UNIVERSITY OF CAPE COAST

VALIDATION OF THE FAO AQUACROP MODEL FOR IRRIGATED HOT PEPPER (*Capsicum frustescensvarlegon 18*) IN THE COASTAL SAVANNAH ECOLOGICAL ZONE OF GHANA

JOHN B. ZAYZAY,Jr.

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BY

JOHN B. ZAYZAY, Jr

A THESIS SUBMITTED TO THE DEPARTMENT OF
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UNIVERSITY OF CAPE COAST, IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE AWARD OF MASTER OF
PHILOSOPHY IN IRRIGATION TECHNOLOGY

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DECLARATION

Candidate’s Declaration

I hereby declare that this study is the result of my own original research and that no part of it has been presented for another degree in this university or elsewhere

Candidate’s Signature…………………………………..Date…………………

Name: John B. Zayzay, Jr.

Supervisors’ Declaration

We hereby declare that the presentation of this study was supervised in accordance with the guideline on thesis laid by the University of Cape Coast.

Principal Supervisor’s Signature……………………Date…......................

Name: Prof. L.K. Sam- Amoah

Co-Supervisor’s Signature………………………….. Date…......................

Name: Rev. Prof. J. D. Owusu- Sekyere

ABSTRACT

Validation of FAO AquaCrop model for irrigated hot pepper in the coastal savannah of Ghana was carried out using two field experiments between August, 2014 and January, 2015 at the School of Agriculture Research and Teaching Farm, University of Cape Coast in the Central Region of Ghana. The first experiment's results were used to calibrate the model while the second were used to validate the model. Experimental design was the Randomized Complete Block Design consisting of four treatments (T_1-T_4) of different levels of irrigation water applied: T_1- full irrigation (100%), T_2- 90% irrigation, T_3-80% irrigation and T_4- 70% irrigation. They were replicated three times (R_1-R_3). Agronomic parameters such as plant height, canopy development, and yield production along with water productivity of hot pepper were used to assess the effect of deficit irrigation on the growth and yield of the hot pepper and also used as parameterized variables for the calibration of the model. The optimum water requirement determined for the hot pepper ranged from 315.7mm to 318.3mm while the total fruit yield varied from 0.31t/ha to 1.20t/ha. However, the level of irrigation water affected the plant height, the canopy cover and the yield. Water productivity was also affected by total fruit yield in proportion to water applied. The AquaCrop model was validated and results obtained from the model agreed quite well with measured data. In general, the model performed well for the crop water requirement for all the treatments, water productivity predictions and the fruit yield but less satisfactorily for canopy development.

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To the family, you were always there for me through prayers, encouragements and your endless supports. I love you and you always have a place in my heart.

DEDICATION

This work is dedicated in memory of my late father Mr. John B Zayzay,Sr and My mother Mrs. Maria Mcwilliam Zayzay.

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LIST OF ABREVIATIONS

ANOVA	-	Analysis of variance
CC	-	Canopy Cover
cm	-	Centimeter
DAT	-	Days after transplanting
ETc	-	Crop evaportranspiration
ETo	-	Reference crop evaportranspiration
FAO	-	Food and Agriculture Organization
g	-	Grams
ha	-	Hectares
HI	-	Harvest index
Kc	-	Crop coefficient
N-RMSE	-	Normalized root mean square error
T	-	Treatment
t	-	Tones
RMSE	-	Root mean square error
Sed	-	Standard error of the difference of means
WP	-	Water Productivity
WUE	-	Water use efficiency

CHAPTER ONE

INTRODUCTION

Background of the study

Basically, water is important for plant growth and food production. However, competition between municipal, industry and agriculture for the available water is high. Therefore, estimating irrigation water requirement accurately is important for agriculture, water project planning and management. Worldwide, the application of water and its management have been an essential factor in raising productivity of agriculture and ensuring predictability in outputs. Therefore, solutions allowing greater production using less water are critical future priorities. The finite total amount of available water is crucial for economy, health and welfare of a very large part of the developing world.

Irrigated agriculture makes a major contribution to food security, producing nearly 40 percent of food and agricultural commodities on 17 percent of agricultural land (FAO, 1996b). However, irrigated areas have almost doubled in recent decades and contributed much to the growth in agricultural productivity. Moreover, irrigated agriculture uses more than 70 percent of the water withdrawn from the earth’s rivers but in developing countries, the proportion exceeds 80 percent. The scope for further irrigation development to meet food requirements in the coming years is, however, severely constrained by decreasing water resources and growing competition for clean water. While on a global scale water resources are still ample, serious water shortages are being experienced in the arid and semi-arid regions as existing water resources reach full exploitation. The dependency on water has become a critical constraint on food production and threatens to slow down development, endangering food supplies and aggravating rural poverty. The great challenge for the coming decades will therefore be the task of increasing food production with less water, particularly in countries with limited water and resources.

In the context of improving water productivity of a crop, there is a growing interest in deficit irrigation, an irrigation whereby water supply is reduced below maximum levels and mild stress is allowed with minimal effects on yield. Under conditions of scarce water supply and drought, deficit irrigation can lead to greater economic gains than maximizing yields per unit of water for a given crop. However, this approach requires precise knowledge of crop response to water as drought tolerance varies considerably by species, cultivar and stage of growth. Deficit irrigation and drip irrigation are new practices to improve Water Use Efficiency (WUE) of irrigated agriculture. Deficit irrigation has been practiced researched by several authors (English and Raja, 1996; Pandey, 2000; Fabeiro, Martin de Santa Olalla and de Juan, 2001; Ali, Hoque, Hassan and Khait, 2007; Owusu-Sekyere, Asante and Osie-Bonsu, 2010) and proven to be effective. On the contrary, traditional irrigation aims at providing sufficient water to crops to avoid water deficit at all stages, so as to achieve maximum yield(Lorite, Mateos, Orgaz and Fereres, 2007), while deficit irrigation practices deliberately underirrigate crops (Dag'delen,Yilmaz, Sezgin and Guerbeuz, 2006). Reduced yield as a result of deficit irrigation, especially under water limiting situation, may be compensated by increased production from the additional irrigated area with the water saved by deficit irrigation (Ali *et al.*,2007). Producing more crops per unit of agricultural water use holds a key to both food and environmental security. A variety of options exist for improving the productivity of water in agriculture through the following targets: i) breeding, ii) better management practices by improving water use efficiency and sustainability, iii) decreasing water losses through soil evaporation, iv) increase soil water storage within the plant root zone through better soil and water management practices and v) through supporting policies and institutions (FAO/IAEA, 2008). Deficit irrigation could help not only in reducing production costs, but also in conserving water and minimizing leaching of nutrients and pesticides into ground water. However, to implement such a strategy for crops, there is need to investigate the disadvantages and benefits of deficit irrigation, especially for water stress sensitive crops. Doorenbos and Kassam (1979) presented an important approach to determine the yield response to water of field vegetable and tree crop (which the AquaCrop is also build upon), through the following equation:

$$\frac{Yx - sa}{Yx} = ky\,\frac{(ETx - ETa)}{ET\,\square} \quad \text{……………………………………………………………...} \ (1)$$

Where: Y_x and Y_a are the maximum and actual yield respectively, ET_x and ET_a are the maximum and actual evapotranspiration respectively, k_y is the proportionality factor between relative yield loss and relative reduction in evaporatranspiration.

Loomis, Rabbinge and Ng, (1979), define simulation models as simplification or abstraction of a real system. For biological systems like crops, models are composed of a number of components and processes interacting over a range of organizational levels (Sinclair and Seligman, 1996). These crop models are useful for different purposes primarily, to interpret experimental results and as agronomic research tools for research knowledge synthesis.

The Aquacrop model simulates attaina ble yields of the major herbaceous crops in rain fed, supplemental, deficit and full irrigation environments. It offers possibilities for developing efficient strategies for managing water resources for agriculture. The Aquacrop model is a canopy-level and engineering type of model, focused on simulating attainable crop biomass and harvestable yield in response to water available. The model is based on water productivity as a key driver of agricultural production.

Pepper is among the most susceptible horticultural plants to drought stress because of the wide range of transpiring leaf surface and high stomatal conductance (Alvino, Centritto and de Lenenzi, 1994) and having a shallow root system (Dimitrov and Ovtcharrow, 1995). For high yields, and adequate water supply a relatively moist soils are required during the entire growing season.

Hot pepper is a high value cash crop which is used in many ways. They are used in soups and stews and many sauces of different kinds. It is commercially cultivated in Mexico, China, Korea, East Indies, USA, Africa (Ghana) and many countries in the world. The total world production of hot pepper has been estimated to be 14-15 million ton a year (Weiss, 2002). Nutritionally, pepper contains Vitamins A, C and E with 83% moisture, 0.3% fat, 3% protein, 6% carbohydrate and 7% fibre (Cobbley and Steele, 1976). Hot pepper cultivation is known to in warm and semi-arid countries. However, water is often a limiting factor for production. Therefore, this necessitates optimization of water management and the parameterization of the AquaCrop model in a given agro-ecological environment.

Statement of the Problem

For the coming years, additional food supplies will be required to feed the world and this may depend on irrigation (IIMI, 1992). Crop production and productivity reduction is strongly related to water stress from dry spells and drought. Drought is a major problem worldwide affecting over 1.2 billion ha of rain fed agricultural land (Passioura, 2007). There are strong evidences for climate change, which would result in even further decrease annual rainfall year by year (Kimura, 2007). Research has indicated that in developing countries, an estimated 95% of agriculture is mainly rain fed resulting in high yield losses every year, low quality produce, high cost of production, as well as crop failure especially when the rain fails. Therefore, the inappropriate use and overexploitation of irrigation water for crops remains a challenge.

Low crop productivity due to over or under application of irrigation water that lead to water logging and salinization of soil. By farmers not having the ability to predict yield of crops by the use of tools such as the AquaCrop which takes account of prevailing scenario, they may venture into unprofitable investments which may incur losses to them. Simulation models that qualify the effect of water on yield at farm level can be valuable tools in water and irrigation management. Many of such models for maize include, the CERES-Maize model(Jones and Kiniry,1986), the Muchow-Sinclair-Bennett (MSB) model (Muchow, Sinclair and Bennet,1990), the EPIC phase model (Cavero, Farre, Debaeke and Faci, 2000), CropSyst (Stockle, Donatelli and Nelson,

2003) and the Hybrid-Maize model (Yang, Dobermann, Lindquist, Walters Arkebauer and Cassman, 2004). Unfortunately, most of these models are quite sophisticated, demanding advanced skills for their calibration and operation, and require large number of parameters, some are even cultivar-specific and they are not easily measured or accessible by the end users.

However, Sam-Amoah, Darko, Owusu-Sekyere (2013) tested the AquaCrop model on hot pepper through a potted experiment. Though the model could not simulate accurately the yield of the irrigation treatment with the exception of the 90% irrigation treatment which was simulated with the lowest deviation of 4%, the model was able to simulate the seasonal water requirement to an appreciable accuracy (Sam-Amoah *et al*. 2013).

Objectives of the study

General Objective

The general objective of the study was to validate the AquaCrop model for hot pepper through field experiment.

Specific Objective

In order to achieve the above general objective, the following specific objectives were pursued:

1. To determine the effect of deficit irrigation on the growth and yield of hot pepper
2. To determine the Water Productivity(WP) for pepper at various water applications
3. To calibrate and validate the AquaCrop model for pepper under local climatic and field conditions for the different water applications and

4. To compare the growth and yield simulated by AquaCrop with those obtained by field experiment.

Justification

Innovations are needed to increase the water use efficiency of the available water for agricultural production (Costa, Ortuno and Chaves, 2007). Therefore, optimizing irrigation water management for the production of crop could result in increased productivity and water savings. Irrigation accounts for two thirds of water use worldwide and as much as 90 percent in many developing countries (Geerts and Raes, 2009; UN-Water, 2007). A rise in the demand for agricultural products, calls for the need to optimize and increase productivity to overcome yield reduction due to poor and/or erratic rainfall distribution (Hillel and Vlek, 2005).

It is recognized that promotion of irrigation is an important strategy for achieving increased agricultural production, food security and poverty reduction in sub-Saharan Africa and Ghana in particular. Some other benefits of irrigation include the direct cut on water stress, increased investment in input such as fertilizers and improved cultivars affected by uncertainty of crop production under rain fed condition (Smith, 2000; Hillel and Vlek, 2005).

Improved return from agriculture inputs and in environmental quality from irrigation can be achieved, among others, through practicing irrigation scheduling (Itier, Maraux, Ruelle and Deumier, 1996; Home, Panda and Kar, 2002) and deficit irrigation (English and Raja, 1996; Nautiyal, Joshi and Dayal, 2002; Zhang, Pei, Li and Wang, 2002). Irrigation scheduling is a practice that enables the use of right amount of water at the right time for plant production and deficit irrigation is an optimization strategy in which irrigation is applied during water stressed-sensitive growth stages of the a crop (English,1990).

The AquaCrop model is exclusively based on the water driven growth module, in that transpiration is converted into biomass through water productivity (WP) parameters which enable it to simulate attainable yields of crops. Therefore, the calibration and validation of the AquaCrop model for pepper under local climatic conditions is also necessary as this would make it easier to predict and determine the expected yield and performance of crop with the data inputs used and parameters fed into the model. This would help farmers plan in advance for their expected returns from all input data parameters provided for the model.

Improving the water use efficiency (WUE) for pepper production is therefore of paramount importance to obtain “more crop per drop” with declining worldwide irrigation resources and the uncertainty in precipitation from global climate change. Peppers have very important uses in the diet of man. The long viability of the seeds and the ease of transport as well as disposal of the fruits and seeds, have been instrumental in spread of pepper through the world’s tropics and sub-tropics (Purseglove, 1977). It is a desirable ingredient in meal preparation due to its pungency.

However, this study seeks to calibrate and validate the AquaCrop model and determine the effect of deficit irrigation on the growth and yield of pepper through field experiment, and compare the results with those simulated by AquaCrop.

CHAPTER TWO

LITERATURE REVIEW

Origin and Distribution of pepper

Hot pepper is a major vegetable crop and an important constituent of local dishes in West Africa. Hot pepper is believed to be indigenous to Central and Tropical America. It has been suggested the hot pepper in West Africa came from another parts of Africa or from overseas and hybridization of those introduced (Yanney-Wilson, 1960). Peppers are now widely grown throughout most tropical areas such as Senegal, Liberia, Ghana and Nigeria (Norman, 1992). It is also thought that the Portuguese introduced the peppers to West Africa in the 15th Century (Norman, 1992).

Growth and development of pepper

Pepper (*Capsicum frustescens*) is a short-lived perennial small shrub which is characterized by greenish white corolla, more than one pedicel at a node, and not so large fruits that are very variable in size, shape and pungency (Norman, 1992). It grows to the height of about 1.5m. The stem is branched, erect and prostrate. The leaves alternate with unequal shape, oval or oblong, acute apex of 1.5-10cm in length and 0.5-5cm wide. The flowers are small, single or in group of 2-3 pedicels long, erect, 1.5-2.5cm in length. The calyx is cup-shaped with no distinct contractions between the calyx and the pedicel. The calyx is small, yellow-green with the petals yellow or green-white, 0.5-

1.0cm in diameter with 5 stamens. The fruit is a small narrow berry, which is variable in size up to 75mm long and 10mm in diameter with often 2- 3 fruits per node. The fruits are yellow or red when ripe with many seeds usually highly pungent (Tindall, 1983). The fruit is a long slender fruit of about 18cm, it varies in colour due to the presence of lycopene, xanthophylls and carotene with the later being dominant in yellow types.

Food value and Use of Pepper

Hot peppers when ripe are comparatively richer than the mature green sweet peppers (Norman, 1992). They contain 84% moisture. The approximate nutrient value per 100g fresh edible portion is energy, 46 cal; protein 2.0g; fat,2.0g; total sugar,55g, other carbonhydrates, 0.3g; vitamin A,11, 000 I.U.; thiamine,0.10mg; riboflavin, 0.10mg; niacin,1.0mg; vitamin C, 240mg; Ca, 18mg; Fe,1.0mg; Mg,27mg; P,45mg, K,240mg and Na,9mg (Norman, 1992).

Hot peppers are used in stews and soups. They are also used in gravys, pickles, and sauces; and they are ground to powder (the cayenne of commerce) which is used to flavor stews, curries, meats, and are also used medicinally as it is mixed with some herbs and used to cure fevers and colds (Norman, 1992).

Irrigation of Pepper

Peppers grow on a wide range of soils but thrive on sandy loams or loams that contain ample organic matter. The soils must be well drained, free from root knot nematodes and bacterial wilt organism. For successful production, a pH range from 5.5 to 6.8 is desired. Most hot peppers are grown under rain-fed conditions in West Africa except in irrigated areas (Norman, 1992).For optimum production; the soil moisture supply must be reasonably uniform during the growing season. Dry soils may cause poor fruit set or dropping of flowers and young fruits. The plants must therefore be irrigated periodically. Irrigation could be hand, sprinkler, drip or furrows. Irrigation is also important in the maintenance of a steady growth rate and that of sufficient foliage to protect the fruits from sunscald. The number of frequency of irrigations during growing period will depend on the type of soil, atmospheric temperature and humidity.

Harvesting and yielding of hot pepper

Both the annual and perennial hot peppers are ready for harvesting 8-9 weeks after planting (Norman, 1992). Most of the hot peppers cultivars are harvested ripe though some cultivars are however harvested mature green. Harvesting is once or twice a week. Harvesting of cultivars with small fruits is very time-consuming and entails a lot of labour. The yields of annual hot peppers range from 15 to 55t/ha. The yields are variable and dependent on cultivar which differs in size of fruits and of plants, and on the system of cultivation. Obviously, yields of peppers grown under rain-fed conditions are lower than those grown with irrigation and good cultural practices.

Water Scarcity

The sustainability of plant growth and development and ecosystems depends on the amount and quality of water received. The world, however, faces an ever increasing shortage of water due to both depletion and the deterioration of the water quality (Burt, Clemments, Strekoff, Solomon, Bliesner, Hardy and Coward, 1997).

The discussions of water scarcity are mostly based on calculations by the hydrologist Malin Falkenmark, which set water scarcity at 1,000m^3/year/person and water stress at 1,700m^3/year/person (de Villiers, 1999). Many countries in the Middle East and North Africa are considered to have absolute water scarcity, and the number of countries with absolute water scarcity is increasing. Thus, by 2025, 1.8 billion people will live in countries with absolute water scarcity (IWMI, 2000). This will increase the competition for water amongst the various sectors: domestic, industrial, environmental and agriculture, most likely leading to a reduction of water allocated to agriculture (Gupta, 1999).

According to IWMI (2000), some countries are likely to face economic water scarcity even where water is potentially available, because the costs of developing these water resources are prohibitive, and many countries in sub Saharan Africa will lack the finance to undertake these developments.

In some basins, water withdrawals for agriculture have been excessive such that even massive rivers like the Yellow River and the Colorado run dry at their tail ends due to over consumption in the upstream regions (Postel, 1996).

Rivers are not the only water source suffering from excessive withdrawals for agriculture. Underground water levels are declining as humans extract more water than is naturally recharged. Aquifers in Texas, The Arabian Peninsula, Libya, Israel, Gaza, Spain, Punjab (India) and Northern China have recorded decreases in the level of their water table between 40m and beyond 120m (Postel, 1999). Cities, such as Bangkok and Mexico City, are subsiding as aquifers underneath them are pumped dry (Postel, 1999).

The estimate of world population at the beginning of the 21st century was about 6.2 billion, and is expected to rise to about 9 billion people in 2050 (UNFPA,1999). This means that more water be required for domestic use thereby increasing the competition between farmers and urban populations. This is already apparent in China, California and Southeast Asia, where cities are redirecting water away from agricultural lands (Gleick, 1998).

With rising population, food consumption also rises, since food production requires water. It is estimated that the human population in 2050 consumes twice the number of calories as in 1999 (UNFPA, 1999). As at now, some countries of the Middle East and West Africa already import more than 30 percent of their grain since limited water resources restrict their capability to be self-sufficient in food production (Postel, 1999). Not only is the population rising, but also the affluence of the world is increasing and this puts further pressure on water resources (Kirpich,Haman and Stules, 1999).

Water availability for crop production in semi-arid and arid regions

Arid and Semi- Arid regions comprise almost 40% of the world's land area (Parr, Stewart, Hornick and Singh, 1990; Gamo, 1999). Aridity is commonly expressed as a function of rainfall and temperature. A climatic aridity index, which is a ratio of precipitation to potential evaportranspiration, is calculated following Penman's procedure, which takes into account atmospheric humidity, solar radiation, temperature and wind. Arid zone has aridity index ranging from 0.2 to 0.5 (FAO, 1989. According to the FreeDictionary (2008), semi- arid is defined as: "land that is characterized by relatively low annual rainfall ranging from 250mm to 500mm and having scrubby vegetation with short, coarse, grasses and not completely arid". Arid is defined as, land lacking water, especially having insufficient rainfall to support trees or woody plants.

Arid and semi- arid are characterized by unreliable rainfall, high radiation load and high evaporative demand with soils generally of poor structural stability and low fertility (Parr *et al.*, 1990; Monteith & Virmani, 1991). Farmers in these regions are more concerned about disaster avoidance than yield maximization for the fact that crop risk is given (Badini & Dioni, 2001).

Crop productions in arid and semi-arid regions of the world are largely limited for lack of adequate water supply during the growth season. Traditionally, irrigation has been practiced as the way to meet shortage in crop production. As water is becoming a scarcer resource in these regions, there is a need to adopt irrigation and cultural practices that guarantee greater water- use efficiency.

Plant response to soil water stress

Several authors (Slabbers, 1980; Brouwer and de Wi, 1989; Zhang, 2003; Cakir, 2004) have reported on the effect of soil water shortage on crop yield. Plants cannot survive without water and therefore, they show some symptoms of wilt when exerted to water stress during their growth stages. However, plants have the ability to recover their growth when soil is supplied water again after dry periods if critical water stress is not reached. Optimal growth in plants occurs when plants extract water at soil moisture content, between field capacity and wilting point (Veihmeyer and Hendrickson, 1950).

When water stress status occurs in a given stage during plants growing period, it influences the plant growth, the actual yield and the evaportranspiration (Moutonnet, 2000). The response of yield to water stress is expressed through an empirical linear equation which was developed by Doorenbos and Kassam (1979). For years, this approach has been widely adopted and used to estimate yield response to water by planners, economists and engineers (Vaux and Pruitt, 1983). Furthermore, other software developed as such as AquaCrop uses this approach to simulate yield due to water limitation (Smith, 1992).

Water stress effects on pepper crops

The water requirements for pepper range from between 600 mm to 1250 mm per season depending on regional climate and cultivar (Doorenbos & Kassam, 1979). The wide variation in water requirements of pepper is attributed to broad genetic variation within the species and the wide range of environments the crop is adapted to. The hot pepper plant has a shallow root system, which extracts 70 to 80% of its water from the top 0.3m soil (Dimitrov & Dvtcharrom, 1995). This, together with high stomatal density, a large transpiring leaf surface and an elevated stomatal opening, predispose the pepper crop to be vulnerable to water stress (Delfine, Alvino, Loreto and Santarelli, 2000).

Like other crops, optimum supply of water throughout the growing season is essential for optimum production of hot peppers. Water supply that is below the optimum levels leads to deterioration in both quantity and quality of the pepper yield. Mild water stresses in plants usually directly affect (cell elongation), whereas, photosynthesis and translocation are less sensitive to water stress (Kramer & Boyer, 1995). The biochemistry of photosynthesis (namely; Rubisco characteristics) was not affected in sweet pepper by mild water stress; rather the observed reduction in photosynthesis was caused by limitation of carbon dioxide (CO_2) conductance due to partial closure of stomata (Delfine *et al.,* 2000) as stomata serve for both CO_2 conduction and transpiration.

Pepper plants are most sensitive to water stress during flowering and fruit development stages (Katerji, Mastorilli and Hamdy, 1993). According to Costa and Gaianquito (2002), increased fruit dry yield was due to the effect of increased water supply or irrigation mainly attributed to a significant increment in fruit dry yield. Improvement of average diameters and lengths of fruits, and pericarp thickness were also observed as more water was applied (Costa and Guianquito, 2002). The reduction in fruit number due to water stress was attributed to flower abortion (Dorji *et al.,* 2005). Water stressing the pepper plant at the beginning of fruit set resulted in lower fruit number per plant and a high proportion of undersized fruits. Furthermore, the percentage of non-marketable fruits showed a significant share of blossom-end rot when plants are stressed at the beginning of fruit set or if continuously exposed to acute water stress throughout the growing season (Costa and Guianquito, 2002).

Water stress not only affects production of a crop but also some quality traits of the produce. The quality attributes that are affected by water stress in hot pepper: total soluble solids, colour development, blossom end-rot symptoms, pericarp thickness, fruit diameter, fruit length, and nutritional value of fruits. Costa & Guianquito (2002) observed a high proportion of discarded fruits due to blossom end- rot symptom in water stressed crops. The high proportion of undersized fruits in wet treatment was attributed to the high rate of fruit set in the treatment, compared to dry one.

Conflicting results have been reported regarding the practicality of deficit irrigation for water conservation in hot pepper. (Kang, Xiaotao, Zhijun and Peter, 2001) and Dorji *et al.* (2005) suggest the use of deficit irrigation in hot pepper. However, others confirmed the sensitivity of pepper to water stress and the beneficial effects of abundant irrigation. Costa & Guianquito (2002) and Beese, Horton and Wieringa (1982) observed significant yield increases in water levels above 100% evaportranspiration, indicating yield increases with additional water beyond the well watered control. The inconsistency of the results reported may be attributed to differences in cultivar used (Ismail & Davies, 1997) and the growing conditions (Pellitro, Pardo, Simon and Cerrolaza, 1993).

Crop Yield Response Factor (ky)

Crop response factor (ky) relates the relative yield decrease to the relative evaportranspiration deficit caused by a lack of adequate water. Crop yield response factors for a variety of crop species have been independently studied by the Food and Agriculture Organization of the United Nation (FAO) and the International Atomic Energy Agency (IAEA). The results have been published in a technical document of the (IAEA, 1996) and in several technical reports and books (Doorenbos and Kassam, 1979; Allen,Pereira, Raes and Smith, 1998; Kirda and Kanber, 1999).

Irrigation is needed for successful crop production where soil moisture and natural precipitation is not sufficient to meet the crop water demand. Irrigation schedule is usually made for a crop depending on the demand of the crop at different growth stages. Researchers have established from these research results that irrigation demand of crops varies widely depending on the stage of the crop (Hassan, Sarkar, Ali and Karim, 2002).

Generally, the decrease in yield due to water deficit during the vegetative and ripening period is relatively small, while during the flowering and yield formation periods, it is larger. However, Kirda and Kanber (1999) observed that crop yield response varies with the growth stage in which an irrigation deficit is suffered. Irrigation deficit suffered at one stage in the vegetative growth cycle of the crop has little or no significant effect on crop yield, but an irrigation deficit suffered at a more critical stage in the plant cycle (mostly during the flowering ,fruit setting or grain formation stage) dramatically affect yield (Kirda, 2002; Fereres and Sariano, 2007). Soybean yields decrease significantly more when an irrigation deficiency occurs during the flowering and pod development stages, when compared to an irrigation deficiency suffered during the vegetative growth stage (Kirda, 2002).

To achieve high yield, an adequate water supply is required during growth seasons. The period at the beginning of the flowering stages is most sensitive to water shortage, while maximum yield was obtained with full irrigation (Blum, 2005). Therefore, consideration must be given to the stage of plant in its growth cycle if the value of supplemental irrigation has to be determined. As a result, a series of empirical derived crop yield response factor (Ky) have been developed corresponding to irrigation deficits suffered at specific stages in the growth cycle and for a continuous irrigation deficit suffered over the entire growth cycle as presented in Table 1.

Table 1: Seasonal Yield Response Factors (Ky)

Crop	Ky	Crop	Ky
Alfalfa	1.1	Potato	1.1
Banana	1.2-1.35	Safflower	0.8
Beans	1.15	Sorghum	0.9
Cabbage	0.95	Soybeans	0.85
Citrus	1.1-1.3	Spring wheat	1.15
Cotton	0.85	Sugar beet	1
Groundnut	0.7	Sunflower	0.95
Maize	1.25	Tomato	1.05
Onion	1.1	Watermelon	1.1
Peas	1.15	Winter Wheat	1.05
Pepper	1.1		

Source: Allen *et al*., 1998

Water Use efficiency (WUE) in irrigated agriculture

Evaluation of the efficiency of agricultural water use (eg, Wallace, 2000) indicates that for rain-fed crop, the portion of rainfall used for crop transpiration is low, from 15-30% (Rockstorm and Fulkenmark, 2000). Comparably, lower values have been reported by Wallace and Gregory (2002) for irrigated agriculture (13-18% of irrigation water delivered). Further water scarcity is currently considered (Jury and Vaux, 2005). Food production soon is limited by water availability as it is more difficult to find additional water supplies for agriculture as a result of competition from other sectors.

Obviously, the solution to this competition for water resources lies mostly on improving the efficiency of water use for food production.

Efficiency literally means a measure of the output obtained from a given input. Water use efficiency in irrigated agriculture is defined in several ways depending on the nature of the inputs and out puts under examination. Water use efficiency is defined as a ratio of biomass accumulation, which is usually expressed as carbon dioxide assimilation(A),total dry matter yield (B),or crop grain yield(G) to water consumed, expressed as transpiration (T), evaportranspiration (ET), or total water input to the system (I).

Water availability is generally the most important natural factor limiting productivity and expansion of agriculture in environments where water is scarce. To satisfy food demands and growing competition of water, more efficient use of water in both rain fed and irrigated agriculture is essential. Such measures would include rainfall conservation, reduction of irrigation water losses and adoption of cultural practices that enhance water use efficiency (Smith, 2000; Passioura, 2006).

Various strategies are required to enhance water use efficiency in irrigated and rain-fed agriculture. One way is breeding crop varieties that use water efficiently. Others include better management of water resources and changes in crop management. Water use efficiency can also be enhanced by adopting water saving and efficient irrigation method like drip irrigation (Costa *et al.*, 2007). Wallace and Batchelor (1997) proposed four ways for enhancing water use efficiency in irrigated agriculture as presented in Table 2.

Table 2: Ways for enhancing water use efficiency in irrigated agriculture

Improvement category	Options
Agronomic	Crop management to enhance precipitation capture or reduce water evaporation (eg. Crop residues, conservation till, and plant spacing); improved varieties, that maximize cropped area during periods of lower water demands and/or periods when rainfall may have greater like likelihood of occurrence.
Engineering	Irrigation systems that reduces application losses, improve distribution uniformity, or both cropping systems that can enhance rainfall capture(eg. crop residues, deep chiseling or paratilling, furrow diking, and dammer-diker pitting)
Management	Demand-based irrigation scheduling; slight to moderate deficit irrigation to promote deeper soil water extraction; avoiding root zone salinity yield thresholds; preventive equipment maintenance to reduce unexpected equipment failure
Institutional	User participation in an irrigation district (or scheme) operation and maintenance; water pricing and legal incentives to reduce water use and penalties for inefficient use; training and educational opportunities for learning newer and advanced techniques.

Source: Wallace and Batchelor (1997)

Enhancing the efficient use of water resources by adopting drip irrigation has been reported (Musick and Dusek, 1980; Howell, Schneider, Dusek and Copeland, 1995; Howell, Schneider and Evett , 1997). Since WUE is the yield divided by the water used by the crop to produce the yield, any factor that increases the crop water requirement without increasing the yield reduces WUE. Similarly, any factor that reduces the water requirement of the crop without reducing the yield will increase WUE. Water requirement of crops are greatest in arid and semi-arid regions, while by rainfall is least (Hillel, 1980). It is the large vapour pressure deficit of the air that forces the large water consumption by crop yield. Tanner and Sinclair (1983) presented data that supported the concept of greater WUE in humid region using corn as the model crop. Their mean WUE was 1.8kgm^{-3} for several semi-arid sites while averaging > 2.5kgm^{-3} in humid sites. The foregoing observation reflects higher vapour pressure deficit and evaporative demand in arid and semi-arid regions.

Water Productivity

Ali *et al.* (2009) reported that, in a crop production system, water productivity is the relationship between crop produced and the amount of water involved in crop production. Water productivity is crucial in agriculture as it aims to increase yield production per unit of water used, both under rainfed and irrigated conditions. These aims of WP can be either achieved by 1) increasing the marketable yield of the crops for each unit of water transpired, 2) reducing the outflow/losses, or 3) enhancing the effective use of rainfall or irrigation water stored in the soil, and of the marginal quality water.

The first option refers to the need for improving crop yield; the second one intends to increase the beneficial use (water uptake-transpiration) of water supply against the non-beneficial losses (evaporation); the third aims to utilize efficiently the water resources. All these options lead to the improvement of the on-farm management aspect of crop growth, through the application of the best crop management practices which will permit to use less water for irrigation, decrease evaporation losses, optimize fertilizer supply, allow better pest control, minimize energy consumption and improve soil conditions. This is particularly important in arid and semi –arid regions with limited water supply, where the farmers are constrained to applied deficit irrigation strategies and to manage water supply in accordance with the sensitivity of the crop's growing stage to water stress. In these situations, the increase of WUE would lead to better WP and it would favor the farmers' interest to improve economic returns from the investments in irrigation water supply.

Deficit Irrigation

Fereses and Soriano (2007) defined deficit irrigation as the application of water below the evaportranspiration (ET) requirements. Irrigation water supply under deficit irrigation is to meet maximum ET while optimizing yield. The economic and ecological advantage that could be derived from deficit irrigation are many. In economic terms, the potential benefits of deficit irrigation derive from three factors: increased irrigation efficiency, reduce costs of irrigation and the opportunity cost of water (English, 1990; English and Raja, 1996). The ecological benefits of deficit irrigation include preventing rising water table, in areas where the water table is near the soil surface. Deficit irrigation can also help in minimizing leaching of agrochemical to ground water (Homes, Panda and Kar, 2002).

Deficit irrigation is of various forms depending on how, when, where and why it is administered (Fereres and Soriano, 2007). In the humid and sub-humid zones, irrigation has been used to supplement rainfall as a tactical measure during drought spells to stabilize production. This type of irrigation is called supplemental irrigation (Debaeke and Abourdrare, 2004) and the goal is to maximize yield and eliminate yield fluctuation caused by water deficit. Similarly, in arid zones, small amount of irrigation water are applied to winter crops that are normally grown under rain fed conditions (Oweis, Pale and Rayan, 1998).

Another form of deficit irrigation is called sustained irrigation or limited irrigation (Wang, Liu and Zhang, 2002) where irrigation water is applied below ET continuously throughout the growing season. The theoretical basis of this type of irrigation includes crop-water relation, impacts of the water deficit on the crop growth at different stages and the physiological drought resistance of crops (Wang *et al.*, 2002). Another variant of deficit irrigation is called regulated deficit irrigation (RDI) with a theoretical basis of crop physiological and biochemistry. RDI is conducted on crops according to their characteristics and water requirement. In RDI, certain water stresses are imposed at the beginning of some crop growth stages which can change intrinsic plant physiological and biochemical process, regulate the distribution of photosynthetic products to different tissue organs and control the growth dynamics between the aerial parts and the roots to improve reproductive growth and to eventually increase crop yield (Wang *et al.*, 2002). Another form of deficit irrigation system relatively newly introduced is called controlled alternative irrigation or partial root zone drying(PRD) where alternate sides of the root system are irrigated during alternate period(Wang *et al*., 2002; Chaves and Oliveira, 2004). In this irrigation system, the plant water status is ensured by the wet part of the root system, whereas the decrease in the water use derives from the closure of the stomata promoted by dehydrating roots. The principle of PRD is that crop roots can produce signals during water stress and the signals can be transmitted to leaf stomata to control their apertures at optimum 2001), mango (Speer *et al*., 2007) and wine grapes (Bravdo and Naor, 1996; MacCarthy *et al*., 2002; Fereres and Evens, 2006). The two main reasons for this are that firstly, economic returns for tree crops are often associated with factors such as crop quality and secondly, the yield determining processes in many fruit trees are sensitive to water deprivation at some developmental stages (Johnson and Handerson, 2002).

Conflicting results were reported on the effects of deficit irrigation on annual crops, probably depending on the type and intensity of deficit irrigation and crop species considered. A study conducted by Zhang *et al*. (2002) on winter wheat in the North China plain revealed water-savings 25-75 percent by applying deficit irrigation at various growth stages, without significant yield loss. Similar results have been reported for groundnuts in India (Nautiyal *et al*., 2002). In hot pepper, Dorji *et al*. (2005) observed a 21 percent increment in total soluble solids and better colour development with deficit irrigation as compared to partial root zone drying and full irrigation. Sam-Amoah *et al*. (2013) also observed during a work on hot pepper that, 20 percent irrigation deficit did not have a significant reduction of the yield.

However, Shock and Feibert (2002) reported a reduction in potato tuber yield of as much as 17 percent due to deficit irrigation. They further reported a significant reduction in both external and internal tuber quality because of deficit irrigation.

Besides yield and quality reduction due to deficit irrigation in some crop species, the other consequence of deficit irrigation is the greater risk of increased soil salinity due to reduced leaching and its impact on the sustainability of irrigation (Fereres and Soriano, 2007). This is more evident in arid and semi-arid areas where water is scare (Smedema and Shiati, 2002). This is because the rainfall in these areas is not sufficient to provide the leaching requirement to remove excess salts accumulation in the root zone (soil surface), as evaportranspiration usually removes the water, leaving the precipitated salts. Thus, adoption of deficit irrigation without taking precautionary measures to periodically perform leaching of concentrated salts poses a problem for sustainability of irrigation.

Water-saving Technique

Water-saving techniques refer to a complete implementation and use of every possible water-saving measure in the whole farm production, including the full use of natural precipitation, as well as the efficient management of an irrigation water network (Wang *et al*., 2002; Deng, Shan, Zhang and Tuner, 2006), and these include:

Irrigation Water Management

The scarcity of water affects its availability in agricultural production systems thus, water-saving technologies and strategies are reaching considerable studies world-wide. The purpose of saving-water irrigation strategies is to use water efficiently in order to lead a sustainable agriculture. In other words, saving-water irrigation practices use less water while still keeping crop production at an acceptable level (Li, 2006). The quality and efficiency of water management determine the yield and quality of vegetable productions. The optimum frequency and amount of applied water is a function of climate and weather condition, crop species, variety, stage of growth and rooting characteristics, soil water retention capacity and texture, irrigation system and management factors (Phene, 1989). Too much water or too little water causes abnormal plant growth, predisposes plants to infection by pathogens and causes nutritional disorders. If water is scarce and supplies are inconsistent or variable, then timely irrigation and conservation of soil moisture reserves are the most important agronomic interventions to maintain yields during drought stress.

There are several methods of applying irrigation water and the choice depends on the crop, water supply, soil characteristics and topography. Application of irrigation water could be through overhead, surface, drip or sub-irrigation systems. Surface irrigation methods are utilized in more than 80 percent of the world's irrigated land yet, its field level application efficiency if often 40-50 percent (von Westarp, 2004).

Irrigation Use Efficiency

Irrigation use efficiency refers to the use of irrigation practices with the most economical exploitation of the water resources. This entails irrigation management that enables reduced water supply to crop, while still achieving a high yield, minimizing leakage and evaporation from water storage and conveyor facilities. In order to plan and strategize for efficient irrigation systems, accurate crop development models are needed in evaluating the effects of water deficits on crop yield or productivity, water requirement and water use efficiency (WUE) under water limiting conditions (Lee, Theodore, Steve, Terry and Pasquale , 2009).

Quality of Irrigation Water

Gupta and Gupta (2000) reported that, not all water is suitable for irrigation. The suitability of water for irrigation purposes depends upon the constituents of the soil to be irrigated. A particular crop or soil but the same water may be useful for irrigating another crop or soil. The following parameters are very important as they affect the quality of irrigation water.

i. pH value
ii. Total dissolved solids
iii. Sediments
iv. Proportion of Sodium ions to other Cations
v. Concentration of toxic elements
vi. Concentration of bicarbonates and
vii. Bacterial contamination.

Types of Irrigation

Irrigation can generally be group into sprinkler, drip (trickle) and surface (gravity) application systems (James, 1998). In well developed irrigation areas of the world, irrigation technologies are advanced and almost all irrigation is pressurized and served by sprinkler, mini-sprinkler and drip system. However, in developing countries, gravity methods of irrigation dominate. Sprinkler irrigation systems use sprinkler operating at pressures ranging from 70-700kpa (James, 1998) to form and distribute droplets of water over the land surface.

Drip Irrigation

Drip irrigation is the frequent slow application of water either directly onto the land surface or into the root of the crop (James, 1998). Drip irrigation delivers water directly to plants through small plastic tubes. Under drip irrigation, water losses due to run-off and deep percolation are minimized. Water savings of 50-80 percent are achieved under drip irrigation when compared to conventional surface irrigation methods (AVRDC, 2005). Crop production per unit of water consumed by plant evaportranspiration is typically increased by 10-50 percent (AVRDC, 2005). Thus more plants can be irrigated per unit of water by drip irrigation and with less labour. In general, the use of low cost-cost drip irrigation is cost effective, labour-saving and allows more plants to be grown per unit of water, thereby both saving water and increasing farmer's incomes at the same time.

Irrigation Scheduling

Irrigation scheduling is generally based on management skills which usually result in few but excessive applications (Fereres, Goldhamer and Parsons, 2003). Scheduling irrigation can however be improved when factors such as plant evaporative demand and soil characteristics are taken into account. Better irrigation scheduling methods are needed in the arid and semi arid parts of the world where water resources are scarce. Scientific irrigation scheduling methods have been available for several decades, and there has been a rise in the use of these methods (Leib, Hattendorf, Elliott and Matthews 2002). However, as Howell *et al.* (1996) pointed out, notable improvements in irrigation scheduling are needed to meet the scarce water challenges facing growers today.

Determining irrigation timing and amount traditionally involves selecting a desired allowable soil water depletion target for the given crop/soil system, calculating daily ETc using the Kc method, and using the soil water balance equation to estimate root zone soil water depletion. Therefore, when irrigation scheduling is supported by accurate Etc estimates, irrigation systems can be operated to provide the appropriate crop water requirement and attain high water application efficiencies with little leaching.

Once the crop water and irrigation requirements have been calculated, the next step is the preparation of field irrigation schedules. There parameters have to be considered in preparing an irrigation schedule:

- The daily crop water requirements
- The soil, particularly its total available moisture or water-holding capacity and
- The effective root zone depth.

Plant response to irrigation is influenced by the physical condition, fertility and biological status of the soil. Soil condition, texture, structure depth, organic matters, bulk density, salinity, sodicity, acidity, drainage, topography, fertility and chemical characteristics all affect the extent to which a plant root system penetrates into and uses available moisture and nutrients in the soil. Many of these factors influence the water-holding capacity at the soil and the ability of the plants to use the water. The irrigation system used should match all or most of these conditions. Soil to be irrigated must also have adequate surface and subsurface drainage, especially in the case of surface irrigation. Internal drainage within the crop root zone can either be natural or from an installed subsurface drainage system.

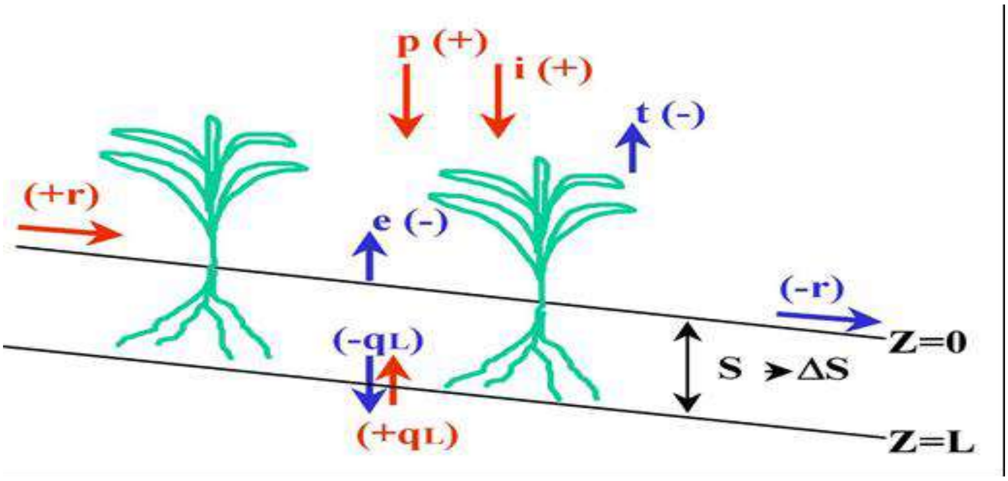
Soil Water Balance

The soil water balance is an accounting of the inputs and outs of water. The water balance of a place, whether it is an agricultural field, water shed, or continent can be determined by calculating the input, output and storage changes of water at the earth's surface (Ritter, 2006). The major input of water is from precipitation and irrigation and output is evaportranspiration as shown in the below equation.

$$\Delta S = (P+I)-(q + ET) \qquad (2)$$

The principle of the soil water balance method has been illustrated in the below in Figure 1. The objective of this method is to obtain a balance of incoming and outgoing soil water so that adequate available water is maintained for the plants. Inputs include incoming water in any form, whether from rainfall or irrigation while output may include any form of water removal from the soil.

Water removal, more commonly referred to as evaportranspiration (ET), is usually expressed in depth (mm or inches) per day. It consists of water removal by the plant (transpiration) and water loss due to evaporation from the soil surface. Two variations of the water balance method are use.



Where: i=irrigation, p= rainfall, r= runoff, ΔS= change in moisture content of soil, e= evaporation

Figure 1: Components of water balance

Water cycling in water shed or in a cropped field can be characterized and quantified by a water balance, which is the computation of all water fluxes at the boundaries of the system under consideration. It is an itemized statement of all gains, losses and changes of water storage within a specified elementary volume of soil. Its knowledge is of extreme importance for the correct water management of natural and agro-systems. It gives an indication of the strength of each component, which is important for their control and to ensure the utmost productivity with a minimum interference on the environment.

To use either variation of soil type or the available water-holding capacity of the soil should be known in addition to the root zone. This zone will vary according to the rooting depth of the particular crop. In order to determine the total water available in the root-zone, it is desirable to try to manage only a percentage of this total water, usually 50 percent. As water is removed as daily (ET), these amounts are subtracted from the adjusted water available column. When the water available approaches zero balance, it becomes appropriate to irrigate. The amount of water to be added depends on the soil type, but will usually be the same as the 50 percent value calculated earlier plus an added amount to account for application efficiencies less the 100 percent.

Water transport in the soil-plant-atmosphere continuum is an important process that is central to energy, carbon and solute balances. All these parts are integrated in a system, so changes in one part of the system will affect the others and the dynamic interactions and feedback between processes need to be considered. Water balance is based on the law of mass conservation in that any change in the water content of a given soil volume during a specific period, must equal the differences between the amount of water added to the soil volume and the amount of water withdrawn from it. When water is added to the soil volume from outside by infiltration or capillary rise, the water content of the soil volume will increase. Similarly, the water content of the soil volume will decrease when water is withdrawn by evaportranspiration or deep drainage (Zhang *et al.*, 2002).

Evapotranspiration (ET)

Crop Evapotranspiration (ET_c)

Crops need water right from the time of sowing continuously. The rate of water use is not, however, the same for all the crops. Crop water requirement is the depth of water (mm) needed to meet the water loss through ET from disease-free crop growing in a large field under non-restricting condition including soil water and fertility and achieving full production potential under the growing environment (Doorenbos and Pruitt, 1977). This concept accommodates all processes affecting the water use by crop but excludes the influences of local advection, water stress, poor soil and poor fertility management, or inappropriate farming conditions. Crop water need mainly depends on (Allen *et al*., 1998):

- The climate; in a sunny and hot climate, crops need more water per day than in a cloudy and cool climate,
- The crop type; crops like maize or sugarcanes need more water than crops like pepper or onion and
- The growth stage of the crop; fully grown crops need more water than crops that have just been planted. Under bare soil conditions or the initial growth stage of the crop growth, loss from field is mostly through evaporation, but it decreases to give way to transpiration loss as the crop grows to cover the surface of the soil, sometimes, complete 100 percent losses of water through transpiration is reported (Allen *et al*., 1998). The extent of evaporation gives an indication on how much water has been lost and thus need to be added to replenish or compensate for the loss.

Factors affecting Crop Evaportranspiration (ETc)

The main factors affecting evaportranspiration are climatic parameters, crop characteristics, management practices and environmental aspects. The main climatic factors affecting evaportranspiration are solar radiation, air temperature, air humidity and wind speed. The crop type, variety and development stages affect evaportranspiration, differences in crop resistance to transpiration, crop height, and crop rooting characteristics result in different evaportranspiration levels in different types of crops under identical environmental conditions.

Factors such as soil salinity, poor land fertility, limited use of fertilizers and chemicals, lack of pest and disease control, poor soil management and limited water availability at the root zone may limit the crop development and reduce evaportranspiration (Savva and Frenken, 2002). Other factors that affect evaportranspiration are ground cover and plant density. Cultivation practices and the type of irrigation system used can alter the microclimate, affect crop characteristics or affect the wetting of the soil and crop surface (Savva and Frenken, 2002). All these affect evaportranspiration.

Reference Crop Evaportranspiration (ET_o)

Reference crop evaportranspiration (ET_o) is defined as the rate of evaportranspiration from a large area, covered by green grass, which grow actively, completely shades the ground and which is not short of water (Allen *et al*., 1998). The reference crop evaportranspiration (ET_o), is ca climate parameter expressing the evaporative power of the atmosphere. According to Allen *et al*. (1998), the reference is a hypothetical grass reference crop with specific characteristics that provides a standard to which evaportranspiration of other crops can be related. It is needed to calculate the specific crop evaportranspiration (ET_o). that is, an evapotranspiring surface not short of water, being disease free, and well fertilized crop, growing on large field under optimum soil water condition and achieving full production under the given climate condition. It is expresses in mm/day.

Crop Coefficient (Kc)

The crop coeffient (Kc) relates to the actual rate at which a crop uses water (Etc) to ETo. Crop coefficient (Kc) for a crop is determined experimentally and reflects the physiology of the crop and the degree of crop cover. Hot pepper has four growth stages namely: the initial stage which is the period from sowing or transplanting until the crop covers about 10% of the ground; the crop development stage which starts at the end of the initial stage and lasts until the full ground cover has been reached (ground cover 70-80%); the mid-season stage which starts at the end of the crop development stage which starts at end of the mid-season stage and lasts until the last day of the harvest, it includes ripening. The Kc represents the fraction of the potential evaportranspiration used by the crop and usually varies among growth stages.

Crop coefficients are low early in the season due to small leaf area and hence low water use, and approach unity as the canopy reaches maximum development. The computation of crop factor, Kc, depends on factors such as the crop type, the climatic conditions of the environment and the growth stages of the crop. Several Kc values for pepper at different growth stages have been estimated by researchers in some agro-climatical regions. Kc values for pepper at various growth stages are as follows: initial stage = 0.35, crop development stage = 0.70, mid-season stage =1.05 and late season stage = 0.90 (FAO, 1998). Sam-Amoah *et al.* (2013) also reported ranges of Kc values for hot pepper at various growth stages as: initial= 0.41-0.74, development stage=0.72-0.83, mid-season stage =0.98-1.03 and late season stage = 0.5-0.74. This implies that different crops at different growth stages have different

Kc values. Below is the Kc graph representing the various stages of a crop's growth (FAO, 1998)

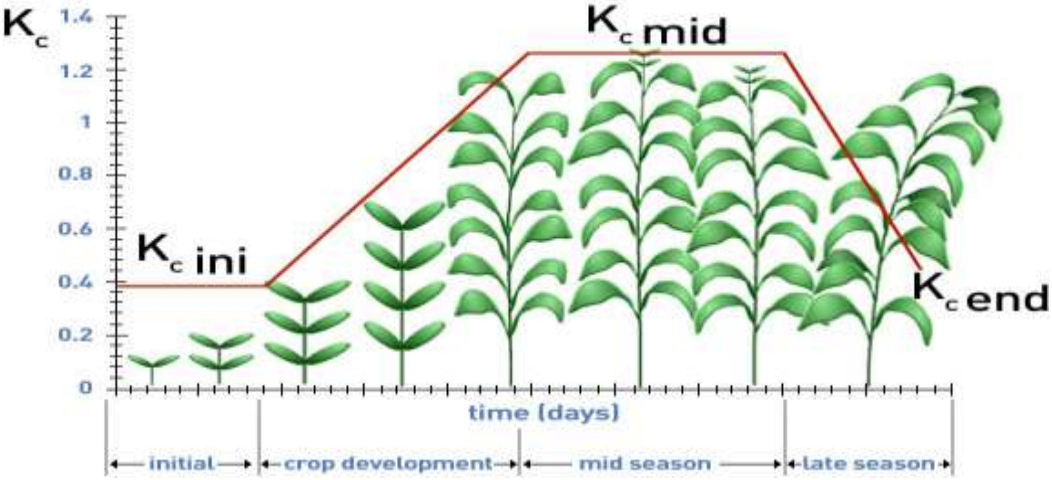


Figure 2; Kc graph representing the various stages of a growth (source: FAO, 1998)

Pan Evaporation

The evaporation rate from pans filled with water is easily obtained. In the absence of rain, the amount of water evaporated during a period (mm/day) corresponds with the decrease in water depth in that period. Pans provide a measurement of the integrated effect of radiation, wind, temperature and humidity on evaporation from an open water surface. Although the pan responds in a similar fashion to the significant difference in loss of water from water surface and from cropped surface. Reflection of solar radiation from water in the shallow pan might be different from the assumed 23% for the grass reference surface. Storage of heat within the pan can be appreciable and may cause significant evaporation during the night while most crops transpire only during the day time. There are also differences in turbulence, temperature and humidity of air immediately above the respective surfaces. Heat transfer through the sides of the pan occurs and affects the energy balance.

Notwithstanding, the difference between pan-evaporation and evaportranspiration of cropped surfaces, the use of pans to predict reference crop evaportranspiration (ETo) for periods of 10 days or longer may be warranted (Allen *et al*., 1998).

Pan Coefficient (Kpan)

FAO (1977) reported that, when using the evaporation pan to estimate the reference crop evaportranspiration (ETo), a comparison is made between the evaporation from the water surface in the pan and evaportranspiration of the standard grass as the water in the pan and the grass do not react in exactly the same way to climate. Therefore, a special coefficient is used (Kpan) to relate one to the other, the pan coefficient Kpan, depends on:

1. The type of pan used
2. The pan environment: if the pan is placed in a fallow area and
3. The climate: the humidity and wind speed.

For the Class A evaporation pan, the Kpan varies between 0.35 and 0.85. The Kpan is high if:

1. The pan is placed in a follow area
2. The humidity is high and
3. The wind speed is low.

The AquaCrop Model

AquaCrop was developed by FAO to replace the approached developed by Doorenbos and Kassam (1979), which relates yield response to water deficit of field, vegetable and tree crops. Among the significant departures of the model from its precursors, is that it separates 1) the ET into soil evaporation (E) and crop transpiration (T) and 2) the final yield (Y) into biomass (B) and harvest index (HI) (Raes, Steduto and Hanks, 2009). The separation of Y and B and HI allows the distinction of the functional relationship between the environment and HI. One of the important key features of AquaCrop is the simulation of green canopy cover (CC) instead of leaf area index (LAI). The impact of water deficit is expected to be accounted for by the variation of the green LAI. This variable is critical in plant modeling (Duchemin, Maisongrande, Boulet and Benhadj, 2008). Since the model uses canopy ground cover instead of LAI, the CC must be monitored at the field. In AquaCrop, the inputs are saved in climate, crop, soil type, management (irrigation) and initial soil water condition files (Raes *et al*., 2009a). Those model parameters that do not change with time such as normalized WP, HIo, CDC and Tr are considered conservative parameters (nearly constant). The location and cultivar-dependent parameter, as well as weather data, irrigation schedule and planting density are referred to as user defined parameters.

Yield response to water as developed by Doorenbos and Kassam (1979) is given in the equation below.

$$\frac{Yx-Ya}{Yx} = ky\frac{(ETx-ETa)}{ETx} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where, Yx and Ya are the maximum and actual yield; and ETx and ETa are the maximum and actual evaportranspiration respectively and Ky is the proportionality factor between relative yield loss and relative reduction in evaportranspiration or the crop yield response factor.

AquaCrop model separates evaportranspiration (ET) into soil evaporation (Es) and crop transpiration (Ta) by using a green canopy cover and calculates the final yield(Y) from biomass (B) by using water productivity coefficient (WP) and harvest index (HI). The separation of ET into Ta and Es avoids the consumptive use of water (Es), which is important especially during incomplete ground cover. This separation led to the conceptual equation at the core of the AquaCrop growth engine, (Equation 3).

$$\text{挠} = WP.\sum(\frac{Ta}{ETo}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where, WP is the water productivity (biomass per unit of cumulative transpiration), which tends to be constant for a given climatic condition (De Wit, 1958; Hanks, 1983; Tanner and Sincliar, 1983). By normalizing appropriately for different climatic conditions WP becomes a conservative parameter (Steduto, Hsiao and Fereres, 2007). Thus, stepping from (Equation 1 and 3) has a fundamental implication for the robustness and generality of the model. It is worth noting that both equations are expressions of a water-driven growth-engine in terms of crop model design (Steduto, 2003). The other improvement from (Equation 1) to AquaCrop is the time scale used. In case of (Equation 1), the relationship is used seasonally or for different phases of the crop lasting weeks or months, while in the case of (Equation 3) the relationship is used for daily time steps, a period closer to and approaching the time scale of crop responses to water deficits (Acevedo, Hsiao and Henderson, 1971). As in other models, AquaCrop structures its soil-crop atmosphere continuum by including: (i) the soil, with its water balance; (ii) the plant, with its growth, development and yield process; and (iii) the atmosphere, with thermal regime, rainfall, evaporative demand and carbon dioxide concentration. Additionally, some management aspects are explicit, with emphasis on irrigation, but also the levels of soil fertility as they affect crop development, water productivity and crop adjustments to stresses and therefore final yield. Pests and disease are not considered.

The procedures incorporated in AquaCrop include infiltration of water, drainage out of the root zone, evaporation and transpiration rate, biomass production and yield formation. Users can pause the simulation at each time step to observe the response of crop growth to the change in water. AquaCrop simulates output hydrological parameters including soil water content in the profile and in compartment and net irrigation requirement (Raes *et al.*, 2009). Additionally, users can use AquaCrop for simulating crop sequence and analyzing future climate scenarios (FAO, 2011).

The functional relationships between the AquaCrop components are depicted in Figure 3. The atmosphere and the soil components are largely in common with many other models. The plant component and its relations to soil water status and evaporative demand of the atmosphere are more distinctive, with effects of water stress separated into four elements, that on leaf and hence canopy growth, on stomata opening and hence transpiration, on canopy senescence and on harvest index (HI).

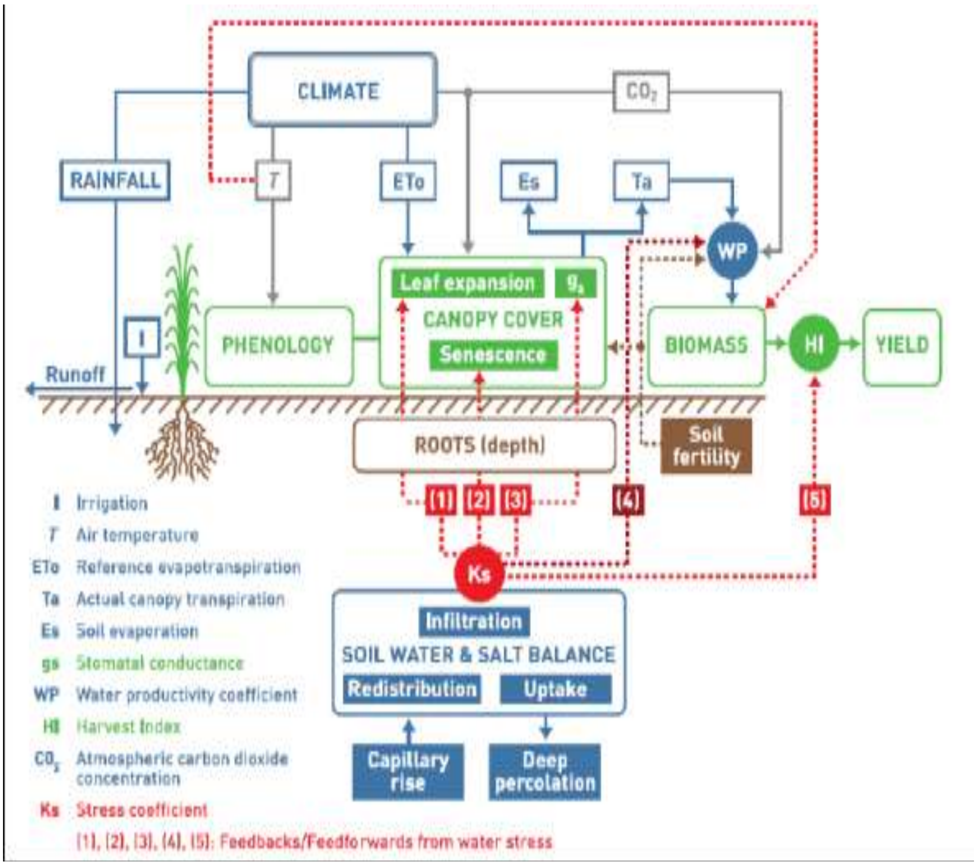


Figure 3: Flow Chart of AquaCrop indicating the main component of the soil-plant-atmosphere continuum (Source: Steduto *et al*., 2009)

CHAPTER THREE

WATER REQUIREMENT, WATER PRODUCTIVITY (WP) AND EFFECT OF DEFICIT IRRIGATION ON SOME AGRONOMIC PARAMETERS OF HOT PEPPER (*Capsicum frutescents var Legon 18)*

Introduction

Growing crops under natural conditions is usually different from the ideal. Hence, the techniques of irrigation and drainage are utilized to maintain soil moisture within a desirable range. These manipulations by humans help to increase the output from natural resources in the form of more food production, and boost the economic development of poor rural areas. Rejsberman (2003) recommended that more focus be placed on increasing the overall water productivity (WP) of crops to address water scarcity, because water is a major constraint for agriculture in years to come, particularly in Asia and Africa. Industrial and domestic need of water is drastically increasing and therefore in the future, agriculture may experience decrease in available water. Therefore, to ensure the highest crop production with the least water use, it becomes important to know the water requirement of the crops (Taygi, Sharma and Luthra, 2000).

Pepper is among the high valued cash crops which are produced by small holders and commercial growers for domestic use and export. Its production has been challenged by the lack of proper alternative irrigation methods, inputs, strategies, etc. (Alemu and Ermias, 2000). Therefore, estimating ETc and the Kc for crops for a particular environment is necessary in order to have proper and timely irrigation schedules which help to optimize yields and net benefits from the crop production. With the view of making the most out of available water for crop production, this study focuses on the water requirement, WP and effect of deficit irrigation on the growth and yield of hot pepper.

Materials and Methods

Experimental Location

Two experiments were carried out at the University of Cape Coast, School of Agriculture Teaching and Research Farm which lies within the coastal savannah vegetation zone of Ghana. It lies on latitude 01-15^0 South at an altitude of 1.1m. The soil characteristic of the site is described as slightly acidic in reaction and with a pH of 6.5. Owusu-Sekyere, Alhassan and Nyarko. (2011) reported that the annual temperature of the site ranges from 23.2-33.2^{0}C with an annual mean of 27.6^{o}C and relative humidity ranging from 81.3-84.4%. The site experiences two rainy seasons namely: the major season which starts from May and ends in July and the minor season that starts around September and ends around mid-November to give way to the dry harmattan season that runs through to the end of March.

Experimental Design and Field Layout

The experiments involved the growing of hot pepper (*Capsicum frutescens var legon 18*) on raised beds 1.95m x 1.20m. The first experiment was done between August, 2014 and December, 2014. Results obtained from the first experiment were used to calibrate the AquaCrop model. The second experiment was done between September, 2014 and January, 2015. Results obtained from the second experiment were used to validate the AquaCrop Model.

A Randomized Complete Block design was used with four irrigation treatments of different levels (T_1-T_4) consisting of 16 plants per plot with spacing 0.65m x 0.40m. 4 plants were sampled per plot. Each treatment was replicated three times (R_1-R_3) under a rain shelter.

Treatments

The treatments used for the study were different levels of irrigation water applied. They were as followed:

T_1 = 100% ETc for full irrigation water level

T_2 = 90% ETc for irrigation at 10% deficit

T_3 = 80% ETc for irrigation at 20% deficit

T_4 = 70% ETc for irrigation at 30% deficit.

Test crop and Agronomic Practices

Hot pepper seeds of Legon 18 variety were used to nurse on raised bed in rows 10-15cm apart. Watering was done two times every day until first germination of seeds was observed. For each of the experiment, transplanting of relatively uniformly sized seedlings was done three (3) weeks after planting. Weeding was also done by hand as soon as they appeared. To reduce the effect of pests and diseases on the growth and yield of the crop, spraying was done two times during each of the experimental period as per the recommended quantity.

Monitoring of growth stages

For monitoring of plant growth stages, four stages were monitored and considered for the two experiments namely: the initial stage (which excluded nursery), the developmental stage (vegetative stage), the mid-season stage (flowering and fruiting stage) and the late season stage (full maturity and ripening of fruits). During each of the experiments, the number of days each growth stage lasted was: 18 days, 30 days, 46 days and 18days for the initial stage, developmental stage, mid-season stage and the late stage respectively. These were later characterized by senescence which involved the drying of leaves and later falling.

Soil analysis

Soil samples were taken from each plot and analyzed for physical and chemical fertility status. Table 3 shows the initial physical and chemical properties of the soil.

Table 3: Laboratory results of the initial soil physical and chemical properties of the experimental site.

Nitrogen(N) %	Phosphorous(P) µgP/g	Potassium(K) Cmolkg	pH	FC %
0.801	141.04	1.04	5.7	28.82

Irrigation regime and application

A two-day irrigation interval was adopted for the experimental periods. The US Class A evaporation pan was used to monitor the rate of evaporation and subsequently the reference crop evaportranspiration (ETo). (ETo) was calculated as given in [Equation 3.1].Crop water requirement (ETc) was calculated adopting Kc values from Sam-Amoah *et al.*(2013) and using Equation 3.2.

$ET_0 = Epan\ X\ Kpan$ ………………………………………………... (3.1)

$ETc = K_c\ X\ ET_o$ …………………………………………………......….. (3.2)

Where $ET_c =$ Crop evaportranspiration or Crop water requirement (mm/day), K_c =Crop factor, ET_o = Reference crop evaportranspiration, Epan = Pan Evaportranspiration, Kpan= Pan coefficient (0.8)

Water Productivity (WP)

Water productivity (g/mm) was determined by dividing the mean harvested fruit weight (g) per treatment by the ETc (mm) as given in Equation 3.4.

$WP=\frac{Y(g)}{ETc(mm)}$ ……………………………………………………………. (3.4)

Where WP= Water Productivity (g/mm), Y=mean fruit weight (g) and ETc= Crop Evaportranspiration for the growing season.

Growth Parameters that were measured

Plant height: Plant height at the various growth stages were measured using a meter rule. Data obtained were summed up and divided by the number of plants to obtain the mean plant height.

Number of fruits per treatment: The number of fruits per treatment was determined by counting the number of harvested fruits on each plant per plot of a treatment and divided by the number of plots per treatment up to obtain the mean number of fruit per treatment.

Mean fruit weight: The number of fruits per plot was weighed using an electronic analytical balance then summed up and divided by the number of plots per treatment

Green canopy cover: Green canopy cover was measured at two weeks' interval, over the whole growing season by a digital camera. Imagines of the canopy cover captured were inputted into Photoshop software (Adobe Photoshop 2014cc) to analysis the percentage covered.

Data Analysis

Data collected were subjected to Analysis of Variance (ANOVA) using Genstat statistical package, 4th Edition. The treatment means were tested using the Duncan Multiple Range Test at probability level of 5%.

Results and Discussions

The two experiments recorded 315.70 mm and 318.30 mm for the first and second experiments respectively as water requirements for hot pepper grown in Cape Coast. Both experiments lasted for 112 days after transplanting. The Kc values, 0.41, 0.72, 0.98 and 0.74 for the initial, development, mid-season and late season stages respectively were adopted from Sam-Amoah *et al.* (2013). Tables 4 and Table 5 depict the growth period, ETo, ETc

and Kc for all the growth stages for both experiments.

Table 4: ETo, ETc and Kc for all the growth stages for the first experiment

Growth Stage	Period (days)	ETo	ETc 100%	ETc 90%	Etc 80%	ETc 70%	Kc 100%	Kc 90%	Kc 80%	Kc 70%
Initial	18	54.40	22.30	16.90	12.90	9.90	0.41	0.34	0.26	0.20
Dev.	30	87.20	62.80	57.00	54.40	43.20	0.72	0.60	0.56	0.47
Mid.	46	194.80	190.90	155.80	126.60	107.10	0.98	0.80	0.65	0.55
Late	18	53.6	39.7	21.40	18.20	15.00	0.74	0.40	0.34	0.28
Sum	**112**	**339.4**	**315.7**	**251.1**	**212.10**	**175.30**				

Table 5: ETo, ETc and Kc for all the growth stages for the second experiment

Growth Stage	Period (days)	ETo	ETc 100%	ETc 90%	Etc 80%	ETc 70%	Kc 100%	Kc 90%	Kc 80%	Kc 70%
Initial	18	61.60	25.3	18.80	14.40	11.00	0.41	0.34	0.26	0.20
Dev.	30	108.00	77.80	64.80	60.50	50.80	0.72	0.60	0.56	0.47
Mid.	46	172.40	169.00	137.90	112.10	94.80	0.98	0.80	0.65	0.55
Late	18	62.40	46.20	25.00	21.20	17.50	0.74	0.40	0.34	0.28
Sum	**112**	**404.4**	**318.30**	**246.5**	**208.2**	**174.10**				

Like hot pepper, different crops have different water requirement for different environment under and weather conditions. As shown in Tables 4 and 5, the trend of crop evaportranspiration of hot pepper shows an increase from the initial stage to the mid-season stage after which a decline in ETc was realized during the late stage. This implies that there was less ET of the crop at the initial stage. The smaller amount of water used at the initial stage could be due to less development of the leaf area and canopy establishment to transpire and most of the water used during the initial stage was evaporation from the bare soil. During the development stage, an increase in ETc was realized. This could be attributed to good root soil contact and ample leaf area development for transpiration which satisfy the demand of the atmosphere coupled with evaporation. The highest crop ET was obtained in the mid-season stage; this could be as a result of peak phonological advancement like fruit formation and attainment of maximum leaf area. Finally, during the late season stage, the ETc showed a decrease which could be as a result of senescence of leaves and it was the sign of maturity and declining of growth and development of the crop.

Several authors have done similar work regarding the water requirement for hot pepper. The values of the seasonal ETc for hot pepper found in this study are different from the ranges given by Allen *et al*. (1998) for hot pepper, which ranges from 600 mm to 900 mm, depending on the region, climate and variety. Growing conditions, climate and cultivar differences may have contributed to the observed differences between the results of ETc obtained and those of FAO estimation. Adopting the Kc values from Sam-Amoah *et al.* (2013) however shows, values recorded in this research were a bit lower than values in similar work done by Sam-Amoah *et al.* (2013) of hot pepper in a potted experiment which resulted in water requirement of hot pepper ranging from 319.5 mm to 432.05 mm. Differences observed in this study from that of Sam-Amoah *et al.*(2013) and other authors can be attributed to the length of time taken for the growing period, climatic condition and the planting environment.

Generally, this work conforms to work done by Agodzo, Leir, Duran and Smith (2003) which indicated that the crop water requirement of hot pepper ranged between 300mm- 700mm depending on the climatic condition and the season of the crop and the location.

Table 6: Water Productivity (WP) of hot pepper under the various treatments

Treatment	**First Experiment**				**Second Experiment**			
	Mean fruit weight g	**ETc mm**	**WP* g/mm**	**WP* Kg/m^3**	**Mean fruit weight g**	**ETc mm**	**WP* g/mm**	**WP* Kg/m^3**
T_2	248.90	251.10	0.99a	0.43	247.09	246.50	1.01a	0.43
T_1	280.90	315.70	0.89ab	0.38	280.19	318.30	0.88ab	0.39
T_3	120.20	212.10	0.57ab	0.25	122.60	208.20	0.59ab	0.25
T_4	73.60	175.30	0.42b	0.18	75.50	174.10	0.43b	0.19
			s.e.d=0.2079				s.e.d=0.2086	

Treatment means with the same letters are not significantly different at 5% probability level but means with different letters are significantly different from the rest.

From Table 6, it can be seen that of all the treatments applied, T_2 (90%) had the highest water productivity ranging from 0.99g/mm-1.01g/mm closely followed by T_1 which obtained a productivity of 0.88g/mm-0.89g/mm. However, T_3 and T_4 obtained water productivities of 0.57g/mm-0.59g/mm and 0.42g/mm-0.43g/mm respectively. However, statistically T_2 was not significantly ($P<0.05$) different from T_1 and T_3 but different from T_4. T_1 also was not statistically different from T_3 and T_4 while there was no statistically significant difference between T_3 and T_4.

Nagaz, *et al.* (2012) reported that, apart from the total amount of irrigation water applied, the timing of irrigation is also important. Water stress during different growth stages affect water productivity differently. The results can be compared with that presented by Gencoglan, Alkinci, Ucan, Alkinci and Gencoglan (2006); Dagdelen, Yilmaz, Sezgin and Guerbeuz (2004) and Nagaz,*et al.* (2012) that WP is significantly influenced by irrigation water applied. However, the low and high water productivity of hot pepper in respect to irrigation water applied can be attributed to the result of low and high yield obtained in proportion to the total water applied for the growing season. The influences of irrigation water management on water productivity have been described by many authors; for example, Oktem, Simsek and Oktem(2003); Zhang, Sui and Li(1998); Yazar *et al* (2002a); Kang, Zhang, Xiaotao, Zhijun and Peter(2001). Therefore, deficit irrigation practices have been researched to quantify the effects on the yield of crops and to find optimum water productivity values. However, from this work, it can be seen that the water productivity of T_2 was not significantly different from those of T_1 and T_3 during the period but was different at T_4. This implies that in term of water conservation as a means to produce more food and to reduce production cost, deficit irrigation at 10 -20% of the required crop water can be practiced to obtain a relatively appreciable yield from water saved.

Table 7: Mean plant height (cm) for the water levels applied at the various stages of the plant growth for the first experiments.

Treatment	FIRST EXPERIMENT			
	INITIAL 18 DAT (cm)	DEVELOPMENTAL 48 DAT (cm)	MID-SEASON 94DAT (cm)	LATE SEASON 112DAT (cm)
T_1	29.63a	42.21a	54.40a	67.89a
T_2	26.27ab	40.50ab	51.97ab	62.89a
T_3	21.27bc	37.33b	48.23b	60.99a
T_4	16.40c	31.03c	37.47c	48.63b
	Sed.=2.222	Sed.=1.448	Sed.=2.127	Sed.= 3.01

Treatment means with the same letters are not significantly different at 5% probability level but means with different letters are significantly different from the rest.

Table 8: Mean plant height (cm) for the water level applied at the various stages of the plant growth for the second experiments.

Treatment	SECOND EXPERIMENT			
	INITIAL 18 DAT (cm)	DEVELOPMENTAL 48 DAT (cm)	MID-SEASON 94DAT (cm)	LATE SEASON 112DAT (cm)
T_1	30.08a	42.87a	54.54a	67.92a
T_2	26.06a	40.75ab	52.17a	63.13a
T_3	20.38b	37.45b	49.22b	60.81a
T_4	20.38b	31.35c	38.16b	48.84b
	Sed.=2.127	Sed.=1.409	Sed.=2.622	Sed.=2.91

Treatment means with the same letters are not significantly different at 5% probability level but means with different letters are significantly different from the rest.

The plant height of the hot pepper for four growth stages at the various irrigation levels are presented in Tables 7 and 8 for both experiments. From both experiments, it can be observed that T_1 (Full irrigation) obtained the highest mean plant height. The first experiment shows that though T_1 obtained the highest mean plant height it was not significantly different from T_2 (90%ETc) and T_3 (80%ETc) which obtained mean plant heights of 67.89cm, 62.89cm and 60.99cm respectively. However, the three treatments $T_{1,}$ T_2 and T_3 were significantly ($P<0.05$) different from T_4 (70%ETc) which obtained a main plant height value of 48.63cm.

Similarly, results from the second experiment show that treatments $T_{1,}$ T_2 and T_3 which obtained mean plant height values of 67.92cm, 63.13cm and 60.81cm respectively, were not significantly($P<0.05$) different from each other. However, T_4 obtained a mean plant height value of 48.84cm and was significantly different from the rest of the treatments.

Water typically makes up 80-95% of the mass of growing plant tissues. The mean plant height decrease with irrigation water applied and thus, T_1 has the highest mean plant height. Antony and Singanhype (2004) reported that fully irrigated crop gave the highest mean plant height which may be as a result of increased soil water content which allows easy up take by roots and enhance cells elongation of the plant. Also, Allen *et al.* (1998) indicated that plants grow rapidly with increase in crop water use. Plant growth is also rapid when its water use is optimum by which it may transpire enough water by the leaves thus increasing leaf area and canopy cover, plant height and root development. The mean plant heights did not statistically differ amongst treatments $T_{1,}T_2$ and T_3; indicating that water stress did not significantly affect mean plant height of hot pepper up to 20% water deficit, but T_4 gave the lowest mean plant height. Similarly, Techawongstein, Nawata and Shigenaga (1992); Owusu-Sekyere *et al.*, (2010); and Sam-Amoah *et al.*, (2013) have reported water stress as a limiting factor affecting the height of hot pepper.

Table 9: Mean fruit yield and weight per treatment for the two experiments

	First Experiment			**Second Experiment**		
Treatment	**Mean number of fruit per treatment**	**Mean fruit weight per treatment (g)**	**Mean yield (tons/ha)**	**Mean number of fruit per treatment**	**Mean fruit weight per treatment (g)**	**Mean yield (tons/ha)**
T_1	56.67a	280.90a	1.20	56.40a	280.19a	1.20
T_2	53.00ab	248.90ab	1.07	52.67a	247.09ab	1.07
T_3	40.11bc	120.20bc	0.51	44.43ab	122.60bc	0.51
T_4	31.00c	73.60c	0.31	35.00b	75.50c	0.34
	Sed.=3.95	Sed.=58.20		Sed.=4.10	Sed.=58.10	

Treatment means with the same letters are not significantly different at 5% probability level but means with different letters are significantly different from the rest.

Table 9 shows the result of the mean number of fruits per treatment and the mean fruit weight for both experiments. From the Table, it can be seen that during the first experiment, T_1(Full Irrigation) produced 56.67 fruits per treatment as the highest which was closely followed by T_2,$T_{3,}$ and T_4 which produced 53.00,40.11 and 31.00 fruits respectively. Statistically, T_1 was not significantly different from T_2. However, T_1 was significantly ($P<0.05$) different from T_3 and $T_{4.}$ There were no significant different as between T_2 and T_3 but T_2 was significantly different from T_4. T_4 produced the lowest mean number of fruit but was not significantly different from T_3. Also from Table 9, it can be seen that during the second experiment T_1 (full irrigation) produced the highest mean number of fruits which was not significantly different from T_2 and T_3 but was significantly different from T_4. Similarly, T_3 was not significantly different from T_4.

Pepper plants are most sensitive to water stress during flowering and fruit development (Katerji *et al.,* 1993). Therefore, fully irrigated crop, T_1 gave the highest yield which may be because increasing soil water content led to increasing plant height and number of branches resulting in an increase number of fruit and total yield. The results can be compared with results reported by Antony and Singanhype (2004), Owusu-Sekyere *et al* (2010) and Sam-Amoah *et al*. (2013). This implies the possibility of employing strategies which may save water for increased production which may offset reduction in yield. T_4 produced the lowest mean number of fruits in both experiment. This reduction in fruit can be seen as a confirmation of hot pepper sensitivity to water stress during the reproductive stages Dorji *et al.* (2005). Dorji *et al.* (2005) reported that fruit reduction could also be as a result of flora abortion.

In both experiments, T_1 produced the highest fruits weighing 280.9g and 280.19g respectively. T_2, T_3 and T_4 obtained mean fruit weights of 248.9g, 120.2g and 73.6g and 247.1g, 122.6g and 75.5g respectively for both experiments. However, when subjected to the ANOVA, the weight of T_1 was not significantly different from T_2 but was significantly different from T_3 and T_4. T_2 however did not differ significantly from T_3 but was significantly different from T_4. There were also no significant difference between T_3 and T_4.Water highly affects the yield of crops. Alvino *et al* (1994) asserted that pepper leaves photosynthesize more efficiently when water is abundant, this result in higher percentage of large, heavy marketable fruits. This confirms the findings of this work by T_1 (full irrigation) obtaining the highest fruit weight.

T_4 obtained the lowest fruit weight. The reduction of fresh fruit yield of hot pepper could be due to deficit irrigation because decreasing the soil water content in the soil reduces the fruit size, fruit number and the total fruit weight of hot pepper (Fernander *et al*., 2005). The greatest reduction in yields occurs when there is a continuous water shortage until the first time of harvest (Jaimez *et al*., 2000; Delfine *et al*., 2001; Costa and Gianquinto, 2002; Sezen *et al*., 2006).

Table 10: Measured Green Canopy Cover (%) for Experiment One

Treatment	FIRST EXPERIMENT							
	Initial	Percentage covered	Developmental	Percentage covered	Mid-season	Percentage covered	Late season	Percentage covered
	18 DAT	18 DAT	48 DAT	48 DAT	94 DAT	94 DAT	112 DAT	112 DAT
	%	%	%	%	%	%	%	%
T1	18.45a	10.00	55.28a	67.50	63.77a	80.3	56.81a	70.00
T2	17.99a	9.60	53.55ab	64.70	62.35a	77.7	56.10a	68.70
T3	16.87a	8.50	49.55b	57.90	58.56a	72.7	47.68b	54.70
T4	15.23a	7.10	48.26b	55.70	55.76a	68.3	45.38b	50.70
	Sed.= 1.407		Sed.=2.118		Sed.=3.95		Sed.= 2.552	

Mean green canopy covers within a column with the same letter are not significantly different from each other at probability level of 5%

Table 11: Measured Green Canopy Cover (%) for Experiment Two

Treatment	SECOND EXPERIMENT							
	Initial	Percentage covered	Developmental	Percentage covered	Mid-season	Percentage covered	Late season	Percentage covered
	18DAT	18 DAT	48 DAT	48 DAT	94 DAT	94 DAT	112 DAT	112 DAT
	%	%	%	%	%	%	%	%
T1	18.39a	10.00	55.33a	67.60	63.65a	80.10	56.81a	70.00
T2	17.66a	9.20	53.95ab	63.30	62.10a	77.40	56.16a	68.8
T3	16.87a	8.50	49.78bc	58.30	58.70a	72.90	48.28b	55.7
T4	15.53a	7.40	48.32c	56.10	55.84a	68.50	45.80b	51.4
	Sed.=1.17		Sed=2.15		Sed=3.86		Sed=2.559	

Mean green canopy covers within a column with the same letter are not significantly different from each other at probability level of 5%

Tables 10 and 11 show the results of green canopy development of hot pepper during the growing periods of the two experiments. From the tables, it can be seen that hot pepper canopy developed increasingly from 18DAT-112DAT. During the initial stage at 18DAT, it was observed that, for both experiments, hot pepper achieved 10% of its canopy cover while it developed. It achieved canopy cover of 67.50%-67.50%, 80.10%-80.30% and 70.00% at 48DAT, 94DAT and 112DAT for experiment 1 and 2 respectively. When results obtained were transformed using the arcsine transformation and subjected to ANOVA at probability level of 5%, it was observed that at 18DAT, there were no significant difference between the treatments (T_1-T_4).

However, T_1 achieved the highest canopy cover of 10% and was closely followed by T_2,T_3 and T_4 which obtained canopy cover of 9.20% - 9.60%, 8.5% and 7.10% - 7.40% for experiment 1 & 2 respectively. The amount of moisture transpired by the crop and evaporated from the bare soil to satisfy the demand of the atmosphere is associated with leaf area development and canopy cover which increases or decreases the area that is exposed to direct sunlight. The values of canopy cover presented at 18DAT show that the rest of the soil surface was exposed to direct sunlight, indicating that crop evaportranspiration at this stage is mostly satisfied from soil evaporation. Allen *et al.* (1998) also indicated that at transplanting, nearly 100% of ET comes from evaporation, while at full crop cover (mid-season stage) more than 90% of ET comes from transpiration.

Crop use more water in the developmental stage than the initial stage. During the developmental stage, T_1 obtained a cover of 67.50% -67.60% followed by T_2,T_3 and T_4 which obtained canopy cover of 63.30% - 64.70%,58.3% - 57.90% and 56.1% - 55.70% respectively for experiments 1 & 2. Statistically, T_1 was not different from T_2 but was different from T_3 and T_4. However, T_2 was not statistically different from T_3 and T_4. As asserted by Allen *et al.* (1998), the full canopy cover was obtained during the mid-season stage. T_1 obtained the highest canopy cover ranging from 80.1% -80.3%. T_2 followed with canopy covers ranging from 77.4% - 77.7% which was followed by T_3 and T_4 (72.70% -72.9% and 68.3% - 68.3%) respectively for the both experiments 1 and 2. Steyn (1997) reported that the size of canopy cover has a direct influence on evaportranspiration. Tables 4 and 5 shows that ETc increased throughout the crop growth stage was highest during the mid-season stage after which a decline was observed in the late season stage. Statistically, percentage of canopy covered during the mid-season was not significantly different from each other.

However, it is important to note that during the late season stage, a declined was observed in the percent canopy covered in hot pepper.T_1 recorded a decreased canopy cover to 70% followed by T_2 which obtained covers ranging from 68.7% -68.8%. Statistically, T_1 was not different from T_2 but was different from T_3 and T_4. Sharp declined was observed in the canopy cover of T_3 and T_4 probably because of the water shortages. T_3 obtained late covers of 54.7% - 55.7% while T_4 obtained covers of 50.7% - 51.4%.

Nitrogen (N), Phosphorous (P) and Potassium (K) Utilization

The N, P and K utilization by the various treatments for the late stage is shown in Figures 4, 5 and 6.

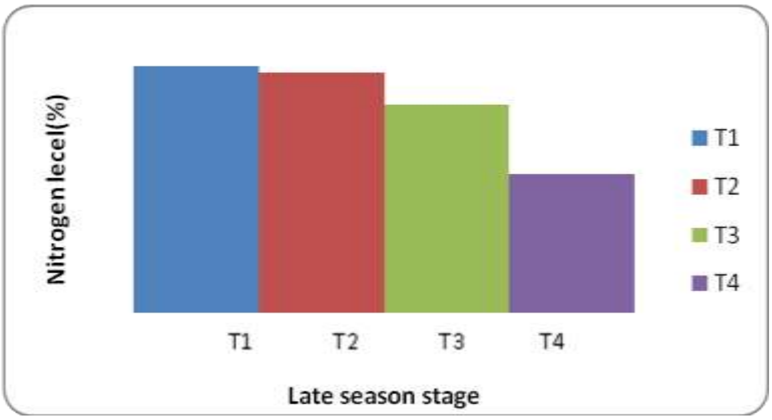


Figure 1: Levels of nitrogen in the soil at the late stage

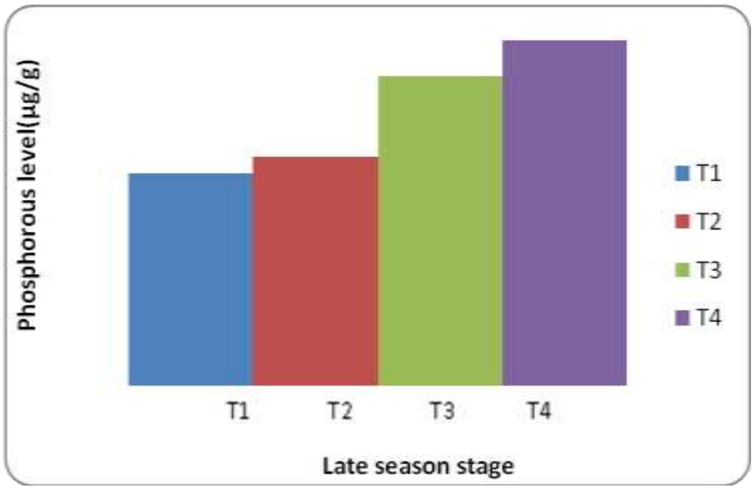


Figure 2: Levels of phosphorous in the soil at the late season stage

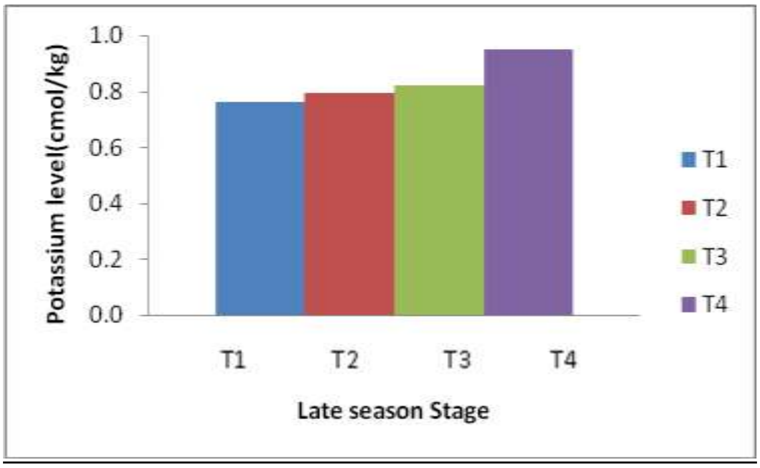


Figure 3: Levels of potassium in the soil at the late season stage

The availability of soil water affects the uptake of soil NPK level by plants. These nutrients coupled with cultivar type, agronomic practices, environment, weather condition, help to enhance growth and yield of crops. From the figures, N utilization was observed more by T_4 followed by T_3, T_2 and T_1. N uptake by plant helps to increase plant height and yield components. However, it can be concluded that T_1 did not obtain the highest yield and mean plant height as a result of N utilization. This is in agreement with reports by Owusu-Sekyere *et al.* (2010) and Sam-Amoah *et al*. (2013) that water uptake did not favour the uptake of N. It was however observed that T_1 utilized the most P of the soil P level which was followed by T_2, T_3 and T_4. T_4 did not really utilize the P level of the soil which may be as a result of water stress which reduces the soil water content. Similarly as reported by Owusu-Sekyere *et al*. (2010) and Sam-Amoah *et al*. (2013), K level utilization in this work showed that T_1 utilized most of the soil K, followed by T_2, T_3 and T_4 in that order.

Conclusion

The Crop water requirement determined ranged from 315.7mm to 318.30mm for hot pepper grown in Cape Coast, Ghana. Thus, results show that the Kc values adopted from Sam-Amoah *et al.* (2013) were quite accurate in determining ETc for hot pepper in the coastal savannah ecological zone of Ghana. Water productivity of hot pepper was influenced by the total yield produced in proportion to the amount of water applied. However, it is important to note that the water productivity of 20% deficit irrigation did not significantly differ from that of fully irrigated hot pepper and 10% deficit irrigated hot pepper. It was also noted that agronomic parameters such as mean plant height and canopy cover along with yield were influenced by level of irrigation. However, it was also noted that at highest canopy cover during the mid-season stage, significant difference did not occur between treatments, but in the late stage did not significant ($P<0.05$) differences were observed.

CHAPTER FOUR

VALIDATION OF THE AQUACROP MODEL FOR FULL AND DEFICIT IRRIGATED HOT PEPPER FOR CAPE COAST, GHANA

Introduction

On a global scale, irrigated agriculture uses about 72% of available fresh water resources (Geerts, Raes, Gracia, Miranda, Cusicanqui, Taboada and Steduto, 2009).Therefore, the rapid increase of the world's population and the corresponding demand for extra water by other sectors such as industries and municipal compels the agricultural sector to use its irrigation water more efficiently in other to produce more food to meet the global demand. This has pushed the agricultural sector to define optimum strategies in planning and management of available water resources in the sector and this is becoming a national and global priority (Salaza, Wesstrom, Youssef, Wayne, Skaggs and Joel, 2009).

To address these needs, FAO has developed a yield-response to water model named the AquaCrop model. That simulates attainable yields of major field and vegetable crops. Although the model is simple, it gives particular attention to fundamental processes involved in crop productivity and in the responses to water, from physiological and agronomical background perspectives (Bitri, Grazhdani and Ahmeti, 2014). The ease of the use of AquaCrop model, the low requirement of input parameters, and its sufficient degree of simulation accuracy make it a valuable tool for estimating crop productivity under rainfed conditions, supplementary and deficit irrigation, and on farm management strategies for improving agriculture (Heng, Hsiao, Evett, Howell and Steduto, 2009). This makes the AquaCrop an important tool in evaluating the effects of water deficits on crop yield or productivity (Heng *et al.*, 2009).

AquaCrop Model has been tested in many parts of the world for several crops such as maize (Heng *et al.*, 2009), potato (Bitri *et al.*, 2014), hot pepper (Sam-Amoah *et al*., 2013) and its simulation performances were relatively accurate. Therefore, the objective of this work was to validate the AquaCrop model for irrigated hot pepper grown in Cape Coast, a coastal savanna town in the Central region of Ghana.

Materials and Methods

Experimental Location

Two field experiments were carried out at the University of Cape Coast, School of Agriculture Teaching and Research Farm which lies within the costal savannah vegetation zone of Ghana. The Farm lies on latitude 01-15^0 south at an altitude of 1.1m. The soil characteristic of the site is described as slightly acidic in reaction and with a pH of 6.5. Owusu-Sekyere *et al.* (2011) reported that the annual temperature of the site is in the range 23.2-33.2^0C with an annual mean of 27.6^oc and relative humidity ranging from 81.3-84.4%. The experimental location experiences two rainy seasons namely: the major season which starts from May and ends in July and the minor season that starts around September and ends around mid-November to give way to the dry harmattan season that runs through the end of March.

Experimental Design and Field Layout

The experiments involved the growing of hot pepper (*Capsicum frutescens var legon 18*) on raised beds 1.95m x 1.20m. The first experiment was undertaken between August, 2014 and December, 2014. Results obtained from the first experiment were used to calibrate the AquaCrop model. The second experiment was undertaken between September, 2014 and January, 2015. Results obtained from the second experiment were used to validate the AquaCrop Model.

The Randomized Complete Block design was used with four irrigation treatments of different levels (T_1-T_4) consisting of 16 plants per plot with spacing of 0.65m x 0.40m. 4 plants were sampled per plot. Each treatment was replicated three times (R_1-R_3) under a rain shelter.

Treatments

The treatments used for the study were different levels of irrigation water applied. They were as followed:

T_1 = 100% ETc for full irrigation water level

T_2 = 90% ETc for irrigation at 10% deficit

T_3 = 80% ETc for irrigation at 20% deficit

T_4 = 70% ETc for irrigation at 30% deficit.

Operation of the AquaCrop Model

The AquaCrop model uses green crop canopy ground cover (CC) instead of LAI. Therefore, CC was monitored throughout the growing season. In AquaCrop, inputs were saved in climate, crop, soil type, management (irrigation) files (Raes *et. al.*, 2009a). Model parameters that do not change with time such as normalized water productivity (WP*), harvest index (HI), Canopy development coefficient (CDC) and actual transpiration (Ta) were considered conservatives. (Steduto, Hsiao, Raes and Fereres, 2009) gave a detailed description of the AquaCrop model. Finally, the model was run to simulate crop growth and yield and data generated was compared with measured data.

Creating Data input files

Creating Climate File

Creating climate file in AquaCrop involved selecting or creating a Temperature file, ETo file, Rain file and CO_2 file. To create these files, the type of data was specified ie, (daily, 10-daily or monthly data), the time range and the data. However, for this study daily was specified.

Temperature data was collected from the nearest meteorological station in Cape Coast, Ghana and rainfall data covering the period of experiment was entered as zero since a rain shelter was used. A US Class A evaporation pan was used to estimate the daily reference evaportranspiration (ETo) over the growing season by using the equation:

ETo =Kpan X Epan ……………………………………………...…. (3.1)

Where Kpan = Pan Coefficient, Epan = Pan evaporation (mm/day).

Creating Crop file

When creating the crop file, the type of crop was selected (Fruit/grain producing) and a few parameters were specified considering the duration of the experimental period including the percentage cover of canopy development during the growing period and plant density. AquaCrop then generated the complete set of required crop parameters from the specified parameters. Crop files were created for each of the treatment.

Creating an Irrigation file

Creating an irrigation file which included the irrigation schedule, the time and the application depth of irrigation events for the experiment were specified. Irrigation files were created for each of the treatment. During the growing period, 56 days out of the 112 days were irrigation days and depths of irrigation (ETc) specified were calculated by the equation:

$ETc = K_c X ET_o$ ………………………………………………………... (3.2)

Where $ET_{c\,=}$ Crop evaportranspiration or Crop water requirement (mm/day), K_c =Crop factor, ET_o = Reference crop evaportranspiration

Creating a Soil File

To create a soil file, the soil type and field capacity of the soil were specified .With the aid of this information, AquaCrop then generated the complete set of soil parameters.

Calibration

Parameterization of AquaCrop

As stated earlier, some crop parameters were assumed to be conservatives (values do not change) and user-specific parameters were results collected from the experiments as shown in Tables 12 and 13.

Table 12: Conservative parameters used to run simulations

Parameter	Value	Units/Meaning
Base temperature	10	^{0}C
Upper temperature	30	^{0}C
Soil H_2O depletion factor, canopy expansion	0.25	Upper threshold(p-exp)
Soil H_2O depletion factor, canopy expansion	0.50	Lower threshold(p-exp)
Positive effect on Harvest Index	small	
Negative effect on Harvest Index	small	
Maximum possible increase of Harvest Index	15	%
H_2O productivity normalized for ETo & CO_2	17	g/m^2(WP*)
H_2O productivity normalized for ETo & CO_2 during yield formation	100	g/m^2(WP*)

Table 13: Experimental or user specific information used to calibrate the AquaCrop Model

Parameter	Unit	Measured/Calibrated for Treatments			
		T_1	T_2	T_3	T_4
Soil surface covered by individual seedling	cm^2/plant at (90%) recover	16	16	16	16
Number of plant per hectare	Ha^{-1}	38,462	38,462	38,462	38,462
Time from transplanting to recovery	days	7	7	7	7
Maximum canopy cover, CCx	%	80.3	77.7	72.7	68.3
Time from transplanting to start of senescence	Days	90	90	90	90

Table 13: (Continued)

Time of Transplanting to maturity(Length of crop cycle)	Days	112	112	112	112
Time from transplanting to flowering	Days	63	63	63	63
Length of Flowering stage	Days	13	13	13	13
Maximum effective rooting depth	m	0.80	0.80	0.80	0.80
Time from sowing to maximum rooting depth	Days	50	50	50	50
Rainfall	mm	0	0	0	0
ETo	mm	339.40	339.40	339.40	339.40
Etc	mm	315.70	251.10	212.10	175.30
Soil Texture		Sandy loam	Sandy loam	Sandy loam	Sandy loam

Validation of the AquaCrop model

An important step of a model's verification is validation. Validation of the AquaCrop model in this study involved the comparison between independent field measurements and outputs created by the model. This study considered water requirements (ETc), maximum canopy cover (CCx), total fruit yield and water productivity (WP) of irrigated hot pepper in Cape coast, Central region of Ghana. Tables 13 and 14 present a summary of outputs of the AquaCrop model in comparison with measured data.

To compare the simulated data against the observed data, two statistical indices were considered: the root mean square error (RMSE), which is calculated as,

RMSE = $\sqrt{\frac{1}{N}\sum_{i=1}^{N}(Oi - Si)^2}$ ……….. (4.1) and the normalized root mean square error(N-RMSE) which is calculated as,

N-RMSE=$\sqrt{\frac{1}{N}}\sum_{--=1}^{N}(Oi-Si)^2$ X $\frac{100}{M}$, (Loague and Green, 1991)……. (4.2)

Where S*i* and O*i* are the simulated and observed (measured) values of samples taken during the season (eg. Biomass and CC), or at the end of the season (eg. grain yield), N is the number of observed variables and M is the mean of the observed variable.

The RMSE is a measure of the overall, or mean deviation between the observed and simulated values. It is a synthetic indicator of the model uncertainty. RMSE takes on the units of the variable being simulated. Therefore, the closer the RMSE is to zero, the better the model simulation performance. The normalized RMSE gives a measure (%) of the relative difference of simulated versus observed data. By the N-RMSE, the simulation is considered excellent with a normalized RMSE of less than 10%, good if the N-RMSE is greater than 10% and less than 20%, fair if N-RMSE is greater than 20 and less than 30% and poor if the N-RMSE is greater than 30% (Jamieson, Porter and Wilson,1991).

Results and discussion

Table 14: Summary of simulated and measured Crop water requirement and total fruit yield for hot pepper

Treatment	Simulation period	Seasonal ETc(mm)				Fruit yield(t/ha)			
		Measred	Simulated	RMSE	N-RMSE %	Measured	Simulated	RMSE	N-RMSE %
T_1	4/09/2014-24/12/2014	318.30	321.0	1.35	1.70	1.20	1.19	0.01	1.42
T_2	4/09/2014-24/12/2014	246.50	248.8	1.15	1.87	1.07	0.92	0.15	15.16
T_3	4/09/2014-24/12/2014	208.20	209.0	0.40	0.76	0.51	0.37	0.14	13.70
T_4	4/09/2014-24/12/2014	174.10	170.0	2.05	4.71	0.34	0.14	0.20	21.37

Table 15: Summary of simulated and measured maximum canopy cover and water productivity of hot pepper

Treatment	Simulation period	Max. CC (%)				WP* (kg/m^3)			
		Measured	Simulated	RMSE	N-RMSE %	Measured	Simulated	RMSE	N-RMSE %
T_1	4/09/2014-24/12/2014	80.10	88.00	3.95	19.73	0.38	0.26	0.20	11.53
T_2	4/09/2014-24/12/2014	77.40	88.00	5.30	27.39	0.43	0.29	0.14	14.91
T_3	4/09/2014-24/12/2014	72.90	88.00	7.55	41.43	0.25	0.16	0.09	10.90
T_4	4/09/2014-24/12/2014	68.50	87.00	9.25	54.01	0.19	0.20	0.01	1.00

Crop water requirement and total fruit yield for hot pepper

From Table 14, it can be seen that AquaCrop was able to simulate quite accurately the water requirement of all the treatments (T_1-T_4). The calculated RMSE and N-RMSE were 1.35mm, 1.15mm, 0.40mm and 2.05mm and 1.70%, 1.87%, 0.76% and 4.71% for T_1, T_2, T_3 and T_4 respectively. Table 15 shows that the model was validated for its ability to quite simulate the crop ET over the season as measured during the period. Heng *et al.* (2009) reported that due to high input temperature, prediction of crop ET for irrigated and water deficit field maize lead to the over estimation of the seasonal ET by AquaCrop. Similarly, relative high temperature data were imputed for the period of this work. However, the model slightly estimated the crop ET over the measured values for all treatments. This implies the need for more detail examinations for inputted data. As indicated by the "goodness-of-fit" for crop seasonal ET (Table 14), it can be generally concluded that for all treatments, the model gave excellent prediction of the crop seasonal ET.

Also, from Table 14 it can be concluded that the AquaCrop model simulated very well the fruit yield for hot pepper. The calculated RMSE and N-RMSE were 0.01t/ha, 0.15t/ha, 0.14t/ha and 0.20t/ha and 1.42%, 15.16%, 13.70% and 21.37% for T_1, T_2, T_3 and T_4 respectively. Results in Table 15 shows that good predications were obtained by the model for pepper yield which indicate that the model was properly calibrated (Paredes, de Melo-Abreu, Alves and Pereira, 2014). However, the results showed slight underestimation of crop yield for all treatments except for the fully irrigated treatment which was quite accurate. However, a low estimation error was observed for all treatments. Under estimation and overestimation are likely related to the model trend of estimating transpiration, which is the main deriving variable used for yield estimation (Paredes *et al.,* 2014). Thus, the relative underestimation observer during this work may have been as the result of the model's trend of estimating transpiration. In general, the model showed accuracy in estimating the yield of hot pepper.

Maximum canopy cover and water productivity of hot pepper

Also, from Table 15 it can be seen that the simulated canopy cover by AquaCrop was in partial agreement with measured data. It was relatively able to simulate canopy cover for the pepper with RMSE and N-RMSE of 3.95, 5.30mm, 7.55 and 9.25 and 19.73% 27.39%, 41.43% and 54.01% for $T_{1,}$ T_2, $T_{3,}$ and T_4 respectively. However, the model simulated poorly the CC of T_3 and T_4. Geerks *et al.* (2009) reported that an appropriate parameterization of the CC curve is a major requisite for the AquaCrop model to produce good estimates of soil evaporation, crop transpiration and biomass and hence good yield perdition. However, this requirement is not properly identified by the model developers (eg. Hsiao *et al.,* 2009; Heng *et al.,* 2009; Raes *et al.,* 2012) and other authors. Stated thus, the CC values were obtained by using a digital camera and calibration involved the use of default values. Table 15 shows that, there were tendency for over-estimation of the observed CC as shown by the simulated results. High estimation errors (RMSE>16.6 and N-RMSE>10.5) of CC were observed by Geerk *et al.,* 2009 when assessing the performance of the FAO AquaCrop model to estimate yields and water use and simulated results using default and calibrated values showed tendency of under-estimation of observed CC values. Contrastingly, lower estimation errors (RMSE 3.95-9.25) and quite higher errors (N-RMSE 19.73-54.01) of CC were observed during this work. Bitri *et al.* (2014) indicated that, AquaCrop may not simulate accurately CC because in AquaCrop, as the crop approaches maturity, CC enters in a declining phase due to leaf senesce. Therefore, the starting time for canopy decline is considered to be later than the starting time of leaf senesce. Thus, AquaCrop may not have simulated the CC during this work accurately. Senescence starts generally in the oldest leaf located at the shaded bottom of the canopy that contributes little to transpiration or photosynthesis and is functional at the time when canopy transpiration and photosynthesis start declining and as maturity approached (Bitri *et al., 2014*).

From Table 15, the model simulated very well the WP^* of hot pepper. The calculated RMSE and N-RMSE were 0.20kg/m^3, 0.14 kg/m^3, 0.09 kg/m^3 and 0.01 kg/m^3 and 11.53%, 14.91%, 10.90% and 1.00% for $T_{1,}$ T_2, $T_{3,}$ and T_4 respectively. T_4 was more accurately simulated by the AquaCrop model. During the simulation run for the period, a default WP normalized for ETo (WP*) of 17g/m^{-2} was used in all simulation runs. This resulted in to a good simulated WP^* results for hot pepper. AquaCrop simulates yield and WP better than crop ET (Salemi, Soom, Mousavi, Ganji, Lee, Yusoff and Verdinejad, 2011) as evident in Table 14 and 15. However, the "goodness-of-fit" indices show a slight underestimation of WP except for T_4 which was slightly overestimated. Salemi *et al.* (2011) experienced some differences in the prediction of water productivity values of maize for mostly water stressed treatments as a result of not considering soil and water salinity by the model. Thus, differences observed between predicted and measured WP values can be attributed to the fact that soil and water salinity was not taken into consideration in the AquaCrop model.

Conclusion

After the calibration of the model, it can also be concluded that the model was generally in good agreement with data measured. However, less satisfactory results were predicted for some of the deficit irrigated treatments. AquaCrop simulated quite accurately parameters considered such as: the seasonal water (RMSE ranged from 0.40mm-2.05mm and N-RMSE ranged from 0.76%-4.71%), the fruit yield (RMSE ranged from 0.01t/ha-0.20t/ha and N-RMSE ranged from 1.42% -21.37%) and the water productivity (RMSE ranged from 0.01 kg/m^3- 0.20 kg/m^3 and N-RMSE ranged from 1.00% - 14.91%). However, the model did not satisfactorily predicted results of the canopy cover (RMSE ranged from 3.95- 9.25 and N-RMSE ranged from 19.73% - 54.01%).

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

Conclusion

The objective of the study was to validate the AquaCrop model for irrigated hot pepper using field experimentation in Cape Coast, the Central region of Ghana. From the results of the study, it can be concluded that:

i. Crop water requirement determined during the study suggests that Kc values adopted for the study are quite accurate to determine ETc of hot pepper in Cape Coast, the Central region of Ghana.

ii. The level of irrigation water applied affected the plant height, the development of the canopy cover and yield. Thereby, T_1 (full irrigation) obtaining the highest mean plant height, highest full canopy cover and highest mean number of fruits and weight.

iii. The water productivity of hot pepper was influenced by the amount of fruit yield (t/ha) in proportion to irrigation water applied. Hence, T_2 (90% ETc) hot pepper achieved the highest water productivity.

iv. The calibrated model was able to simulate quite accurately the seasonal water, fruit field and water productivity but did not satisfactorily simulate the canopy cover.

v. The AquaCrop model can be used as a tool to assess the effect of water stress on crops.

Recommendations

i. 10% - 20% off crop water requirement can be used as a deficit irrigation practice to enhance more crops per drop or water productivity.

ii. With parameters inputted, the AquaCrop model can be used for plan and schedule irrigation activities for hot pepper in Cape Coast, the Central region of Ghana.

iii. It is important to repeat this work in different agro-climatic zones

iv. To demonstrate the profitability of deficit irrigation practice, an economic analysis is required

v. The parameterized variables of the AquaCrop model that are readily available or can be easily collected should be tested under different climate, soil type, irrigation methods and field management.

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APPENDICES

UNIVEIRSTY OF CAPE COAST

QUESTIONNAIRE FOR VARIANCE ANALYSES OF THE FIRST EXPERIMENT

APPENDIX A

Analysis of variance

VARIATE: MEAN_PLANT_HEIGHT_INITIAL_STAGE

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	2	13.432	6.716	0.91	
WATER LEVEL APPLIED	3	304.967	101.656	13.72	0.004
Residual	6	44.448	7.408		
Total	11	362.847			

Tables of means

VARIATE: MEAN_PLANT_HEIGHT_INITIAL_STAGE_

Grand mean: 23.33

WATER LEVEL APPLIED:	100% ETC	70% ETC	80% ETC	90% ETC
	29.63	16.40	21.03	26.27

Standard errors of differences of means

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
s.e.d.	2.222

Least significant differences of means (5% level)

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
l.s.d.	5.438

APPENDIX B

Analysis of variance

VARIATE: MEAN_PLANT_HEIGHT_DEVELOPEMENTAL

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	2	5.563	2.781	0.89	
WATER LEVEL APPLIED	3	218.308	72.769	23.29	0.001
Residual	6	18.744	3.124		
Total	11	242.615			

Tables of means

VARIATE: MEAN_PLANT_HEIGHT_DEVELOPEMENTAL

Grand mean: 37.77

WATER LEVEL APPLIED:	100% ETC	70% ETC	80% ETC	90% ETC
	42.21	31.03	37.33	40.50

Standard errors of differences of means

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
s.e.d.	1.443

Least significant differences of means (5% level)

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
l.s.d.	3.531

APPENDIX C
Analysis of variance

VARIATE: MEAN_PLANT_HEIGHT_MID_SEASON

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	2	4.022	2.011	0.30	
WATER LEVEL APPLIED	3	503.097	167.699	24.71	<.001
Residual	6	40.718	6.786		
Total	11	547.837			

Tables of means

VARIATE: MEAN_PLANT_HEIGHT_MID_SEASON

Grand mean: 48.02

WATER LEVEL WATER LEVEL:	100% ETC	70% ETC	80% ETC	90% ETC
	54.40	37.47	48.23	51.97

Standard errors of differences of means

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
s.e.d.	2.127

Least significant differences of means (5% level)

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
l.s.d.	5.205

APPENDIX D
Analysis of variance

VARIATE: MEAN_PLANT_HEIGHT_LATE_SEASON

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	2	23.11	11.55	0.85	
WATER LEVEL APPLIED	3	602.65	200.88	14.77	0.004
Residual	6	81.58	13.60		
Total	11	707.33			

Tables of means

VARIATE: MEAN_PLANT_HEIGHT_LATE_SEASON

Grand mean: 60.0

WATER LEVEL APPLIED:	100% ETC	70% ETC	80% ETC	90% ETC
	67.9	48.6	60.7	63.0

Standard errors of differences of means

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
s.e.d.	3.01

Least significant differences of means (5% level)

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
l.s.d.	7.37

APPENDIX E
Analysis of variance

VARIATE: PERCENTAGE CANOPY COVER INITIAL STAGE

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	2	28.198	14.099	4.75	
Water level applied	3	18.519	6.173	2.08	0.205
Residual	6	17.826	2.971		
Total	11	64.543			

Tables of means

Variate: Percentage Canopy Cover Initial Stage

Grand mean: 17.13

WATER LEVEL APPLIED:	100% ETC	70% ETC	80% ETC	90% ETC
	18.45	15.23	16.87	17.99

Standard errors of differences of means

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
s.e.d.	1.407

Least significant differences of means (5% level)

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
l.s.d.	3.444

APPENDIX F

Analysis of variance

VARIATE: PERCENTAGE CANOPY COVER DEVELOPMENTAL STAGE

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	2	1.592	0.796	0.12	
Water level applied	3	98.122	32.707	4.86	0.048
Residual	6	40.384	6.731		
Total	11	140.098			

Tables of means

Variate: Percentage Canopy Cover Developmental Stage

Grand mean: 51.66

WATER LEVEL APPLIED:	100% ETC	70% ETC	80% ETC	90% ETC
	55.28	48.26	49.55	53.55

Standard errors of differences of means

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
s.e.d.	2.118

Least significant differences of means (5% level)

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
l.s.d.	5.183

APPENDIX G

Analysis of variance

VARIATE: PERCENTAGE CANOPY COVER MID-SEASON STAGE

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	2	38.48	19.24	0.82	
Water level applied	3	119.25	39.75	1.70	0.265
Residual	6	140.32	23.39		
Total	11	298.06			

Tables of means

Variate: Percentage Canopy Cover Mid-season Stage

Grand mean: 60.1

WATER LEVEL APPLIED:	100% ETC	70% ETC	80% ETC	90% ETC
	63.8	55.8	58.6	62.3

Standard errors of differences of means

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
s.e.d.	3.95

Least significant differences of means (5% level)

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
l.s.d.	9.66

APPENDIX H

Analysis of variance

VARIATE: PERCENTAGE CANOPY COVER LATE STAGE

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	2	9.299	4.650	0.48	
Water level applied	3	304.200	101.400	10.38	0.009
Residual	6	58.634	9.772		
Total	11	372.133			

Tables of means

Variate: Percentage Canopy Cover Late Stage

Grand mean: 51.49

WATER LEVEL APPLIED:	100% ETC	70% ETC	80% ETC	90% ETC
	56.81	45.38	47.68	56.10

Standard errors of differences of means

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
s.e.d.	2.552

Least significant differences of means (5% level)

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
l.s.d.	6.246

APPENDIX I

Analysis of variance

VARIATE: MEAN NUMBER OF FRUIT PER TREATMENT

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks	2	282.80	141.40	2.61	
WATER LEVEL APPLIED	3	1259.58	419.86	7.75	0.017
Residual	6	325.06	54.18		
Total	11	1867.44			

Tables of means

Variate: MEAN NUMBER OF FRUIT PER TREATMENT

Grand mean: 45.2

WATER LEVEL APPLIED:	100% ETC	70% ETC	80% ETC	90% ETC
	56.7	31.0	40.1	53.0

Standard errors of differences of means

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
s.e.d.	6.01

Least significant differences of means (5% level)

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
l.s.d.	14.71

APPENDIX J

Analysis of variance

VARIATE: MEAN FRUIT WEIGHT (G) PER TREATMENT

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	2	25258.	12629.	2.48	
WATER LEVEL APPLIED	3	89430.	29810.	5.86	0.032
Residual	6	30530.	5088.		
Total	11	145218.			

Tables of means

Variate: MEAN FRUIT WEIGHT (g) PER TREATMEN

Grand mean: 181.

WATER LEVEL APPLIED:	100% ETC	70% ETC	80% ETC	90% ETC
	281.	74.	120.	249.

Standard errors of differences of means

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
s.e.d.	58.2

Least significant differences of means (5% level)

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
l.s.d.	142.5

APPENDIX K

Analysis of variance

Variate: Water Productivity

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
REP stratum	2	0.30762	0.15381	2.37	
REP.*Units* stratum					
TREATMENT	3	0.64676	0.21559	3.33	0.098
Residual	6	0.38882	0.06480		
Total	11	1.34320			

Tables of means

Variate: Water Productivity

Grand mean 0.717

Water Levels Applied	100% ETC	70% ETC	80% ETC	90% ETC
	0.890	0.420	0.567	0.991

Standard errors of differences of means

Table	Water Level Applied
rep.	3
d.f.	6
s.e.d.	0.2079

Least significant differences of means (5% level)

Table	Water Level applied
rep.	3
d.f.	6
l.s.d.	0.5086

APPENDIX L

VARIANCE ANALYSES OF THE SECOND EXPERIMENT

Analysis of variance

VARIATE: MEAN_PLANT_HEIGHT_INITIAL_STAGE

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	2	11.611	5.805	0.86	
WATER LEVEL APPLIED	3	314.964	104.988	15.47	0.003
Residual	6	40.725	6.787		
Total	11	367.299			

Tables of means

Variate: Mean_Plant_Height_Initial_Stage

Grand mean: 23.33

WATER LEVEL APPLIED:	100% ETC	70% ETC	80% ETC	90% ETC
	30.08	16.77	20.38	26.08

Standard errors of differences of means

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
s.e.d.	2.127

Least significant differences of means (5% level)

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
l.s.d.	5.205

APPENDIX M

Analysis of variance

VARIATE: MEAN_PLANT_HEIGHT_DEVELOPEMENTAL STAGE

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	2	7.406	3.703	1.24	
WATER LEVEL APPLIED	3	227.146	75.715	25.44	<.001
Residual	6	17.860	2.977		
Total	11	252.412			

Tables of means

Variate: MEAN_PLANT_HEIGHT_DEVELOPEMENTAL STAGE

Grand mean: 38.11

WATER LEVEL APPLIED:	100% ETC	70% ETC	80% ETC	90% ETC
	42.87	31.35	37.45	40.75

Standard errors of differences of means

Table	WATER LEVELAPPLIED
rep.	3
d.f.	6
s.e.d.	1.409

Least significant differences of means (5% level)

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
l.s.d.	3.447

APPENDIX N

Analysis of variance

VARIATE: MEAN_PLANT_HEIGHT_MID_SEASON

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	2	6324.0	3162.0	5.15	
WATER LEVEL APPLIED	3	471.85	157.28	15.26	0.003
Residual	6	61.86	10.31		
Total	11	534.90			

Tables of means

Variate: Mean_Plant_Height_Mid_Season

Grand mean: 48.52

WATER LEVEL APPLIED:	100% ETC	70% ETC	80% ETC	90% ETC
	54.54	38.16	49.22	52.17

Standard errors of differences of means

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
s.e.d.	2.622

Least significant differences of means (5% level)

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
l.s.d.	6.415

APPENDIX O

Analysis of variance

VARIATE: MEAN_PLANT_HEIGHT_LATE_SEASON

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	2	22.83	11.41	0.90	
WATER LEVEL APPLIED	3	592.44	197.48	15.55	0.003
Residual	6	76.18	12.70		
Total	11	691.44			

Tables of means

Variate: Mean_Plant_Height_Late_Season

Grand mean: 60.2

WATER LEVEL APPLIED:	100% ETC	70% ETC	80% ETC	90% ETC
	67.9	48.8	60.8	63.1

Standard errors of differences of means

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
s.e.d.	2.91

Least significant differences of means (5% level)

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
l.s.d.	7.12

APPENDIX P

Analysis of variance

VARIATE: PERCENTAGE CANOPY COVER INITIAL STAGE

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	2	24.823	12.412	6.00	
Water level applied	3	13.454	4.485	2.17	0.193
Residual	6	12.415	2.069		
Total	11	50.693			

Tables of means

Variate: Percentage Canopy Cover Initial Stage

Grand mean: 17.11

Water level applied:	100% ETC	70% ETC	80% ETC	90% ETC
	18.39	15.53	16.87	17.66

Standard errors of differences of means

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
s.e.d.	1.175

Least significant differences of means (5% level)

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
l.s.d.	2.874

APPENDIX Q

Analysis of variance

VARIATE: PERCENTAGE CANOPY COVER DEVELOPMENTAL STAGE

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	2	1.894	0.947	0.14	
Water level Applied	3	99.918	33.306	4.77	0.050
Residual	6	41.855	6.976		
Total	11	143.667			

Tables of means

Variate: Percentage Canopy Cover Developmental Stage

Grand mean: 51.85

WATER LEVEL APLIED:	100% ETC	70% ETC	80% ETC	90% ETC
	55.33	48.32	49.78	53.95

Standard errors of differences of means

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
s.e.d.	2.157

Least significant differences of means (5% level)

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
l.s.d.	5.277

APPENDIX R

Analysis of variance

VARIATE: PERCENTAGE CANOPY COVER MID-SEASON STAGE

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	2	35.04	17.52	0.78	
Water level applied	3	110.11	36.70	1.64	0.277
Residual	6	134.15	22.36		
Total	11	279.30			

Tables of means

Variate: Percentage Canopy Cover Mid-season Stage

Grand mean: 60.1

WATER LEVEL APPLIED:	100% ETC	70% ETC	80% ETC	90% ETC
	63.7	55.8	58.7	62.1

Standard errors of differences of means

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
s.e.d.	3.86

Least significant differences of means (5% level)

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
l.s.d.	9.45

APPENDIX S

Analysis of variance

VARIATE: PERCENTAGE CANOPY COVER LATE STAGE

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.	
Block	2	14.759	7.380	0.75	TREATMENT	3
Residual	6	58.943	9.824			
Total	11	351.264				

Tables of means

Variate: Percentage Canopy Cover Late Stage

Grand mean: 51.76

WATER LEVEL APPLIED:	100% ETC	70% ETC	80% ETC	90% ETC
	56.81	45.80	48.28	56.16

Standard errors of differences of means

Table	Water level applied
rep.	3
d.f.	6
s.e.d.	2.559

Least significant differences of means (5% level)

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
l.s.d.	6.262

APPENDIX T

Analysis of variance

VARIATE: MEAN NUMBER OF FRUIT PER TREATMENT

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	2	268.04	134.02	3.16	
WATER LEVEL APPLIED	3	813.45	271.15	6.39	0.027
Residual	6	254.69	42.45		
Total	11	1336.18			

Tables of means

Variate: Mean Number Of Fruit Per Treatment

Grand mean: 47.1

WATER LEVEL APPLIED:	100% ETC	70% ETC	80% ETC	90% ETC
	56.4	35.0	44.4	52.7

Standard errors of differences of means

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
s.e.d.	5.32

Least significant differences of means (5% level)

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
l.s.d.	13.02

APPENDIX U

Analysis of variance

VARIATE: MEAN FRUIT WEIGHT (G) PER TREATMENT

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	2	25257.	12628.	2.49	
WATER LEVEL APPLIED	3	87258.	29086.	5.74	0.034
Residual	6	30383.	5064.		
Total	11	142898.			

Tables of means

Variate: Mean Fruit Weight (G) Per Treatment

Grand mean: 182.

WATER LEVEL APPLIED:	100% ETC	70% ETC	80% ETC	90% ETC
	280.	75.	123.	249.

Standard errors of differences of means

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
s.e.d.	58.1

Least significant differences of means (5% level)

Table	WATER LEVEL APPLIED
rep.	3
d.f.	6
l.s.d.	142.2

APPENDIX V

Analysis of variance

VARIATE: WATER PRODUCTIVITY

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
REP stratum	2	0.31085	0.15542	2.38	
REP.*Units* stratum					
TREATMENT	3	0.62891	0.20964	3.21	0.104
Residual	6	0.39177	0.06530		
Total	11	1.33152			

Tables of means

Variate: Water Productivity

Grand mean 0.728

Water level applied	100% ETC	70% ETC	80% ETC	90% ETC
	0.881	0.433	0.589	1.010

Standard errors of differences of means

Table	Water level applied
rep.	3
d.f.	6
s.e.d.	0.2086

Least significant differences of means (5% level)

Table	Water level applied
rep.	3
d.f.	6
l.s.d.	0.5105

A. variance analyses of the first experiment

B. variance analyses of the second experiment