rate of development (Luo, 2016). Differences were observed in the development of the soybean varieties (Afayak and Jenguma) in the three environments (E1, E2 and E3). The environment E1, which had an average temperature of 36 ^{o}C led to the shortest time to 50 % flowering in both varieties as compared to the other two environments. This observation corresponds with the findings of (Qaseem *et al.*, 2019) that high temperatures caused a reduction in the days to anthesis and maturity of crops. Sinclair *et al*. (2014) simulated that flowering in soybean under West Africa conditions usually occurred between 40 and 50 days after sowing. In this study, flowering occurred at 40 and 41 DAE for Afayak and Jenguma respectively for E3 (near ambient conditions) which falls within the range indicated by Sinclair *et al* (2014). For the variety Afayak, the days to 50 % podding in the higher temperature environment (E1) was shorter (48 DAE) compared to E2 and E3 which took 50 DAE to attain 50 % podding. Adjustments of phenology is a critical coping strategy of crops in adjusting in adverse biophysical environments (Jumrani and Bhatia, 2018)

Conceivably, one impact with increasing temperature which is shortened life cycle of soybean by accelerating the development (Craufurd and Wheeler, 2009; Rose *et al.*, 2016). Higher temperatures have the potential to negatively impact crop production indirectly through accelerated phenology (Menzel *et al.*, 2006; Lobell *et al.*, 2012). The R1-R7 stage which is the reproductive growth periods of soybean are more sensitive to high temperature than vegetative growth periods (Reddy and Kakani, 2007). Kumar *et al*. (2008) found a shorter duration of growth period for soybean sown at higher temperatures. Wheeler *et al*. (2000) concluded that time of flowering of different crops is sensitive to extreme temperatures.

The variety Jenguma appeared to be less sensitive in its development response to increasing temperature. Under all the three environments, 50 % podding was at 52 DAE. The Jenguma variety was developed at the Savannah Agricultural Research Institute (Kariyama, 2014) in northern Ghana where temperatures are generally high. This may explain its adaptation to high temperatures.

Generally, soybean cultivars differ in their sensitivity to high temperatures (Sapra and Anaele, 1991) and it has been reported also that high temperatures are known to have adverse effect on reproductive processes of legumes (Porch and Jahn, 2001; Koti *et al*., 2005; Hatfield *et al*., 2011) which might be the possible reason for differences in soybean response in the varying temperatures in the three environments.

5.2.2 *Effect of Temperature on plant height*

Another development attribute of plants is height. Plant height in both varieties increased over time, with Afayak reaching a maximum height of 41 cm and Jenguma reaching 40 cm. These heights occurred in the highest temperature environment (E1), suggesting that there was a rapid cell division with temperature increase. Earlier research conducted by (Gibson and Mullen, 1996) showed that increase in temperature enhances rapid vegetative growth. Other authors also reported increased height in canola under high temperature conditions (Qaderi *et al*.,2006).

5.2.3 *Effect of temperature on node and leaf appearance rates*

The node and leaf appearance rates on a plant are indicative on the plant's development response to the environment. For example, Granier and Tardieu (1998) observed that temperature was a major climatic factor that strongly influenced node appearance and node initiation rate in annual crops. In soybean, node development is a precursor to leaf development, the main photosynthetic apparatus of the plant. Hence, both node and leaf appearance rates affect the overall growth and yield.

This study indicated that an initial rapid rate of node appearance was more obvious with the Afayak variety under the high temperature environment (E1). The Jenguma variety also showed an increasing rate of node appearance with increased temperature. This is consistent with the results of researches conducted by (Hesketh *et al*. 1973 and Tenorio, 2016). Also, similar trend was observed for number of leaves as node appearance leads to leaf formation (Bastidas *et al*., 2008). Node and leaf appearance increase as temperature increases (Hatfield and Prueger, 2015). Although Jenguma had rapid leaf appearance rates in E1 and E2 at the onset, the total number of leaves by the end of the study did not significantly differ among the environments. Similar findings were also made for maize (Hatfield and Prueger, 2015) and other crops.

5.3 Effect of temperature on plant growth

Increasing temperature negatively impacted on growth of soybean. During the vegetative stage, biomass accumulation under environment E1, which had the highest mean temperature of 36 ^{o}C, was least and was significantly different from the other environment treatments. Hatfield and Prueger (2015) also observed that extremely high temperatures reduced significantly the total vegetative dry weight of maize. Between the varieties, the

Jenguma, which apparently was developed to withstand high temperatures in northern Ghana (Kariyama, 2014) had higher biomass than the Afayak variety.

At flowering, the highest biomass accumulation for both varieties were highest in environment E3 (near ambient). Studies by Luo (2011) suggest that both high and low temperatures can have detrimental effects on crop growth, development and yield especially at the flowering stage. Drastic reductions in the total biomass accumulation at maturity was observed for the environments E1 and E2 as the high temperatures accelerated senescence. High temperature potentially accelerates senescence and decrease leaf chlorophyll content particularly during the grain filling period (Yang *et al*., 2002; Zhao *et al*., 2007).

5.4 Effect of temperature on yield

5.4.1 *Pod weight*

Reduced temperature environment under E3 resulted in the highest pod weights (PDW) among the environments for all the water treatments. The lower pod weights under E1 and E2 could be attributed to increasing temperatures, which on one hand will accelerate plant's development (Horie, 1994) and lead to shorter reproductive life cycle and finally to reduced yield potential (Hatfield and Prueger, 2015) through reduction in seed weight. On the other hand, increased temperatures will also increase plant respiration rates and loss of assimilates (Paembonan *et al*., 1992). In this study, pod weights were reduced as temperature increases from 3.35 g/plant in E3 (near ambient) to 1.29 g/plant in E1 (high temperature). Hatfield *et al*. (2011) stated that increases in temperature has the potential to reduce yield by between 2.5 % and 10 %. Prasad *et al*. (2000) indicated 50 % reduction in pod yield at high temperatures of 38 ^{o}C.

5.4.2 *Seed yield.*

High temperatures are also known to potentially accelerate senescence (Machado and Paulsen, 2001) particularly during grain filling leading to a shorter duration for grain filling (Yang *et al*. 2002; Zhao *et al*. 2007) and ultimately decreases grain yield. As for pod weight, seed weight increased as temperature decreased, as observed in environment E3 (near ambient). Work by Schlenker and Roberts (2009) indicated that yield would gradually increase with temperatures up to a temperature range of 29 °C to 32 °C for crops like corn, soybean and cotton, followed by a sharp decline in yield when temperature increases beyond this range. Given that the average temperature of E1, for which the seed yield was lowest was 36 ^{o}C, the findings in this study agree with the observations by Schlenker and Roberts (2009). The findings in this study is further supported by Tacarindua (2013) who indicated that soybean seed yield was sensitive to increase in temperature resulting in seed yield reduction. Furthermore, the findings in this study buttressed those of Heinemann *et al.* (2006) that soybean seed yields decreased when temperature exceeded 30 ^{o}C. Puteh *et al.* (2013) reported decreased seed yield with increasing air temperature.

In general, increasing temperatures under climate change would likely impact adversely on the development, growth and yield of soybean.

5.5 Effect of Water treatment on plant yield

5.5.1 *Pod weight*

The second component of climate change of relevance to plant growth is rainfall. The observations in this study showed that though dry matter production increased from emergence, through podding to physiological maturity, under all the environments, there was drastic decline when the plants were water stressed. Water deficit situation led to insufficient moisture for proper growth and development, hence photosynthetic activities are disrupted. It is generally known that plants would close their stomata under drought conditions, which also reduces carbon dioxide intake and hence growth declines.

The water stressed treatment (W3; drought) had the lowest mean PDW for all the environments. Drought condition is capable of reducing pod weights irrespective of the temperature differences and this is in agreement with findings by Hatfield and Prueger (2015), which showed that under water deficit conditions, there was reduced biomass and grain yield, both under ambient and high temperature conditions. The pod weight was highest under water treatment W1 (near saturation).

This also corresponds with findings by Tacarindua (2013) that the rate at which dry matter increases after flowering under drought conditions is lower compared to under well-watered conditions.

5.5.2 *Seed yield*

Many studies have shown that even though other environmental factors interfere with crop performance, water deficit was the major limiting environmental factor that led to soybean failure to attain maximum yields (Casagrande *et al*., 2001). In this study, the near saturation water treatment (W1) had highest seed yield among the water treatments in all the environments while W3 (water stressed) had the lowest seed yield. In other studies, it was observed that drought stress caused 45 % reduction in grain yield (Qaseem *et al*., 2019). Also, under water deficit conditions, after flowering, there is rapid transport of metabolites accumulated during the vegetative stage (from leaves and stems) to developing grain which results in accelerated loss of chlorophyll and senescence (Yang *et al*., 2001). In effect, continuous biomass production is impaired, and the final seed production is adversely affected.

5.6 Combined effects of high temperature and drought on plant yield

The interactive effect of increasing temperature environments (E1 and E2) and drought (W3) led to drastic reduction in pod and seed weights. According to Farias *et al*. (2007), if the high temperature is associated with a drought, it leads to further losses in grain production. Also, water deficits aggravate the effect of increasing temperature on plant biomass (Mittler, 2006; Prasad *et al*., 2011).

This drastic yield reduction can be attributed to a number of factors such as higher evaporative demand at increasing temperature which forces the stomata to close and thereafter leads to reduced transpiration and photosynthesis (Long and Ort, 2010). Desclaux *et al*. (2000) found that the number of pods per unit of shoot dry matter of soybean was significantly affected by water deficits in the reproductive stages. Also, if plants are exposed to extreme temperature conditions, water stress could occur quickly because the plant lacks sufficient capacity to extract water from the soil profile to meet the increased atmospheric demand. The effect of temperature and water deficit in this study were severe mainly due to the fact that the combined effect of the stress factors occurred during the reproductive stage which lacks adequate plasticity to recover from the effect of the stress factors. Normally, plants suffering stresses imposed during vegetative stage can recover often when the stress is over.

On an overall basis, the Jenguma variety had higher yields than the Afayak variety. There hasn’t been any previous comparison regarding the performance of these two varieties under increasing temperature and drought conditions, even though Asafo-Adjei *et al.*

(2005) reported higher grain yields for Jenguma than other soybean varieties like Nangbaar and Anidaso under ambient temperature.

Studies have shown that the combined temperature and drought stress significantly reduced grain yield of wheat by 92 % and 50 % from emergence to anthesis and 21 days after anthesis respectively as compared to the independent effect of drought which reduced yield by 69 % and 26 % in both scenarios (Pradhan *et al*., 2012). High temperature and drought led to a decrease in mean grain yield per plot of different wheat cultivars (Ram *et al*., 2017).

The significant reduction in yield due to combined heat and drought stress on soybean was reported by Tacaridua (2013), whereas Hejnak *et al*. (2015) reported similar trends for cotton; Shah and Paulsen (2003) reported same for wheat; and Sehgal *et al*. (2017) reported same for lentils. In all cases, combined stress of high temperature and drought were more detrimental than the individual effect. Thus, the findings of this study agreed with pervious observations.

5.7 Modelling the effects of high temperature and severe drought on soybean growth and yield

One of the aims of this study is to develop and validate a simple model that can predict the growth and yield of soybean under severe climate change conditions. The two main climate factors considered were temperature and water. It was shown that a temperature stress factor could be derived in the form of a quadratic equation that has the base temperature, optimum temperature and maximum temperature as cardinal points. Also, a water stress factor could be derived from soil water content, with the permanent wilting point, critical water content and field capacity as cardinal points. The inclusion of these stress factors into a simple growth rate equation that was solved numerically resulted in a simple plant growth model which run on a daily time scale.

The test of the model showed that temperature stress effect on soybean growth could be adequately predicted on daily basis over the entire growth duration. The reduction in growth due to high temperature was adequately captured. In particular, the combined effect of high temperature stress (E1) and severe water deficit stress (W3) on soybean growth and yield could be well predicted by the simple model. Undoubtedly, many more comprehensive crop models, such as CROPGRO (Boote *et al*., 1998), the legume component of DSSAT, APSIM (McCown *et al*., 1996), CropSyst (Stockle and Nelson, 1994), AquaCrop (FAO, 2009) have been published and indeed some of these have been validated for soybean growth and yield in Ghana (MacCarthy *et al.*, 2017).

However, whether they are capable to respond to such extreme temperatures and severe drought conditions imposed in this study is yet to be tested. Many modeling studies in Ghana and Africa in general have ended up in simple validation. Model improvement in terms of interrogating the physiological basis for relationships in the models have not been the focus. Perhaps, this study could provide a starting point for developing models that can perform better under harsh tropical conditions.

CHAPTER SIX

6 CONCLUSIONS AND RECOMMENDATIONS

From this study, it has been shown that soybean is affected by increased temperature and soil moisture variations. Increasing temperatures reduced time to flowering in both varieties but Jenguma (variety 2) was less sensitive. Also, soil water variation had significant effect on the growth and yield of the two varieties. The combined effect of high temperature and drought was very severe leading to a drastic decline in growth and yield. Between the varieties, the Jenguma, which apparently was developed to withstand high temperatures in northern Ghana had higher biomass than the Afayak variety.

The formulation of temperature and soil water as stress factors used to modify the growth rate resulted in simple but effective model that can be used to predict soybean growth and yield under varying environmental conditions.

The following recommendations are made from this study which include:

the conduct of the experiment under field conditions if possible, to see if similar results could be obtained, and extension of the study to more than two varieties.

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