VALIDATION OF THE AQUACROP MODEL FOR IRRIGATED AFRICAN EGGPLANT (*SOLANUM MACROCARPON*) AT THE UNZA FIELD STATION

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DECLARATION

I, ANGELA BWALYA, declare that the thesis, which I hereby submit for the degree of Master of Agronomy in Soil Science at the University of Zambia, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

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ABSTRACT

Crop growth simulation models are important tools for evaluating effects of water deficits to optimize water use under limited conditions to enhance sustainability and profitability of crop production. Simulation models are also useful tools for improving farm level water management and optimizing water use efficiency. The predominance of rain fed agriculture and on highly unreliable and poorly distributed rainfall in Zambia, makes agricultural production and productivity risky. Given the negative effects of climate change on agriculture experienced through decreasing crop water availability, there is need to consider the efficiency of use of the available water. This is particularly relevant for high value crops that can be grown under rain fed conditions, and are gaining in economic importance among, such as African eggplant. AquaCrop model was used to simulate crop biomass and yield of African eggplant (*Solanum macrocarpon*) in response to varying water application rates. African Eggplant is a minor vegetable crop in most African countries which is currently receiving interest. The main objective of this study was to validate AquaCrop model using irrigated African eggplant under deficit and full irrigation regimes. AquaCrop model was evaluated at the University of Zambia, field station for partially irrigated and rain fed eggplant crop under three water application rates at 50 percent, 75 percent and 100 percent of crop evapotranspiration (ETc). The 100 percent ETc treatment had sub-treatment with plastic cover (100 percent ETc+) and without plastic cover (100 percent ETc) as control. The experimental design was a Randomized Complete Block Design (RCBD) with four replications. Amount of applied irrigation water for the treatments varied from 197 to 364 mm while 194 mm was received as rainfall. The total aboveground biomass produced varied from 6.59 to 8.07 ton/ha, while the final fruit yield varied from 0.89 to 1.46 ton/ha. Water application significantly affected fruit yield ($P<0.05$) and harvest index (HI). However, no significant differences were observed in stem girth diameter, plant height, stover and dry matter produced. Furthermore, the water use efficiency increased with decrease in water application rate. Results from AquaCrop modelling over-estimated aboveground biomass production for all treatments except for the 100 percent water application treatment with plastic mulch cover. This may indicate no water stress during plant growth. For the predicted and measured biomass and canopy cover values, the prediction was comparable to the measured

canopy values. Generally, the model performed satisfactorily for the growth of aboveground biomass, fruit yield, and canopy cover (CC) in the non-water-stressed treatments (100 percent ET with plastic cover) but it was less satisfactory in simulating severely water-stressed treatments. The ease of use of the AquaCrop model, the low requirement of input parameters and its sufficient degree of simulation accuracy, makes it a valuable tool for estimating crop productivity under rain fed conditions, supplementary and deficit irrigation and on-farm water management strategies for improving the efficiency of water use in agriculture.

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CHAPTER 1

1.0 INTRODUCTION

1.1 Background

Zambia is well endowed with vast surface and ground water resources. The total renewable water resources of Zambia amount to about 105 km^3/year, of which about 80 km^3/year are produced internally (AQUASTAT, 2005). Total water withdrawal was 1.737 km^3 in 2000, with agricultural water use accounting for 1.320 km^3 (77 percent), or more than three-quarters of the total domestic water use claiming 0.286 km^3. Future water use is estimated to reach 1.922 km^3/year, assuming that land under irrigation will continue to expand at the rate of 1,200 - 1,500 ha/yr.

1.2 Irrigation Potential

Zambia's irrigation potential is estimated at 2.75 million ha (AQUASTAT, 2005) based on water availability and soil irritability. From this potential, it is believed that 523,000 hectares (ha) can be economically developed. However, only 155,912 ha of land are irrigated which is about 30 percent of the economical irrigation potential. About 88 percent of the area equipped for full or partial control irrigation draws its water from surface water and 12 percent from groundwater. The following categories of irrigated farming are found in the country: (i) Informal irrigation by small-scale farmers; (ii) Smallholder irrigation schemes; (iii) Former quasi-government schemes; and (iv) Private or commercial irrigation schemes. The main irrigated crops are sugar cane, wheat and rice. Other irrigated crops include coffee, bananas, vegetables, citrus fruits, maize and tea. Small-scale farmers practice informal irrigation in their gardens.

The current 155,912 ha of land under irrigation can be broken down as according to the technology used: (i) 32,189 ha is under surface irrigation; sugar cane covers more than 50 percent of this area; (ii) 17,570 ha is irrigated by sprinklers; wheat accounts for 68 percent of this area; (iii) Drip irrigation covers some 5,628 ha; coffee production accounts for 92 percent of this area; (iv) Small-scale farmers grow vegetables in dambos over an area of 100,000 ha, which are equipped with small drains, impoundment furrows and shallow wells for irrigating a wide range of vegetables in the dry season (May-October); (v) Some of the small-scale farmers use treadle pumps to irrigate areas of about 525 ha; it is estimated that more than 3,000 treadle pumps are in use. About 100,000 ha of non-equipped lowland areas are cultivated particularly in the rainy season in the interfluves. Around 10 ha around Lake Kariba are used for flood recession cropping (AQUASTAT, 2005).

1.3 Challenges and Opportunities

Zambia lies within the tropics and because of its high altitude, much of the country enjoys a subtropical climate which is characterised by the cool and hot dry season from May to October and hence, presenting a conducive environment for irrigated agriculture. Water availability for agricultural production is greatly affected by erratic rainfall distribution as rain fed agriculture is predominant. 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 of annual rainfall year by year (Kimura, 2007).The inappropriate use and overexploitation of irrigation water for irrigated crops remains a challenge.

Low crop productivity due to over or under application of irrigation water may lead to water logging and low soil pH which affect crop performance. There is inadequate information and knowledge for agriculture extension packages for irrigation management, adapted to local conditions. Irrigated agriculture has made an important contribution to the expansion of national and world food supplies since the 1960s and is expected to play a major role in feeding the growing world population. However, water availability for irrigation may have to be reduced in many regions in favour of rapidly increasing non-agricultural water uses in industry and households, as well as for environmental purposes (Molden, 2006). With growing irrigation-water demand worldwide, the challenge is to produce more food with less water. Therefore, innovations are needed to increase the water use efficiency of the available water for agricultural production (Costa *et al*., 2007).

Optimizing irrigation water management for the crop production could result in increased productivity and water savings. This goal will be realistic only if appropriate strategies are found for water savings and for more efficient water uses in agriculture. One important strategy is to better manage water and increase its productivity (Molden, 1997; Molden *et al*., 2001). Drip irrigation, mulching and protected cultivation, have contributed to improved Water Use Efficiency (WUE) in agriculture by significantly reducing runoff and evapotranspiration losses (Stanghellini *et al*., 2003; Jones, 2004; Kirnak and Demirtas, 2006). It is also necessary to develop new irrigation scheduling approaches, not necessarily based on full crop water requirement, but ones designed to ensure the optimal use of available water.

Developing an optimum irrigation schedule, would be very beneficial to the different types of farmers that already grow or are interested in growing the African eggplant. This irrigation schedule will help them know how much water the crop would require during its growing period, up to its maturity. That way, it would help farmers cut down on unnecessary losses of water as a result of their lack of knowledge on the optimum water requirements for the crop. Developing an optimum irrigation schedule for this crop would also reduce on the time, energy and cost of conducting a similar research in another location with similar soil physical and chemical characteristics and climatic conditions.

It is necessary to get maximum yield in agriculture by using available water in order to get maximum profit from per unit area, because existing agricultural land and irrigation water are rapidly diminishing, due to the rapid industrialisation and urban development. Therefore, we need to know and supply the right amount of water needed for the plants, that is, plant water consumption. Furthermore, it is essential to develop the most suitable irrigation schedule to get optimum plant yield for different ecological regions, as plant water consumption depends mostly on plant growth, soil and climatic conditions (Ertek *et al*., 2002). This would therefore be a practical and optimal irrigation schedule developed for the farmers, who are involved in growing the African eggplant. This would increase on their water savings and this available water can be useful for other purposes other than irrigation. With the optimal production, farmers would be able to feed themselves and be able to obtain a substantial profit from the high yields obtained from the sale of their produce. That way, poverty levels would reduce as well as the cost of production and living.

The calibration of the AquaCrop model for the African eggplant under local climatic conditions is also necessary as this would make it easier to predict and calculate the expected yield and performance of the crop with the data inputs used and parameters fed in to the AquaCrop model. This would help farmers plan in advance for their expected returns from all the input data parameters provided for the model.

According to the Poverty Reduction Strategy Paper (PRSP, 2005), agriculture is the main source of income and employment for rural women who constitute more than half of the total rural population. From that, it may be concluded that an increase in rural income will result in overall poverty reduction and increased food security; in order to achieve the latter, the country's main focus is on agriculture and particularly on irrigation development.

Since time immemorial, small-scale farmers all over the country have practiced informal irrigation in their gardens, i.e. they applied water in an undocumented, casual, artificial way using buckets, watering cans and hosepipes to grow vegetables, rice, bananas and some local sugar cane varieties along streams, rivers and in dambos (AQUASTAT, 2005). This form of irrigation is usually not capital intensive, is farmer-operated and is often spontaneous in origin, responding to the needs felt by individual farmers. Drought occurrences, for example, directly prompt the genesis of such irrigation developments. Areas irrigated in this manner are usually small in size, ranging from 100 - 200 m^2. However, the introduction of irrigation has improved the efficiency of watering these gardens over a large area.

1.4 Irrigation, Irrigation Scheduling and Deficit Irrigation

Today, 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). There is also the need to take advantage of the long dry season which is conducive for producing more food under irrigated conditions. However, irrigation faces a number of challenges and among them are: producing more food of better quality, while using less water per unit of output; providing rural communities with resources and opportunities to live a healthy and productive life; applying climate-smart technologies that ensure environmental sustainability; and contributing in a productive way to the local and national economy.

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 Zambia in particular. While it can enhance food production, there are also risks of inappropriate use and over-exploitation of water resources due to knowledge gaps on specific crop water requirements under local environmental conditions.

Excess application of water during irrigation is one of the main causes of land degradation through agricultural production. Land becomes unproductive for agriculture due to high build-up of salt in soils, as a result of inappropriate irrigation (Ali *et al*., 2001; Smedema and Shiati, 2002; Hillel and Vlek, 2005). Optimizing the management of irrigation water is important for structural (irrigation system design), economic (saving water and energy) and environmental reasons (salt accumulation) (Annandale *et al*., 1999).

Some of the benefits of irrigation include the direct cut on water stress, increased investment in inputs such as fertilizers and improved cultivars affected by uncertainty of crop production under rain fed conditions (Smith, 2000; Hillel and Vlek, 2005). Irrigation also provides a possibility for multiple cropping per year, especially in areas with prolonged dry periods (Hillel and Vlek, 2005); a strong case for Zambia with a dry season from April to November.

Improved return from agricultural inputs and in environmental quality from irrigation can be achieved, among others, through practicing irrigation scheduling (Itier *et al*., 1996; Home *et al*., 2002) and deficit irrigation (English and Raja, 1996; Nautiyal *et al*., 2002; Zhang *et al*., 2002).

Irrigation scheduling is a practice that enables an irrigator to use the right amount of water at the right time for plant production. The different irrigation scheduling approaches employ soil, plant or atmosphere or a combination of the two or three components of the soil-plant-atmosphere continuum (SPAC) as their basic framework.

Deficit irrigation is an optimization strategy in which irrigation is applied during water stress-sensitive growth stages of a crop (English, 1990). Deficit irrigation aims at increasing water-use efficiency of a crop by reducing evapotranspiration whilst maintaining yield comparable to that of a fully irrigated crop. 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 its sustainable use, (iii) decreasing water losses through soil evaporation, (iv) increasing soil water storage within the plant rooting 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, before implementing such a strategy across all crops, there is need to investigate the disadvantages and benefits of deficit irrigation, especially for water stress sensitive crops.

1.5 AquaCrop Model

1.5.1 Modeling

Simulation models are generally defined as simplification or abstraction of a real system (Loomis *et al*., 1979). 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. Lengthy and expensive field experiments, especially with a high number of treatments, can be preevaluated through a well-proven model (Whisler *et al*., 1986). Optimum management practices, either strategic or tactic, such as planting date, cultivar selection, fertilization, or water and pesticides usage, can be assessed through proven simulation models for making seasonal or within-season decisions (Boote *et al*., 1996). Other uses, such as planning and policy analysis, can benefit from modeling as well.

Efforts in crop simulation modeling, aimed primarily at the integration of physiological knowledge, were started in the late 1960s by several research groups; among them that of de Wit and co-workers (Brouwer and de Wit, 1969). Subsequent efforts led to the development of more advanced models, some of them more oriented toward the single-plant scale, such as CERES (Jones and Kiniry, 1986); WOFOST, a model for soghum and millet; and others more oriented toward canopy-level scale and as management tools to assist in decision making, such as EPIC (Williams *et al*., 1989), its derivation ALMANAC (Kiniry *et al*., 1992), CropSyst (Stockle *et al*., 2003), the DSSAT (Decision Support System for Agrotechnology Transfer cropping system model) (Jones *et al*., 2003), the Wageningen models (van Ittersum *et al*., 2003) and the APSIM models (Keating *et al*., 2003). Scientists, graduate students, and advanced users in highly commercial farming represent the typical users of these models.

The DSSAT (Jones *et al*., 1998) contains a group of models for fifteen of the world's most major food crops, and associated data management and analysis tools. Models that are important within DSSAT are CERES (Ritchie *et al*., 1998), which includes the dry land cereal crops and CROPGRO (Boote *et al*., 1998) for grain legumes. These two models differ considerably in their level of detail, degree of modularity and underlying physiological assumptions. However, they share a common soil model and identical input and output data handling. Although CROPGRO is evolved from, and is designed to simulate grain legumes, it has been adapted for tomato, bell pepper and pasture grass. DSSAT is a product of the IBSNAT (International Benchmark Sites Network for Agrotechnology Transfer) project. The IBSNAT consortium and development of DSSAT have continued under the banner of ICASA (International Consortium for Agricultural Systems Applications), but at a relatively slow pace in the absence of project funds. Models included in DSSAT (including their predecessors) have been used in more regions and for a broader range of applications than any other family of crop models. Both CERES models and

CROPGRO have undergone some testing and application in semi-arid West Africa. Jagtap *et al*. (1999) describe decision applications in a more sub-humid environment in Nigeria. Thornton *et al*. (1997) developed a prototype GIS-based, real-time yield forecasting system for Burkina Faso that uses CERES-Millet and satellite-derived precipitation estimates combined with historic weather data series. CROPGRO-Peanut performed well in recent experiments in northern Benin (Adomu *et al*., in preparation) and Ghana (Naab *et al*., in preparation) when observed disease damage was properly accounted for. Boote and Jones (1988) used its predecessor, PNUTGRO, to evaluate optimum cultivar selection, planting dates and stand density using data from Niamey, Niger, but did not evaluate simulation results with experimental results. For an experiment at Tara, Niger, CERES-Millet substantially over predicted LAI, biomass, grain yield and soil water content (Fechter *et al*., 1991). Lower and drained upper limits of plant-extractable soil water were apparently based on laboratory (probably pressure plate) measurements in this study. On the other hand, Naab *et al*. (in preparation) obtained good predictions of soil water contents and use in groundnut experiments in northern Ghana when values of these hydrological properties were based on field measurements.

APSIM (McCown *et al*., 1996) implements a high degree of modularity of the various modules and processes. The initial motivation was to improve flexibility to model cropping systems and a wider range of soil and management processes. It was developed primarily for Australia's agricultural industry, but now supports a variety of applications in many parts of the world. As a result of a relatively high level of funding and scientific and development staffing, model development is more active for APSIM than for any of the other families of crop models. APSIM includes all of the relevant crops.

CropSyst (van Evert and Campbell, 1994; Stöckle *et al*., 1994) implements model modularity through an object-oriented structure. The result is a relatively user-friendly and flexible simulation environment. CropSyst is one of very few dynamic crop models that incorporate pest (aphid) population dynamics and damage. Its potential use for forecasting spatial distributions of millet yields was demonstrated for Burkina Faso (Badini *et al*., 1997), but without experimental validation of predictions.

EPIC (Williams *et al*., 1989) is a relatively simple generic crop model originally designed primarily to simulate soil erosion under alternative cropping scenarios. It has been used quite widely, in part because of its simplicity and the ease of adapting it for additional crops. ALMANAC is a descendent of EPIC that simulates intercrop systems (Kiniry *et al*., 1992).

CropSys (Caldwell and Hansen, 1993) is a multiple cropping system simulation model that incorporated all of the DSSAT crop models available at the time of its development. It was perhaps the first model to link non-generic crop physiology sub-models under a common soil and ecosystem model. The modified structure solved both the intercrop and the sequencing problem, and permitted very flexible representation of management events. CropSys is the only model considered here that explicitly models sparse canopies both between and within rows. Preliminary field experiments in Hawaii yielded promising results, which led to tentative plans to evaluate the model for West African experiments in collaboration with IITA. Unfortunately, the extent of code reorganization required de-coupling physiological and ecosystem processes and made it impractical to maintain CropSys as the component sole crop models were updated (Caldwell and Hansen, 1993).

AquaCrop, CropSyst and WOFOST differ in the level of complexity describing crop development, in the main growth modules driving the simulation of biomass growth, and in the number of input parameters.

Two main modeling approaches can be distinguished depending on the purpose and objectives of the crop model, namely: *scientific* and *engineering*. The first approach focuses on improving our understanding of crop behaviour, its physiology and its responses to environmental changes. The second approach attempts to provide sound management advice to farmers or provide predictions to policymakers (Passioura, 1996). Scientific modeling is also meant to be more mechanistic, based on laws and theories of how systems function, while engineering modeling is meant to be functional, based on a mixture of well-established theory and robust empirical relationships (Addiscott and Wagenet, 1985).

1.5.2 AquaCrop

AquaCrop model simulates attainable 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 the water available. The model is based on water productivity as a key driver of agricultural production. Recent growth in human population and increased industrialization and living standards around the world, are demanding a greater share of our finite water resources. This makes water an increasingly critical factor limiting crop production. Additionally, the crop response to water deficit remains among the most difficult responses to capture in crop modeling; water deficits vary in intensity, duration and time of occurrence (Hsiao, 1973; Hsiao *et al*., 1976; Bradford and Hsiao, 1982).

The complex relationship between the soil-plant-atmosphere systems makes it difficult for one to know how much water is needed for growing crops. However, simulation models can be of great help in making us understand the interrelationship of factors in this system. Models mimic the processes in the real system and predict variables at every stage in the simulation. In recent years, simulation models have been widely used to explore solutions to water management problems. By using the AquaCrop model in particular, it is easy to evaluate water management techniques and therefore, give better recommendations for efficient water use (Ines *et al*., 2001). AquaCrop however needs to be calibrated and validated for local crops with regard to local soils and climate. As compared to other crop models, AquaCrop has a significantly smaller number of parameters and a better balance between accuracy and robustness. However, despite providing good results in a number of places where it has been tested, it is still undergoing validation on a number of crops under different environmental conditions.

AquaCrop is exclusively based on the water-driven growth module, in that transpiration is converted into biomass through water productivity (WP) parameter. CropSyst is based on both water and radiation driven modules, while WOFOST simulates crop growth using a carbon driven approach and fraction of intercepted radiation (Todorovic *et al*., 2009).

1.6 Objectives:

1.6.1 Main Objectives

The general objective was to validate the AquaCrop model for irrigated African eggplant under deficit and full irrigation regimes.

1.6.2 Specific Objectives

The specific objectives were:

(1) To determine the effect of deficit irrigation on yield production;

(2) To determine the optimum water use and water use efficiency for the African eggplant;

(3) To calibrate and validate the AquaCrop model for the African eggplant under local climatic conditions.

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 Origin and Geographic Distribution of African Eggplant

The African eggplant falls under the genus *Solanum*, which comprises over 1000 species worldwide and, about 100 indigenous species in Africa (Bukenya and Bonsu, 2004). The African eggplant (*Solanum macrocarpon*), a sturdy herbaceous crop, is one of the most commonly consumed fruit vegetables in tropical Africa, ranked third after tomato and onion (PROTA, 2010). In Zambia, eggplant is increasingly becoming a popular fruit vegetable crop grown both under rain fed and irrigated conditions. According to PROTA (2010) annual fruit production in Africa is estimated at 8,000 tons/ha in Senegal, 60,000 tons/ha in Cote d'Ivoire and 4,500 tons/ha in Burkina Faso, with small-scale growers accounting for 80 percent of the total production. The African eggplant is found throughout tropical non-arid parts of Africa (PROTA, 2010). The African eggplant grows well under optimal day temperatures between 25°C and 35°C and night temperatures between 20°C and 27°C. *Solanum macrocarpon* cultivars are mainly grown for their fruits in West Africa (humid coastal and high-rainfall zones) and Southern Africa, while leafy types are commonly grown throughout West and Central Africa (Bukenyaziraba and Bonsu, 2004). The crop is generally considered to be a minor crop in most African countries and has received little research on agronomic requirements (Schippers, 2002).

2.2 Growth and Development

According to Bukenya and Bonsu (2004), eggplant seed takes 7 days to germinate and 60 - 90 days to flowering and fruits are ready for picking 21 to 30 days after fruit on-set. African eggplants grow well in relatively fertile, well-manured light soils (Terra, 1966; Schippers, 2002). Seeds are sown in nursery beds and later transplanted at 30 to 40 days (approximately at 12 to 15 cm plant height) after sowing. In order to promote early fruit bearing, axillary shoots of the plants are often cut out. When the crop remains in the field for a long time, supplementary fertilisation is required at the flowering stage and after the first harvest (AVRDC, 2003).

Moreover, sufficient moisture in the soil is needed for an ideal growth and yield and especially after fruit setting, irrigation frequency should be increased (Schippers, 2002).

2.3 Water Requirements

Eggplant is grown extensively under rain fed conditions and high yields are obtained with rainfall of more than 600 mm when well-distributed over the growing season. Heavy rainfall during the flowering period causes flower shedding and poor fruit setting, and during the ripening period, rotting of fruits.

Crop and water management parameters important for eggplant production are presented in Table 1. Total crop water requirements for eggplant vary from 600 to 900 mm for short growing season and up to 1250 mm for long growing season and with several pickings. The crop coefficient (Kc) relating reference evapotranspiration (ETo) to maximum evapotranspiration (ETm) vary from 0.4 at transplanting to 0.95 - 1.1 during full canopy cover and for fresh African eggplants, 0.8 to 0.9 at the time of harvest (FAOSTAT, 2001).

Table 1: Summary of main crop parameters of eggplant important for water management

Crop characteristic	Initial	Crop Development	Mid- season	Late	Total
Stage length (days)	25/30	35	40	20	125
	30	40	110	30	210
Depletion Coefficient, p	0.2	>>	0.3	0.5	0.3
Root Depth (m)	0.25	>>	>>	0.8	-
Crop Coefficient(Kc)	0.6	>>	1.05	0.9	-
Yield Response Factor(Ky)	-	-	-	-	1.1

(Source: FAOSTAT, 2001)

Eggplant grows well in light-textured soils with adequate water holding capacity and drainage. The plant grows well under optimum pH of 5.5 to 7.0 while under acid soils, liming may be required. Water logged conditions, cause leaf shedding in eggplant. Depending on the fertility status of the soil, optimal fertilizer requirements vary from 100 to 170 kg/ha N, 25 to 50 kg/ha P and 550 to 100 kg/ha K (FAOSTAT, 2001).

2.4 Harvesting and Yield

Studies have shown that eggplant can give a fruit yield of 0.5 kg to 8 kg per plant depending on the cultivar and growing conditions (Lester and Seck, 2004). Under rain fed, this translates to fruit yields varying from 5 to 8 ton/ha, while under optimal irrigation, potential fruit yield vary from 12 to 20 ton/ha. Currently, potential fruit of improved cultivars vary from 50 to 80 ton/ha (Lester and Seck, 2004). The average leaf yield harvested during the dry season is about 30 ton/ha. Brigitte and Heide (2004) suggested weekly harvests of African eggplants and which could continue for 90 days. Other observations have shown that one cropping could be harvested over one to two years, depending on the moisture availability, though with age, fruit yield decline.

2.5 Plant Properties and Uses

Tender and immature Eggplant leaves and fruits are consumed as a vegetable. The leaves are eaten as a separate dish or in sauces together with other ingredients. The leaves, fruits and roots have many different medicinal uses, for example, in Sierra Leone, leaves are heated and chewed to treat throat problems (PROTA, 2010). Roots and fruits are used as a carminative and sedative and to treat colic and hypertension; in Nigeria, fruits are taken as a laxative and to treat heart diseases, while flowers and fruits are chewed to clean the teeth (PROTA, 2010); in Kenya, the juice of boiled roots is drunk to treat hookworms, while crushed leaves are taken to treat stomach problems (Bukenya and Bonsu, 2004). Eggplant is also occasionally grown as an ornamental plant (PROTA, 2010).

African eggplant leaves are rich in calcium and provide all nutritionally important amino acids in adequate quantities (Schippers, 2002). A drawback for all *Solanum* species is that they contain a number of spirosolane alkaloids, including solanine and solanidine, which are bitter-tasting.

These substances are potentially poisonous when eaten raw or not properly cooked (Schippers, 2002).

2.6 Water Management

2.6.1 Water-Saving Techniques

Water-saving techniques refer to a comprehensive exercise, using 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 *et al*., 2006).

2.6.2 Water-Saving Irrigation Management

Water scarcity affect water availability in agricultural production systems, as a result, water-saving technologies and strategies are reaching considerable studies worldwide. The purpose of saving-water irrigation strategies is to use water efficiently in order to lead to a sustainable agriculture. In other words, saving-water irrigation practices uses 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 products. The optimum frequency and amount of applied water is a function of climate and weather conditions, crop species, variety, stage of growth and rooting characteristics, soil water retention capacity and texture, irrigation system and management factor (Phene, 1989). Too much 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 erratic 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 lands yet its field level application efficiency is often 40 - 50 percent (von Westarp, 2004).

2.6.3 Drip Irrigation

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 evapotranspiration 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 drip irrigation is cost effective, labour-saving and allows more plants to be grown per unit of water, thereby both saving water and increasing farmers' incomes at the same time.

2.6.4 Deficit Irrigation

Fereses and Soriano (2007) defined deficit irrigation as the application of water below the evapotranspiration (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 is multifaceted. In economic terms, the potential benefits of deficit irrigation derive from three factors: increased irrigation efficiency, reduced costs of irrigation and the opportunity cost of water (English *et al*., 1990; English and Rajan, 1996). Ecological benefits of deficit irrigation include preventing rising water tables in areas where the water level is near the soil surface. Deficit irrigation can also help in minimizing leaching of agrochemicals to groundwater (Home *et al*., 2002).

Deficit irrigation has various features 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 fluctuations caused by water deficit. Similarly, in arid zones, small amounts of irrigation water are applied to winter crops that are normally grown under rain fed conditions (Oweis *et al*., 1998). Another form of irrigation is called sustained irrigation or limited irrigation (Wang *et al*., 2002) where irrigation water is applied below ET continuously throughout the growing season. The theoretical basis for this type of irrigation includes crop-water relation, impacts of the water deficit on 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 physiology and biochemistry. RDI is conducted on crops according to their characteristics and water requirements. In RDI, certain water stresses are imposed at the beginning of some crop growth stages which can change intrinsic plant physiological and biochemical processes, 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 periods (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 levels.

Deficit irrigation has been reported to be successful in most cases in tree crops such as fruit and nut tree species such as almond (Goldhamer and Viveros, 2000), citrus (Domingal *et al*., 1996), apple (Mpelasoka *et al*., 2001), mango (Spreer *et al*., 2007) and wine grapes (Bravdo and Naor, 1996; MacCarthy *et al*., 2002; Fereres and Evans, 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 not sensitive to water deprivation at some developmental stages (Johnson and Handley, 2000).

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 on the North China plain revealed water-savings of 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. 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 scarce (Smedema and Shiati, 2002). This is because the rainfall in these areas is not sufficient to provide the leaching requirement to remove excess salts accumulated in the root zone (soil surface), as evapotranspiration 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.

2.6.5 Response of Plant to Soil Water Stress

The effects of soil water shortage on crop yield are presented by several authors (Slabbers, 1980; Brouwer *et al*., 1989; Moutonnet, 2000; Zhang *et al*., 2003; Çakir, 2004). Plants cannot survive without water and show a number of symptoms when exerted to water stress during plant 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 occurs when plants extract water at soil moisture content between field capacity and wilting point (Veihmeyer and Hendrickson, 1950). Within this range, the growth of crops will diminish gradually when the soil water content falls below field capacity and cease when the soil water content falls below permanent wilting point. In other words, plants will attain the better growth when the soil water content is close to field capacity.

When water stress status occurs in a given stage during growing period, it influences the plant growth and as a result, this affects actual yield and evapotranspiration (Moutonnet, 2000). The response of yield to water stress is expressed through an empirical linear [Equation 1], developed by Doorenbos and Kassam (1979). For decades, this approach has been widely adopted and used to estimate yield response to water by planners, economists and engineers (Vaux and Pruitt, 1983; Howell *et al*., 1990). The other software developed uses this approach to simulate water-limited yield (Smith, 1992).

2.6.6 Crop Yield Response Factor (Ky)

Crop response factors (Ky) relate the relative yield decrease to the relative evapotranspiration 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 Nations (FAO) and the International Atomic Energy Agency (IAEA). The results have been published in a technical document of the IAEA (IAEA, 1996) and in several technical reports and books (Doorenbos and Kassam, 1979; Allen *et al*., 1998; Kirda *et al*. 1999).

Irrigation is needed for successful crop production, where stored 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. It has been established from research results that irrigation demand of crops varies widely depending on the stage of crop (Hassan *et al*., 2002).

In general, 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 will be large. The researchers have shown that crop yield response varies with the growth stage in which an irrigation deficit is suffered (Kirda and Kanber, 1999). An irrigation deficit suffered at one stage in the growth cycle of the crop may have little to no significant effect on crop yield, while an irrigation deficit suffered at a more critical stage in the plant cycle (generally during the flowering, fruit setting or grain formation stage) may dramatically affect yield (Kirda, 2002; Fereres and Soriano, 2007). For example, 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 the growing season. The period at the beginning of the flowering stage is most sensitive to water shortage, while maximum yield was obtained with full irrigation; almost the maximum yield was generally obtained when irrigation was made to provide adequate water during flowering and fruit formation periods (Blum, 2005). Therefore, consideration must be given to the stage of the plant in its growth cycle if the value of supplemental irrigation has to be determined. As a result, a series of empirically derived crop yield response factors (K_y) 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.

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2.6.7 Increasing Water-Use Efficiency

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

Table 2: Seasonal yield response function

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	Soybean	0.85
Citrus	1.1-1.3	Spring wheat	1.15
Cotton	0.85	Sugar beet	1
Grape	0.85	Sugarcane	1.2
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)

2.6.8 Cultural Practices that Conserve Water and Protect Crops

Various crop management practices such as mulching and the use of shelters and raised beds, help to conserve soil moisture, prevent soil degradation and protect vegetables from heavy rains, high temperatures and flooding. The use of organic and inorganic mulches is common in high-value vegetable production systems. These protective coverings help reduce evaporation, moderate soil temperature, reduce soil runoff and erosion, protect fruits from direct contact with soil and minimize weed growth. In addition, the use of organic materials such as mulch can help enhance soil fertility, structure and other soil properties. In India, mulching improved the growth of eggplant, okra, bottle gourd, round melon, ridge gourd and sponge gourd, compared to the non-mulched controls (Pandita and Singh, 1992). Yields were highest when polythene plastic and *sarkanda* (*Saccharum* spp. and *Canna* spp.) were used as mulching materials. In the lowland tropics where temperatures are high, dark-colored plastic mulch is recommended in combination with rice straw (AVRDC, 1990). Dark plastic mulch prevents sunlight from reaching the soil surface and the straw insulates the plastic from direct sunlight thereby preventing the soil temperature rising too high during the day.

2.6.9 Irrigation Use Efficiency

Irrigation use efficiency refers to the use of irrigated farming practices with the most economical exploitation of the water resources. This entails irrigation management that enables reduced water supply to the 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 *et al*., 2009).

2.7 AquaCrop Model

AquaCrop was developed to replace the approach 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). The separation of Y into B and HI allows the distinction of the functional relations between the environment and B from those between 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 *et al*., 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, HI_0, CDC and Tr are considered conservative parameters (nearly constant). The location and cultivar-dependent parameters, 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 [Equation 1]:

$$\left(\frac{Y_x - Y_a}{Y_x}\right) = K_y \left(\frac{ET_x - ET_a}{ET_x}\right) \qquad \text{[Equation 1]}$$

where Y_x and Y_a are the maximum and actual yield; ET_x and ET_a are the maximum and actual evapotranspiration, respectively and K_y is the proportionality factor between relative yield loss and relative reduction in evapotranspiration or the crop yield response factor.

AquaCrop model separates evapotranspiration (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 confounding effect of the non-productive 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 2]:

$$B = WP.\Sigma\left(\frac{T_a}{ET_o}\right) \qquad \text{[Equation 2]}$$

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 Sinclair, 1983). By normalizing appropriately for different climatic conditions, WP becomes a conservative parameter (Steduto *et al.*, 2007). Thus, stepping from [Equation 1] to [Equation 2] has a fundamental implication for the robustness and generality of the model. It is worth noting though, 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 the 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 2] the relationship is used for daily time steps, a period closer to and approaching the time scale of crop responses to water deficits (Acevedo *et al.*, 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 processes; and (iii) the atmosphere, with its 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 diseases are not considered.

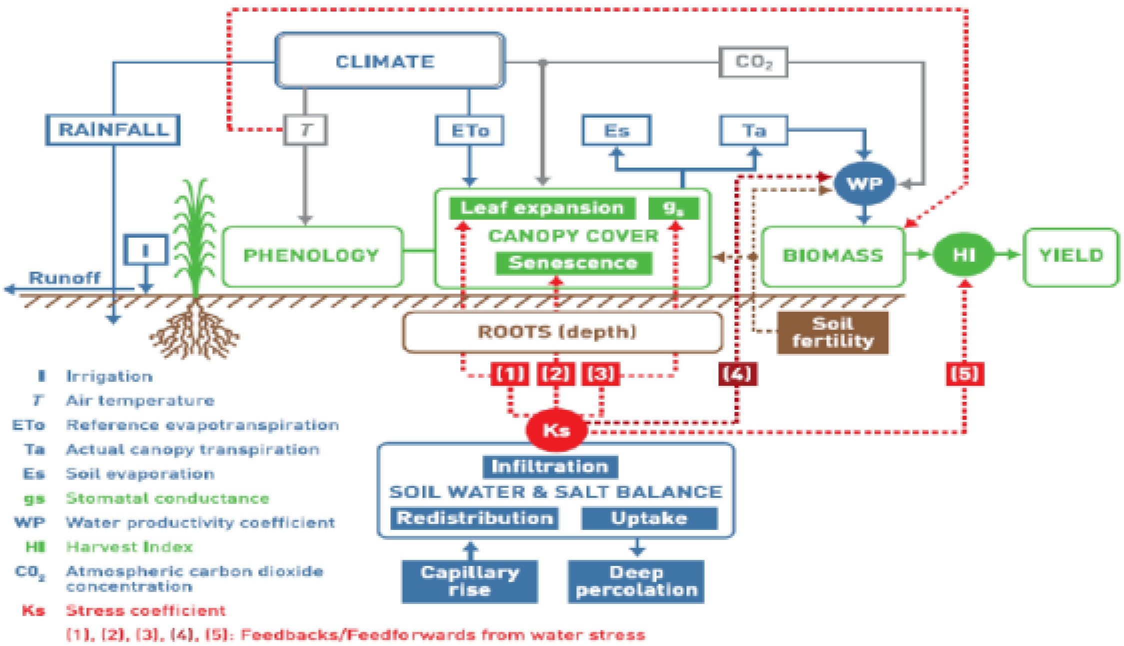
The procedures incorporated in AquaCrop include infiltration of water, drainage out of the root zone, evaporation and transpiration rate, biomass production and yield formation. Users can pause simulation at each time step to observe the response of crop growth to the change in water. AquaCrop simulates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

The functional relationships between the different AquaCrop components are depicted in Figure 1. 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 HI.

2.8 Soil Water Balance

The water balance is an accounting of the inputs and outputs 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 evapotranspiration as shown in [Equation 3].

$$\Delta S = (P + I) - (q + ET) \quad \text{[Equation 3]}$$



Source: Steduto *et al*., 2007; Steduto *et al*., 2009

Figure 1: Flow chart of AquaCrop indicating the main components of the soil–plant–atmosphere continuum

2.8.1 Water Balance Method

The principle of the water balance method is illustrated in Figure 2. The object is to obtain a balance of incoming and outgoing soil water so that adequate available water is maintained for the plant. Inputs include incoming water in any form, whether from rainfall or irrigation. Outputs include any type of water removal.

Water removal, more commonly referred to as evapotranspiration (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 used.

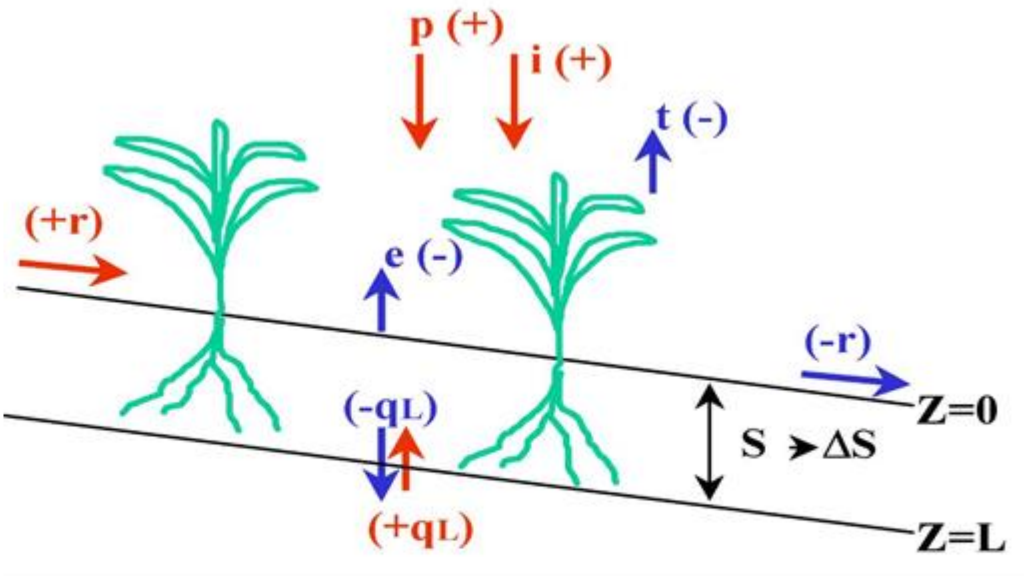


Figure 2: Components of soil water balance

Water cycling in a watershed 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 effective 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 a zero balance, it is time to irrigate. The amount to add 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 than 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 difference 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 evapotranspiration or deep drainage (Zhang *et al*., 2002).

CHAPTER 3

3.0 MATERIALS AND METHODS

3.1 Experimental Location and Field Layout

An experiment was set up at the University of Zambia Field Station, located at latitude 15°23´42´´South and longitude 28°20´13´´East and 1263 m above sea level, during the period August-December, 2011. The land was first cleared of weeds and levelled in readiness for planting. The experimental site covered an area of about 402.05 m^2. It consisted of 16 plots, each with an area of about 20.00 m^2 and plant population per plot of about 30 plants. Micro drip lines were installed with emitters spaced at 30 cm apart. The plant density was 0.90 m inter rows x 0.75 m intra rows (14,815 plants per ha). Each treatment had five micro drip lines. Each plot was equipped with one access tube installed in the centre (Figure 3 and Figure 4) for soil moisture monitoring. A neutron probe meter (CPN 503 model), was used for measuring the soil water content (SWC) in the soil profile at fortnight basis during the growing season. The seventeenth access tube was installed outside the experimental area in order to obtain the moisture content of the dry soil profile. Water meters were connected to the micro drip lines to enable measurement of applied irrigation water.

Figure 3: Experimental site showing the drip irrigated plot and the access tubes

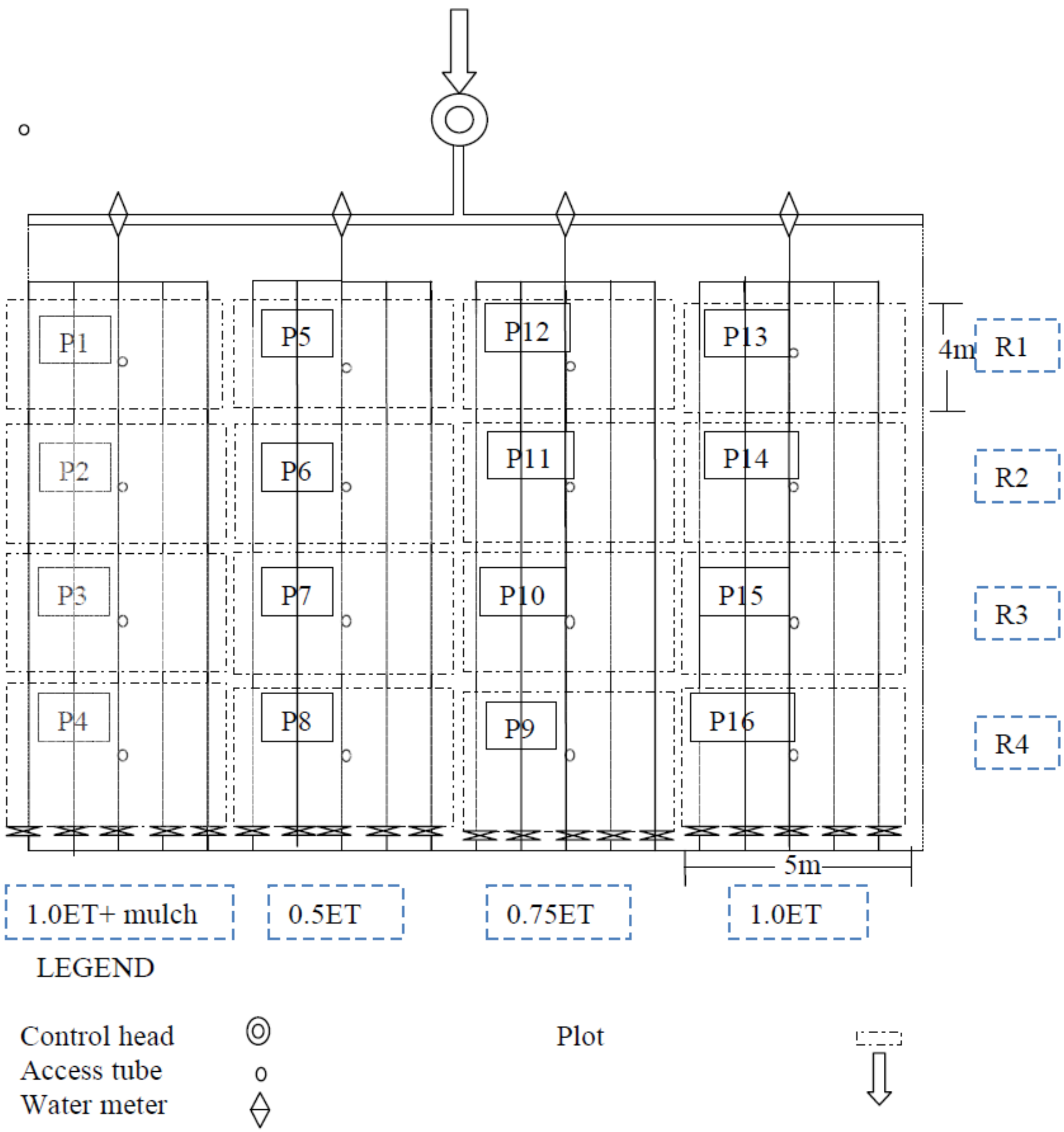


Figure 4: Experimental design of the study site showing the drip irrigated plot and the access tubes with the water source

3.2 Soil Characterization

Representative soil samples were collected from each plot and analyzed for physical and chemical fertility status as presented in Tables 3, 4 and 5. The soil was a deep, well drained and strongly weathered dark reddish brown soil with loamy top soil and clay subsoil, classified as a fine loamy isohyperthermic paleustalf according to USDA classification (USDA, 1992). Soil chemical properties of the site determined from air-dried soil passed through a 2-mm sieve and analyzed for soil pH ($CaCl_2$); organic carbon by wet oxidation with acidified potassium dichromate and external heating followed by colorimetry; exchangeable bases (Ca, Mg and K) extracted in 1 N ammonium acetate solution buffered at pH 7; total nitrogen determined by kjeldhal digestion followed by distillation in excess alkaline and titration with HCl (Anderson and Ingram, 1993) and available phosphorous determined by Bray 1 method (Olsen and Sommers, 1982) are given in Table 3. These results on chemical properties of the soil presented in Table 3 were obtained from composite soil samples collected at random from each plot during land preparation at a depth of 20 cm.

Table 3: Soil chemical characteristics of the 0.20 m depth from the experimental site

Soil property	Range	Mean
pH	6.67-7.41	7.14
Organic carbon (%)	0.94-3.35	1.75
Exch. Ca (cmol/kg)	28-58.75	37.0
Exch. Mg (cmol/kg)	6.25-11.66	9.21
Exch. K (cmol/kg)	0.10-0.26	0.17
Available P (mg/kg soil)	2.90-9.75	4.90
Total soil nitrogen (%)	0.15-1.44	1.41

The soils of the experimental site were found to be slightly acidic to slightly alkaline with low quantities of available phosphorous and exchangeable potassium. The rest of the nutrients were found to be in sufficient quantities.

Tables 4 and 5 show the soil physical and hydraulic properties from a representative soil profile at the experimental site. The bulk density ranged between 1.53 g/cm^3 - 1.58 g/cm^3 with average porosity of 41.3 percent. The average moisture content at field capacity and wilting point was 29.8 percent and 11.5 percent respectively, resulting in average water holding capacity of 183 mm/m.

Table 4: Soil physical properties, bulk density (ρb), texture and water retention characteristics

Soil depth (cm)	ρb (g/cm3)	Sand (%)	Silt (%)	Clay (%)	Textural class (USDA)	FC (v/v)	WP (v/v)	AWC (mm/m)
0-20	1.58	42	32	26	Loam	0.280	0.078	202
20-45	1.57	24	34	42	Clay	0.297	0.124	173
45-80	1.56	28	32	40	Clay	0.303	0.126	177
80-120	1.53	22	34	44	Clay	0.313	0.132	181

FC = field capacity, WP = wilting point, AWC = available water - holding capacity, ρ_b = bulk density

Soil hydraulic properties of a representative soil profile at the experimental site are presented in Table 5**.** The equation developed by van Genuchten (1980) was used to convert water content to matric potential and to calculate drainage for the soil water balance computation.

Table 5: Soil hydraulic properties of a representative soil profile at the site

Soil depth (cm)	θs (v/v)	θr (v/v)	α (cm^{-1})	n	m	Ks (mm/d)
0-20	0.379	0.065	0.0147	1.3751	0.2728	55.4
20-45	0.410	0.085	0.0142	1.3183	0.2414	41.4
45-80	0.409	0.083	0.0145	1.3228	0.2440	45.0
80-120	0.424	0.088	0.0143	1.3240	0.2447	51.8

θs = saturated soil moisture, θr = residual soil moisture, Ks = saturated hydraulic conductivity, α, n and m are curve fitting equation parameter constants for van Genuchten equation

3.3 Test Crop and Agronomic Practices

The African eggplant seeds of a local Zambian variety (Chimumbwa) were used to raise seedlings in a greenhouse using hygrotech growth media. Planting was done on the 1st June, 2011 and seedlings were transplanted ten weeks later. Watering of seedlings was done at least every two days and germination of seeds was first observed two weeks after planting.

Relatively uniformly sized ten week-old seedlings were subsequently selected from the germination trays and transplanted on 14th August, 2011 at planting depth of 15 cm. Two to three seedlings were planted on each planting station and three weeks after crop establishment, thinning was done to one plant per station giving a plant density of 14,815 plants per hectare.

Basal dressing with D-compound (10N: 20P: 10K) fertilizer and top dressing with Ammonium nitrate (35% N) were both applied at a rate of 250 kg/ha. Top dressing with Ammonium nitrate fertilizer was done in a split (on 35th and 65th day after transplanting) application rate of 125 kg/ha. Pests were controlled using chlorban while weeds were manually controlled.

For monitoring plant growth and biomass production, stem girth and plant height were measured weekly on five representative plants from each plot. Data on above ground biomass was also collected through four plant sampling during the growing period to establish the relationships between biomass production and plant height and stem diameter.

3.4 Irrigation Application

Irrigation scheduling was developed using historical weather data from the nearby weather station. Crop water requirement (ETc) was calculated as given in [Equation 4]:

$$ETc = K_c \times ET_o \qquad \text{[Equation 4]}$$

Where ETc is the crop evapotranspiration; Kc is the crop coefficient factor and ETo is the reference evapotranspiration. The irrigation schedule was based on a two-day interval, timed to meet the crop water requirements applied through a metered drip irrigation system.

3.5 Model Input Data

3.5.1 AquaCrop Model

Since the model uses green canopy ground cover instead of LAI, the green canopy cover (CC) was monitored during the growing season. In AquaCrop, the inputs were 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 water productivity (WP*), harvest index (HI), Canopy development coefficient (CDC) and actual transpiration (Ta) were named conservative (nearly constant). Detailed description of the model was given by Steduto *et al*., (2009). The local inputs of weather data were obtained from an automated weather station within the experimental site. Collected weather, crop and soil parameters were measured as input data for the AquaCrop model validation. This model was run to simulate crop growth and data generated was compared with measured data.

The model requires local inputs such as weather data, irrigation schedule and sowing density. In order to run the model, cultivar-specific parameters such as plant density, fruit yield, biomass (B), harvest index (HI_0), effective rooting depth, flowering and maturity time, CC and crop germination were collected and soil water content (SWC) in the root-zone monitored using neutron moisture meter. Canopy cover was measured at weekly or fortnightly intervals, using a digital camera for analysis of green canopy cover. Fruit yield and rooting depth were determined by cutting plants at the ground level during emergence, maximum canopy cover, start of senescence and maturity from randomly selected plants and in addition to yield contributing parameters (plant height, plant population, and biological yield). Soil physical characteristics [soil texture (silty clay loam), soil salinity, water salinity, soil moisture at saturation, field capacity, permanent wilting point, bulk density and saturated hydraulic conductivity] at field site are to be measured as important parameters.

3.5.2 Crop and Soil Parameters

Crop-specific parameters included plant density, yield, biomass, harvest index (HI), effective rooting depth, flowering and maturity time; green canopy cover (CC) and crop germination. Soil parameters included soil texture, available water holding capacity, field capacity and bulk density.

3.5.3 Green Canopy Cover Measurements

Green canopy cover was measured at every seven days interval, over the whole growing season by using a digital camera. This was done by selecting a representative plant from each plot and using it to measure the green canopy cover during the entire growing season.

3.5.4 Calculation of Evapotranspiration (ETo)

The ETo was calculated using ETo calculator, a software based on Penman-Monteith equation (Version three, January 2009; Raes *et al*., 2009b). This method is the recommended standard method and widely used equation for calculating reference ET_o (Allen *et al*., 1998). The inputs for the calculator [maximum air temperature (Tmax), minimum air temperature (Tmin), maximum relative humidity (RHmax), minimum relative humidity (RHmin), sunshine hours (n/N) and wind speed at a height of 2 m (u_2)] were based on actual measured weather data during plant growth.

3.6 Experimental Data Analysis and Treatment Details

In order to evaluate the impacts of water deficit on yield and some agronomic characteristics of the African eggplant, this study was conducted as a completely randomised block design with four treatments in four replications. Three levels of irrigation including: 50 percent, 75 percent and 100 percent of crop water requirement (ETc) were considered and the 100 percent treatment had a black plastic cover so as to eliminate water loss through soil surface evaporation and ensure the only source of water loss was through transpiration.

3.7 Normalized Water Productivity

As emphasized in Steduto *et al*., (2009), central to AquaCrop is the calculation of daily biomass production from simulated daily transpiration (Tr) using normalized water productivity (WP*) and daily reference evapotranspiration (ETo). Water productivity (WP) normalized for evaporative demand was estimated by regressing biomass sampled periodically from the crop against normalized ET (Steduto *et al*., 2007) summed from emergence to the time of each biomass sampling as shown in Table 6. During the growing period, ET accumulated over a given interval was calculated by soil water balance from neutron probe data. Normalization of ET by ETo was done using Equation 13 of Steduto *et al*., (2007).

3.8 Calibration and Validation

3.8.1 Calibration

Based on green canopy measurements and measured crop growth data for the eggplant, the AquaCrop model was calibrated for eggplant. This involved the modification of a default tomato crop file and adapted as crop file for eggplant. The model simulated fruit yield, B, WP and CC of eggplant, considering that SWC was variable. Part of the monitored field data (full irrigation treatment) was used for calibration of the model, while the remaining data (50 percent, and 75 percent) served to validate the model. For each of the simulation runs, the weather data, soil characteristics, irrigation depths, CC development, sowing date, and planting density were entered as input. The cultivars' data, local plant density, estimated maximum rooting depth and time of crop development, were used for model calibration.

Table 6: Normalized water productivity (WP*), plant variety and planting date, and selected crop characteristics of African eggplant

Year	WP*	Plant variety	Planting date	Plant density	Recovered transplant	Senescence	Maturity	Max. root depth
	gm^{-2}			Plants m^{-2}		DAT		m
2011	18.0	*Chimumbwa*	14 August	1.5	5	129	130	1.0

3.8.2 Validation

Validation was carried out by comparing the predicted versus the measured parameters which included green canopy cover, biomass production and soil moisture content. The AquaCrop model was evaluated against the experimental data. The fruit yield, B, WP and CC were simulated for different treatments using the calibrated model.

3.9 Economic Analysis

An economic analysis for eggplant production on drip irrigation system was evaluated for 50, 75, 100 plus cover and 100 without cover as percentage of evapotranspiration. The analysis involved costing of the inputs and comparing with the sales from the harvest. The average market price per kilogram of eggplant was obtained in kwacha and converted to United States dollars. The reference treatment used in the analysis was the 100 percent of evapotranspiration without plastic cover.

CHAPTER 4

4.0 RESULTS AND DISCUSSION

4.1 Model Calibration

Eggplant crop modeling parameters used for calibrating and validating AquaCrop software are presented in Table 7. The modeling parameters were derived from a default crop of tomato and modified for eggplant. These values were used to simulate African eggplant growth under local conditions and were adapted from Heng *et al*. (2009). These parameters included canopy cover growth and canopy decline coefficient; crop coefficient for transpiration at full canopy; water productivity (WP); soil water depletion thresholds for inhibition of leaf growth, stomata conductance and acceleration of canopy senescence; and coefficients for adjusting the harvest index (HI) in relation to inhibition of leaf growth and stomata conductance. These parameters are presumed to be applicable to a wide range of conditions and not specific for a given crop cultivar. The crop characteristics required by the model were adjusted for the studied cultivar using measured data based mainly on green canopy cover. In crop simulation models, calibration is necessary to estimate the model parameter values for different crops, cultivars and ecosystems. Model calibration helps in reducing the parameter uncertainty (Salemi *et al*., 2005).

4.2 Green Canopy Cover, Biomass and Fruit Yield

4.2.1 Green Canopy Cover

The results on green canopy cover analysis are presented in Figure 5. Water application rate had an effect on the development of canopy cover. The treatment under 100 percent of ET with plastic cover had the largest canopy cover while the water stressed treatment (50 percent of ET) had the lowest canopy cover. This could be attributed to the continued water stress during the growing season for the treatment under 50 percent of ET. In addition, the treatment under 100 percent of ET plus plastic cover attained maximum canopy cover earlier (100 days) than the other treatments (>115 days). This could be attributed to the increased water availability as plastic cover prevented water loss through soil surface evaporation. The other treatment (50 percent of ET) on the other hand achieved early maximum canopy cover due to water stress. Water stress forced the crop under this treatment to attain maximum canopy cover much earlier.

Table 7: Calibrated model parameters for simulating eggplant growth

Description	Value	Units or meaning
Base temperature	25.0	^oC
Cut-off temperature	35.0	^oC
Canopy Cover per seedling at 90% emergence (CC_o)	20.0	cm^2
Canopy growth coefficient (CGC)- no fertility stress	6.73	Increase in CC relative to existing CC - %/day
CGC[adj] as calibrated	6.33	% perday
Plant density	14 815	plants/ha
Maximum canopy cover CC_x – no fertility stress	100	function of plant density - %
CC_x[adj] as calibrated	62	%
Canopy decline coefficient(CDC) at senescence	7.2	decrease in CC relative to CC_x %/day
Average decline CC_x as calibrated	0.78	%/day
WP[adj] as calibrated	18.0-16.6	g/m^2
Water productivity normalized to year 2011 (WP*) – no fertility stress	18.0	gm (biomass) m^{-2}, function of atmospheric CO_2
Leaf growth threshold (P_{upper})	0.5	As fraction of TAW, above this leaf growth is inhibited
Leaf growth stress coefficient curve shape	3.0	Moderately convex curve
Stomatal conductance threshold (P_{upper})	0.5	Above this stomata begin to close
Stomata stress coefficient curve shape	3.0	Moderately convex curve
Senescence stress coefficient (P_{upper})	0.7	Above this early canopy senescence begins
Senescence stress coefficient curve shape	3.0	Moderately convex curve
Reference harvest index (HI_o)	63	%

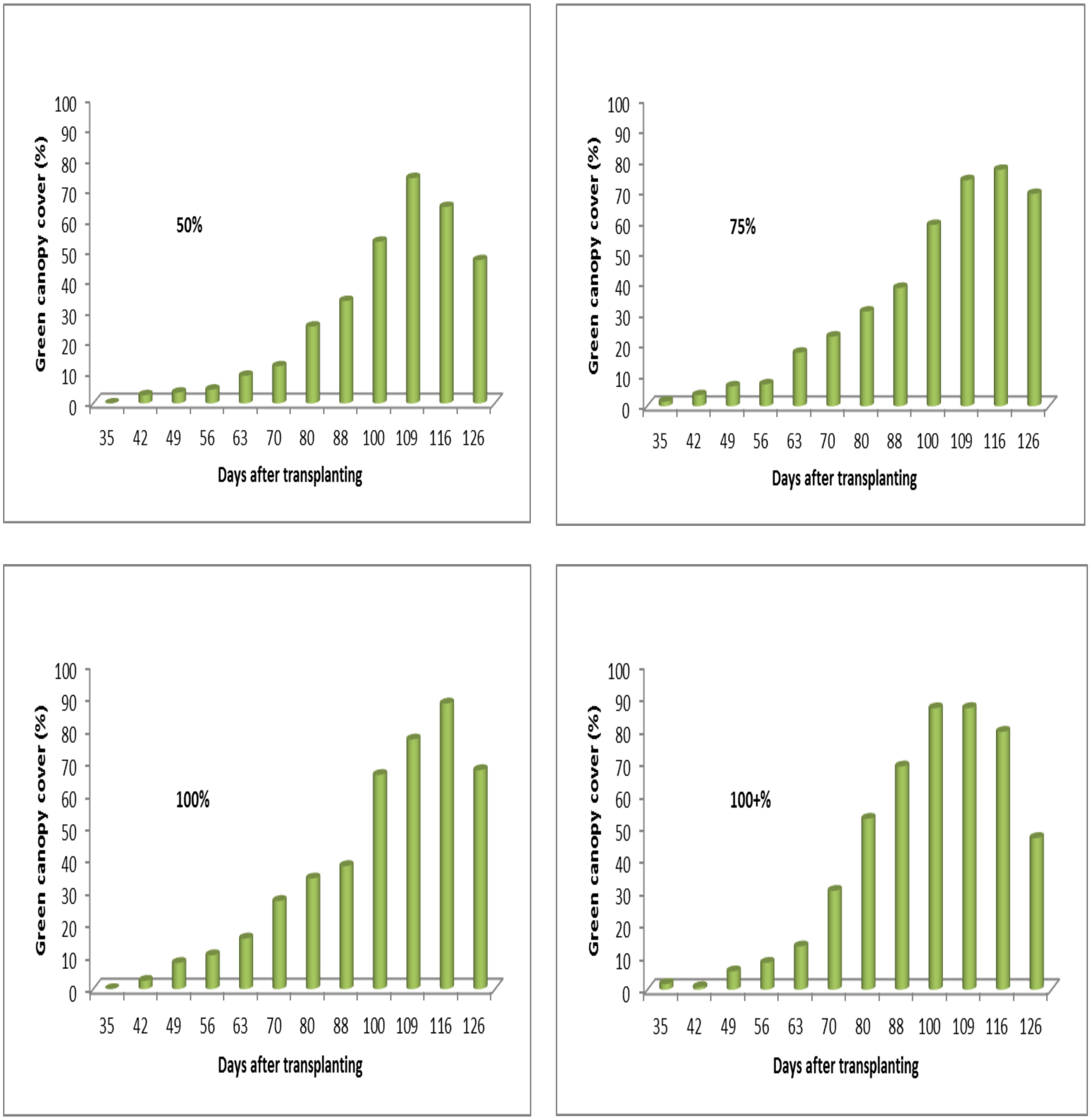


Figure 5: Evolution of green cover during plant growth

Upon achieving maximum green canopy cover, within a few days, senescence was observed in all treatments influenced mainly due to the termination of irrigation water application, as rainfall set in. The treatment under 75 percent of ET and 100 percent of ET without plastic cover attained senescence later than the other two treatments because the plants were still receiving water application through rainfall. The 100 percent ET with plastic cover attained maximum canopy cover early because of water stress resulting from the termination of irrigation, due to commencement of the rain and plastic cover which prevented rainfall infiltration.

An approximate analytical solution for green canopy development by non-linear curve fitting was used to calibrate green canopy cover data as shown in [Equation 5]. The constants α (88.87 percent), β (78.50 percent) and κ (9.01) presented in Table 8 were found to give the best fit for green canopy cover development. Canopy cover (CC) was estimated as a function of time (t) in days after transplanting as given in [Equation 5].

$$CC(t) = \frac{\alpha}{\left[1 + e^{\left(\frac{-(t-\beta)}{k}\right)}\right]} \qquad \text{[Equation 5]}$$

Table 8: Constants used to generate green canopy cover for separating E and T from ET

α (%)	β (%)	κ	MSE	R^2
88.87	78.50	9.01	3.04	0.998

Figure 5 depicts the green canopy cover of African eggplant in all the four treatments. These were taken on the last day of harvest (126 days after transplanting). During the harvest period, it was observed that the canopy cover for the 50 percent of ET was slightly yellow and that of 100 percent of ET with plastic cover had already turned yellow. This is because despite the water stress that the 50 percent of ET was subjected to through irrigation, by that time, rainfall had commenced thereby making this treatment show some recovery from the water stress. The 50 percent of ET and 100 percent of ET with plastic cover showed sparse canopy cover compared with the 75 percent of ET and 100 percent of ET without plastic cover by the final harvest due to water stress but this was clearer for the 100 percent of ET with plastic cover. This yellowing of the 100 percent ET with plastic cover was attributed to the fact that because the soil was covered with plastic and because irrigation was terminated at the onset of the rain, very little rainfall was received in this treatment thereby affecting the greenness of the canopy.

Figure 5: Green canopy cover in all water application rates taken on the final harvest (126th day after transplanting)

However, the treatment with 75 percent of ET and 100 percent of ET without plastic cover showed healthy green canopy cover because they received a luxury of water through rainfall and because water stress on the 75 percent of ET was not too severe compared with the 50 percent of ET. At the time of harvest, it was also observed that the 100 percent of ET without plastic cover showed more vegetative growth but the difference was not much when compared with the 75 percent of ET.

4.2.2 Biomass and Yield

Table 9 presents the effect of water application rate on plant diameter, height, fruit yield, stover, total biomass and harvest index. Results from the statistical analyses showed that there were non-significant differences ($P>0.05$) observed in diameter, height, stover and total biomass but it was observed that the diameter with 75 percent of ET was significantly lower than that of 100 percent of ET plus plastic cover. Fruit yields, heights and harvest indexes with 50, 75 and 100 percent of ET without plastic cover were observed to be significantly lower than that of 100 percent of ET with plastic cover. The highest stover and biomass recorded was with the 100 percent of ET without plastic cover. This is because at the time of harvest when irrigation was already terminated due to the presence of rainfall, this treatment had continued receiving a luxury of water and was never subjected to deficit irrigation, hence the healthy vegetation and higher biomass and stover. This was not the case with the 100 percent plus plastic cover because at the time of harvest, senescence had already commenced due to insufficient input of water from rainfall. Plant diameter varied from 1.95 cm to 2.48 cm with mean average of 2.14 cm. The plant height varied from 100.2 cm to 121.0 cm with mean height of 109.0 cm.

The on-set of rainfall later in the season during fruit development affected yield. The differences in the fruit yield before the onset of rainfall could have been masked by input of water from the rains, because the amount of rainfall received was uniform and therefore, somewhat affecting the results. However, with increased demand for water during the flowering and fruit formation, rainfall was still not enough to support plant growth. The earlier water stress through treatment contributed to differences in fruit yield. Harvest index was also significantly affected by water application rate.

Similar studies by Kirnak *et al*. (2001) observed that irrigation regimes (100, 80, 60 and 40 percent of ET) affected eggplant chlorophyll content, leaf relative water content and vegetative growth. However, the study showed that water stress at 40 percent did not affect plant height and stem diameter. This was attributed to the effect of rainfall, which caused recovery of the water stressed treatments. However, Kirnak *et al*. (2001) also observed that plants grown under severe water stress had less fruit yield and quality than those under optimal condition. The results on fruit yield presented in Table 9 and Figure 6, indicated that the most water stressed level of 50 percent of ET, had the lowest yield.

Table 9: Effect of water application rate on plant diameter, height, fruit yield, stover, total biomass and harvest index

Water application rate (%)	Average diameter (cm)	Average height (cm)	Fruit yield (ton/ha)	Stover (ton/ha)	Total biomass (ton/ha)	HI (%)
50% ET	2.08	100.2	0.89	5.71	6.59	14
75% ET	1.95	108.2	0.95	6.60	7.56	13
100% ET	2.05	106.5	1.15	6.92	8.07	14
100% ET + Cover	2.48	121.0	1.46	6.17	7.64	20
mean	2.14	109.0	1.11	6.35	7.40	15
$LSD_{0.05}$	0.46	21.18	0.41	2.03	2.36	3
CV (%)	13.9	12.6	24.1	20.7	20.5	14
F-pr	0.12	0.24	0.04	0.6	0.59	0.003

The fruit yield response to amount of water applied is presented in Figure 6. The results showed that fruit yield increased with increase in the total amount of water applied. The average fresh fruit yield obtained under 50, 75 and 100 percent of ET with and 100 percent of ET without plastic cover, were, 12.7, 13.6, 16.4 and 20.9 ton/ha respectively. It was found that deficit irrigation at 50 percent of ET yielded the lowest, while the treatment under 100 percent of ET with plastic cover, gave the highest fruit yield. Results show that fruit yield with 50 percent of ET was significantly lower than that of 100 percent of ET with plastic cover. However, fruit yield with 50, 75 and 100 percent of ET without plastic cover were non-significantly different from each other. The applied water under 100 percent of ET with plastic cover treatment had more water which was available only for transpiration process while the other treatments had water shared between soil surface evaporation and transpiration.

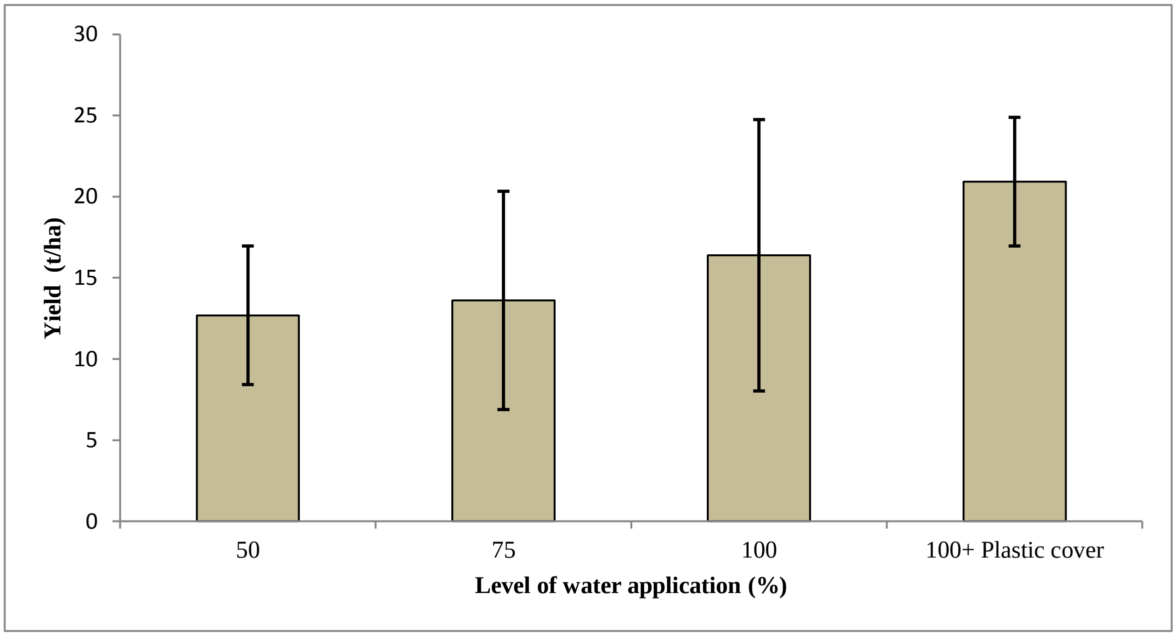


Figure 6: Effect of water application rate of African eggplant fresh fruit yield. Vertical bars represent standard error of the mean

4.3 Water Balance and Water Use

4.3.1 Rainfall and Irrigation Received

Results in Figure 7 present the total amount of irrigation and rainfall during the growing period. Irrigation was done between 9 to 76 days after transplanting, whilst rainfall was first recorded 51 days after transplanting. The higher amount applied during third irrigation was meant to bring the soil water content in the soil profile to field capacity before drip irrigation treatments. The rainfall amount was the same for all the treatments except for the 100 percent of ET with plastic cover. The average water application rate under 50, 75 and 100 percent of ET with and without plastic cover was 5.0, 7.5 and 10.0 mm respectively.

4.3.2 Water Balance Components

Table 10 presents the results on the components of soil water balance. During plant growth, the total applied water through irrigation was 197, 297 and 364 mm representing water application rate of 50, 75 and 100 percent of ET respectively.

During the same period, the treatments received 194 mm water through rainfall. The observed results showed no significant differences in drainage below the root zone and changes in soil water storage. The lack of differences can be due to the high coefficient of variation of the data, which may be attributed to high heterogeneity of soil hydraulic properties. Soil hydraulic properties such as drainage and change in storage are dynamic and not static and because of this, they tend to have a high percent coefficient of variation and are therefore, log-normally distributed. In general, static properties are normally distributed and dynamic soil properties are log-normally distributed and have larger CV's (Fall, 2009). However, there were significant differences in evapotranspiration. The seasonal water consumption (evapotranspiration) ranged from 435.9 mm to 734.2.0 mm and the observed differences in evapotranspiration among the irrigation treatments were attributed to differences in the level of water application. The 100 percent plus plastic cover was acting as mulch in order to reduce on soil evaporation.

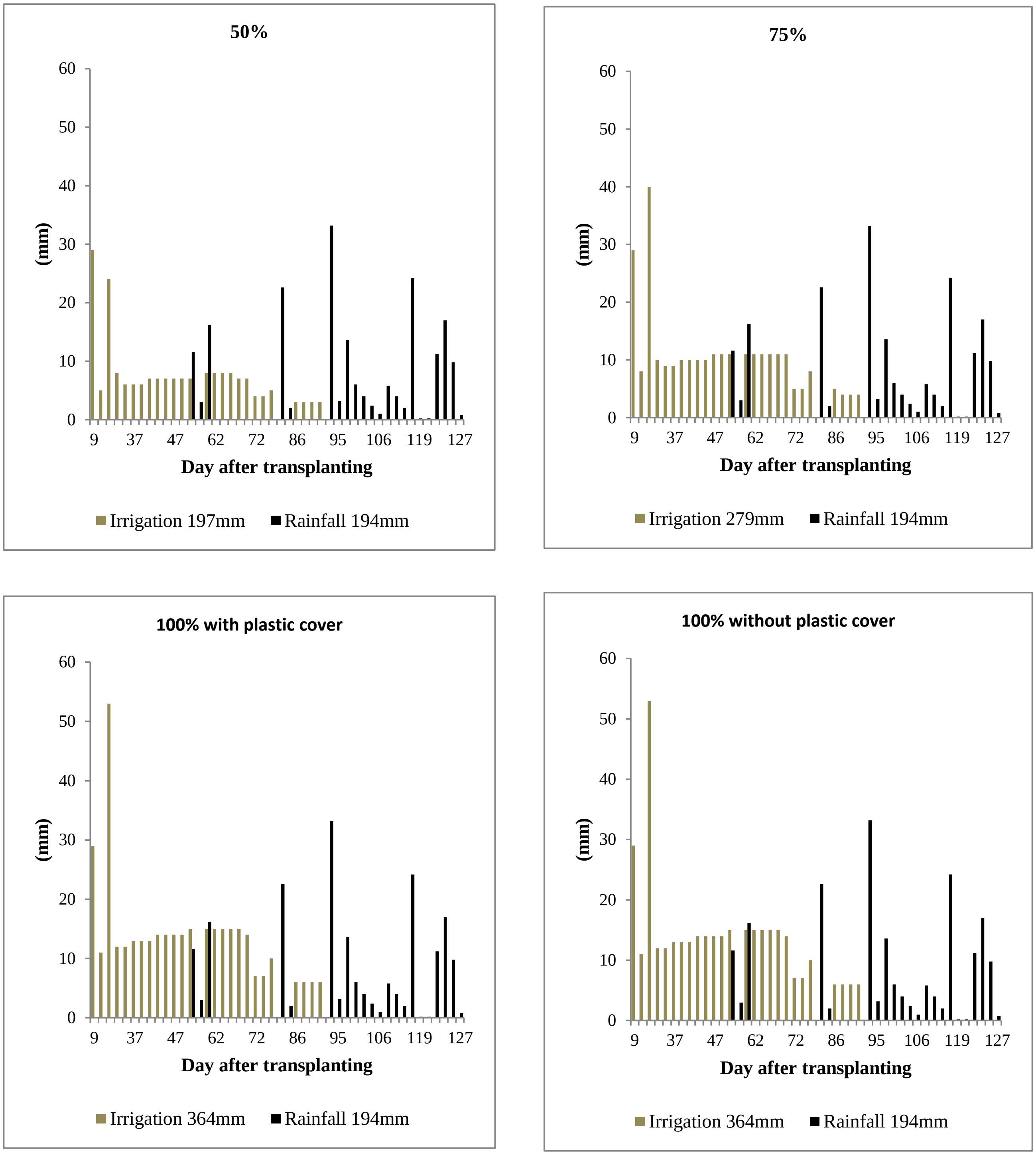


Figure 7: Total amount of water added in irrigation and rainfall for the deficit and fully irrigated treatments

Table 10: Components of soil water balance as affected by water application rate

Water application rate (%)	Rainfall (mm)	Irrigation (mm)	Drainage (mm)	ΔS (mm)	ETc (mm)
50	194	197	27.7	30.4	435.9
75	194	297	23	-23.7	633.4
100	194	364	34	6.1	733.2
100 + Cover	194	364	30	-1.4	734.2
mean			28.7	2.9	634.2
$LSD_{0.05}$			40.92	45.58	55.71
CV (%)			92.6	1037.4	5.7
F-pr			0.95	0.13	<0.001

ΔS: change in soil water content, ETc: crop evapotranspiration

4.3.3 Evapotranspiration Evaporation and Transpiration

Results on ET, T and E are presented in Table 11. These parameters were significantly different as influenced by water application rates. Evapotranspiration increased with increase of applied water. Water loss through soil evaporation was highest under 100 percent of ET without plastic cover treatment (578.8 mm), followed by 75 percent of ET (504.3 mm), 50 percent of ET (304.3 mm) and lastly 100 percent of ET with plastic cover (136.3 mm). The lowest soil evaporation obtained with the 100 percent of ET plus plastic cover was attributed to the fact that the soil was covered and therefore there was no soil evaporation from the soil after covering. Water loss through transpiration was highest under 100 percent of ET with plastic cover (598 mm). The high transpiration leads to increase in biomass production and fruit yield (Pandita and Singh, 1992). Most of the water applied was utilized in the transpiration processes of the crop as there was no soil evaporation. This explains the increase in total biomass and fruit yield observed with the 100 percent of ET plus plastic cover treatment as shown in Table 9 and Figure 6.

Table 11: Effect of water application rate on evapotranspiration, evaporation and transpiration

Water Application Rate (%)	Evapotranspiration (mm)	Evaporation (mm)	Transpiration (mm)
50	435.9	304.3	131.5
75	633.4	504.3	129.1
100 without plastic cover	733.2	578.8	154.4
100+ plastic cover	734.3	136.3	598
mean	634	380.9	253.3
$LSD_{0.05}$	56	38.3	45.2
CV (%)	5.7	6.5	11.6
F-pr	<0.001	<0.001	<0.001

The deficit irrigated treatments of 50 percent of ET and 75 percent of ET recorded the lowest transpiration, (131.5 mm) and (129.1 mm) respectively because the crop received little water application in these treatments, some of which was lost through soil evaporation and drainage and some of it only utilized by the crop through transpiration. On the other hand, 100 percent of ET recorded relatively low transpiration with very high soil evaporation. The bare soil subjected to this treatment, coupled with the luxury of water it received, encouraged the highest soil evaporation because uncovered soil encourages high soil temperatures (AVRDC, 1990) thereby inducing higher soil evaporation rate than transpiration.

The results presented in Figure 8 showed close to uniform evapotranspiration in the early part of the growing season up to about the 35^{th} day after transplanting and afterwards, the lowest evapotranspiration was recorded with 50 percent of ET, followed by 75 percent of ET.

For the 100 percent of ET with and without plastic cover, cumulated evapotranspiration was almost the same from the initial growth stage up to slightly above 55 days after transplanting. Between the 55^{th} and 85^{th} day after transplanting, there was a slight deviation in evapotranspiration with 100 percent of ET being lower than 100 percent of ET without plastic cover. Towards the end of the growing period, between the 85^{th} and 126^{th} day after transplanting, evapotranspiration almost equalized between the two treatments of 100 percent of ET with and without plastic cover.

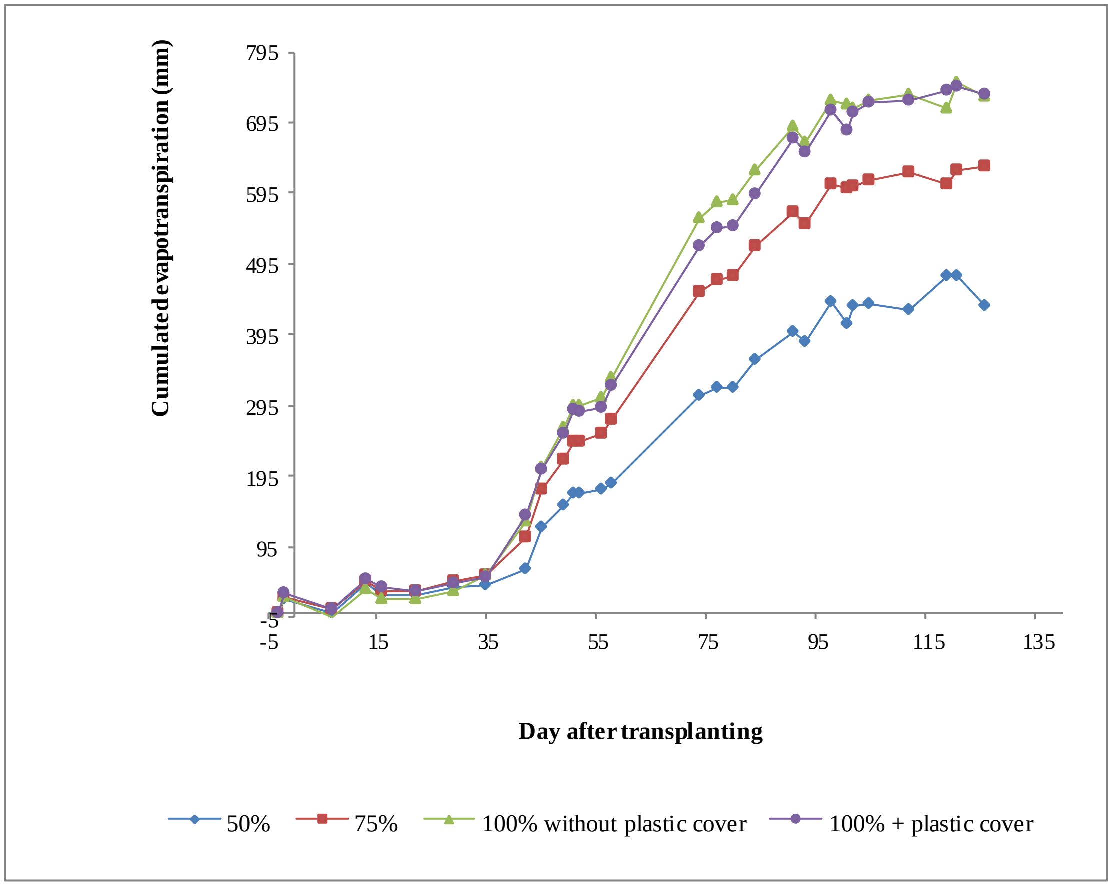


Figure 8: Cumulative evapotranspiration across all irrigation treatments

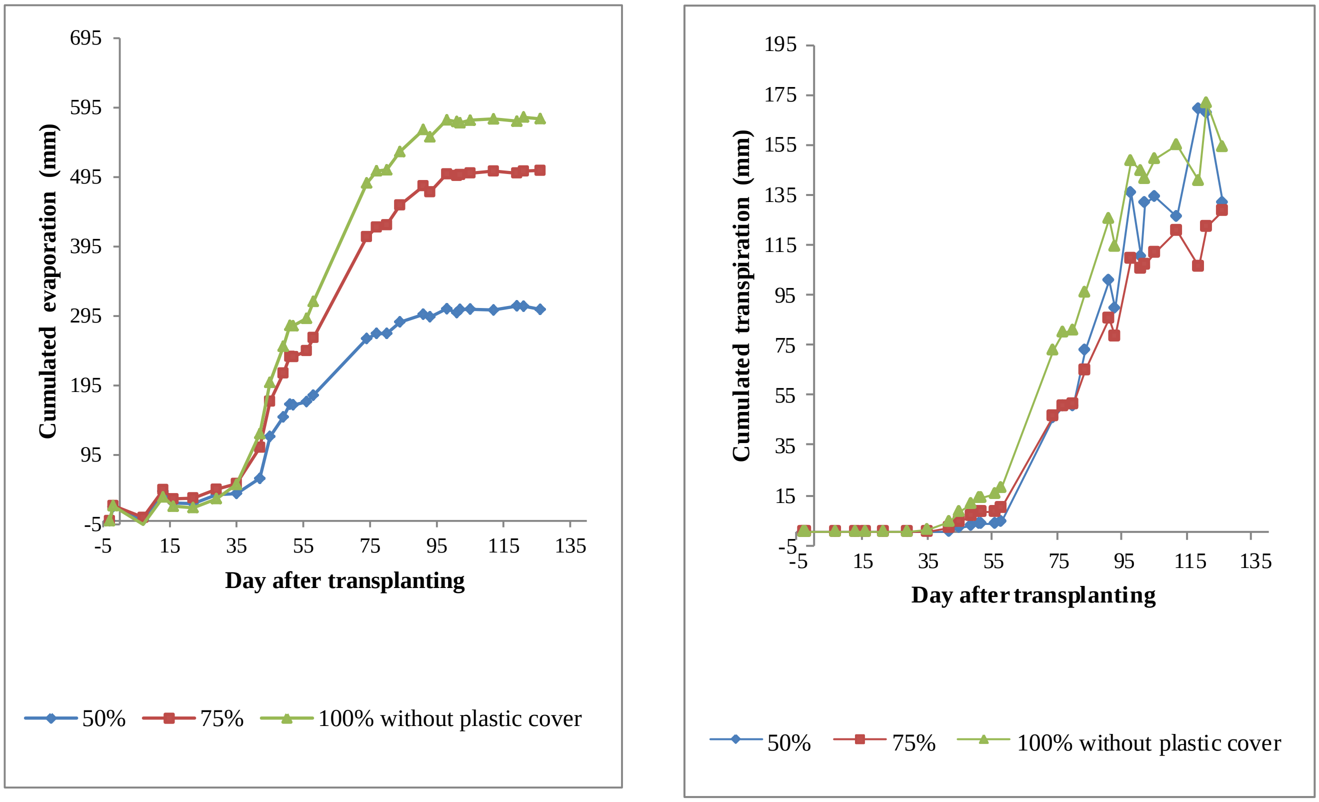


Figure 9: Cumulative evaporation and transpiration across all irrigation treatments during the entire growing period

4.3.4 Water Use Efficiency

Figure 10 summarizes water-use efficiency (WUE) in terms of fruit yield. There was no significant difference in water use efficiency with treatment. However, it was observed that water deficit resulted into higher water use efficiency, partly because there was lower evapotranspiration loss relative to yield. Water stress and ground cover also reduced evaporation losses. The water application levels at 50, 75 and 100 percent of ET without and with plastic cover were, respectively, 33.4, 23.9, 21.6, and 27.5 kg/ha/mm. The water application levels at 50 percent of ET and 100 percent of ET with plastic cover gave proportionally higher yield water use efficiency compared with other water application rates. In addition, water application rate at 75 percent of ET was higher than that at 100 percent of ET without plastic cover. The low water use efficiency for the 100 percent of ET without plastic cover can be attributed to higher irrigation water use, much of which was lost through soil evaporation because of the exposed large surface area of bare soil. These results are in support of a study on AquaCrop validation under deficit irrigation of cotton (Orgaz *et al*., 1992). The lowest ET range gave the highest WUE. Similarly, Kang *et al.* (2001) and Dorji *et al*. (2005) reported significant improvement in WUE due to water stress when applied on pepper.

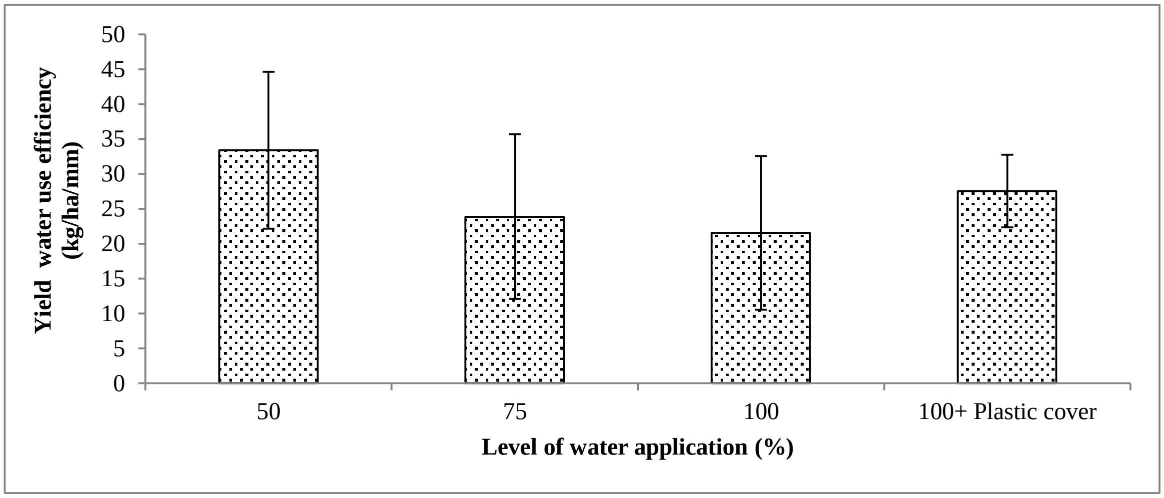


Figure 10: Water use efficiency as a function of treatment. Vertical bars represent standard error of the mean

4.3.5 Soil Water Dynamics

The evolution of soil moisture storage during the growing season for selected soil depths is presented in Figure 11. The results showed that there were higher variations in soil moisture storage in the surface soil layers compared with the deeper soil layers. The variation was more pronounced when depths 0.15 m and 1.05 m were compared. The pronounced variation in the surface layer of 0.15 m could be attributed to water uptake by plant roots, soil surface evaporation and drainage occurring in this zone. The intermittent wetting and drying of the soil profile caused high variation in the surface soil layers. Unlike in the surface soil layers, smaller variations were observed in the sub soil because the effective maximum rooting depth was 1.0 m.

This explains the smaller variations in the deeper soil layers because only fewer roots could reach this depth to extract soil water.

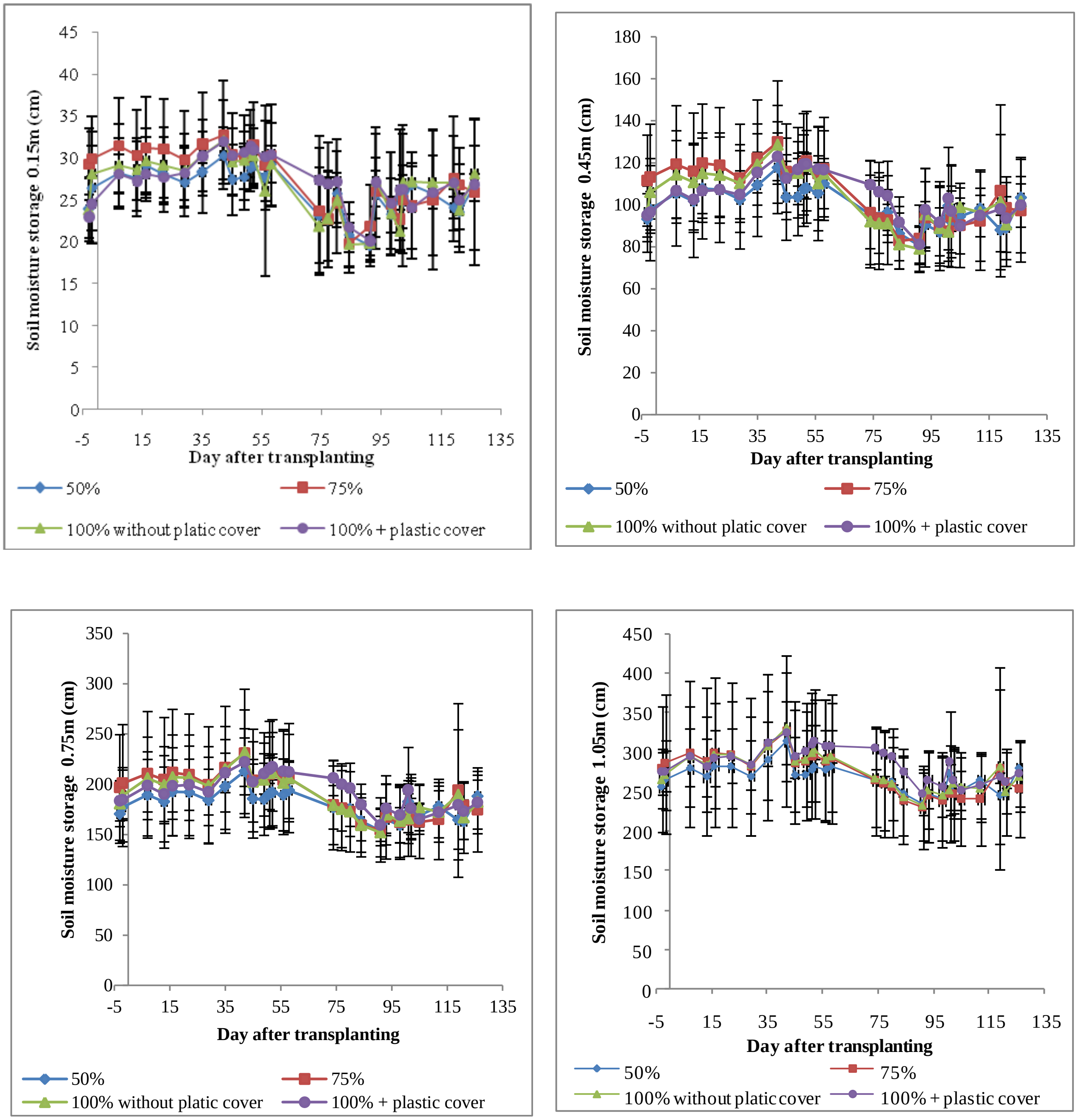


Figure 11: Soil moisture storage in selected 0.15 m soil layers for the 50, 75 and 100% ET irrigation treatments. Vertical bars represent standard error of the mean

4.4 Validation

Results on the comparison of predicted canopy cover (CC) with measured CC are shown in Table 12 and Figure 12. The results in Table 12 show significant differences in the green canopy cover due to treatment effect. This was due to the higher amount of water transpired by the crop and increased vegetative growth. The results showed that the model over predicted green canopy cover in all the treatments and the over prediction increased with decrease in water application rate. This may be attributed to the fact that the model predicts well under no water stress conditions. Consequently, green canopy cover with 100 percent of ET with and without plastic cover, had values close to those of predicted green canopy cover. The deficit irrigated treatments of 50 percent of ET and 75 percent of ET, produced lower green canopy cover values compared with the predicted green canopy cover.

For the deficit irrigated treatment of 50 percent of ET (Figures 12 and 13), the model predicted well only during the initial growing period of the crop from 35 days up to 65 days after transplanting. Thereafter, the model did not predict well because as the crop progressed in growth, the demand for water increased while water supply was inadequate to meet crop water requirements. In addition, treatments under 75 percent of ET had good prediction of crop growth during the initial growth stage (<70 days after transplanting), however, AquaCrop over predicted the green canopy cover.

The treatment under 100 percent of ET without plastic cover showed good prediction of canopy cover during the first 80 days after transplanting. Conversely, the 100 percent of ET with plastic cover showed good agreement in the prediction for most of the growing season up to about 115 days after transplanting. Water stress during most of the growing period was negligible until late season when irrigation was terminated and rainfall set in. Since irrigation was terminated, the treatment with 100 percent of ET with plastic cover experienced water stress until final harvest.

Table 12: Effect of water application rate on Green canopy cover for measured versus predicted results

Level of Water Applied (%)	Measured Green Canopy Cover (%)	Predicted Green Canopy Cover (%)
50	27.1	41.6
75	33.9	43.6
100	36.2	42.3
100+ cover	40.8	43.7
mean	34.5	42.8
$LSD_{0.05}$	13.8	2.9
CV (%)	26.0	4.3
F-pr	0.24	0.35

4.4.1 Comparison of Measured and Predicted Cumulative Biomass

The results on the comparison of measured and predicted cumulative biomass is presented in Figure 13. The overestimation of green canopy cover in AquaCrop model affected the simulation of biomass. The model overestimated biomass in all the treatments with exception of the treatment with 100 percent of ET with plastic cover, as in the case of the simulation of green canopy cover.

4.4.2 Comparison of Measured and Predicted Soil Moisture Content

Results on measured and predicted soil moisture content in selected soil depths are presented in Figures 14 and 15. The trend in the evolution of soil moisture content in the surface layer was similar for the measured and predicted values. However, in all cases, there were both over-estimation and under-estimation of measured soil moisture content. The high variation in the measured data may be attributed to soil heterogeneity, in that some plots had higher clay content than others, despite the blocking of the replications during experimental set-up.

Evolution of soil moisture content in the soil profile at 1.05 m depth is presented in Figure 15. This depth was considered as the maximum rooting depth for eggplant. The result showed that the moisture content at this depth was 20 to 45 percent with the average of 32 percent. There were non-significant differences in the measured and predicted moisture content at this depth. This showed that AquaCrop model was able to predict accurately the soil moisture content for all the treatments at this depth.

The larger deviation in soil moisture for treatment with 75 percent of ET may be due to soil heterogeneity which was observed in some of the plots under this treatment. The deeper soil layer of 1.05 m in Figure 15 revealed that the prediction of the model was good because in all the treatments, the error bars were crossing almost all the data points for the measured and predicted data.

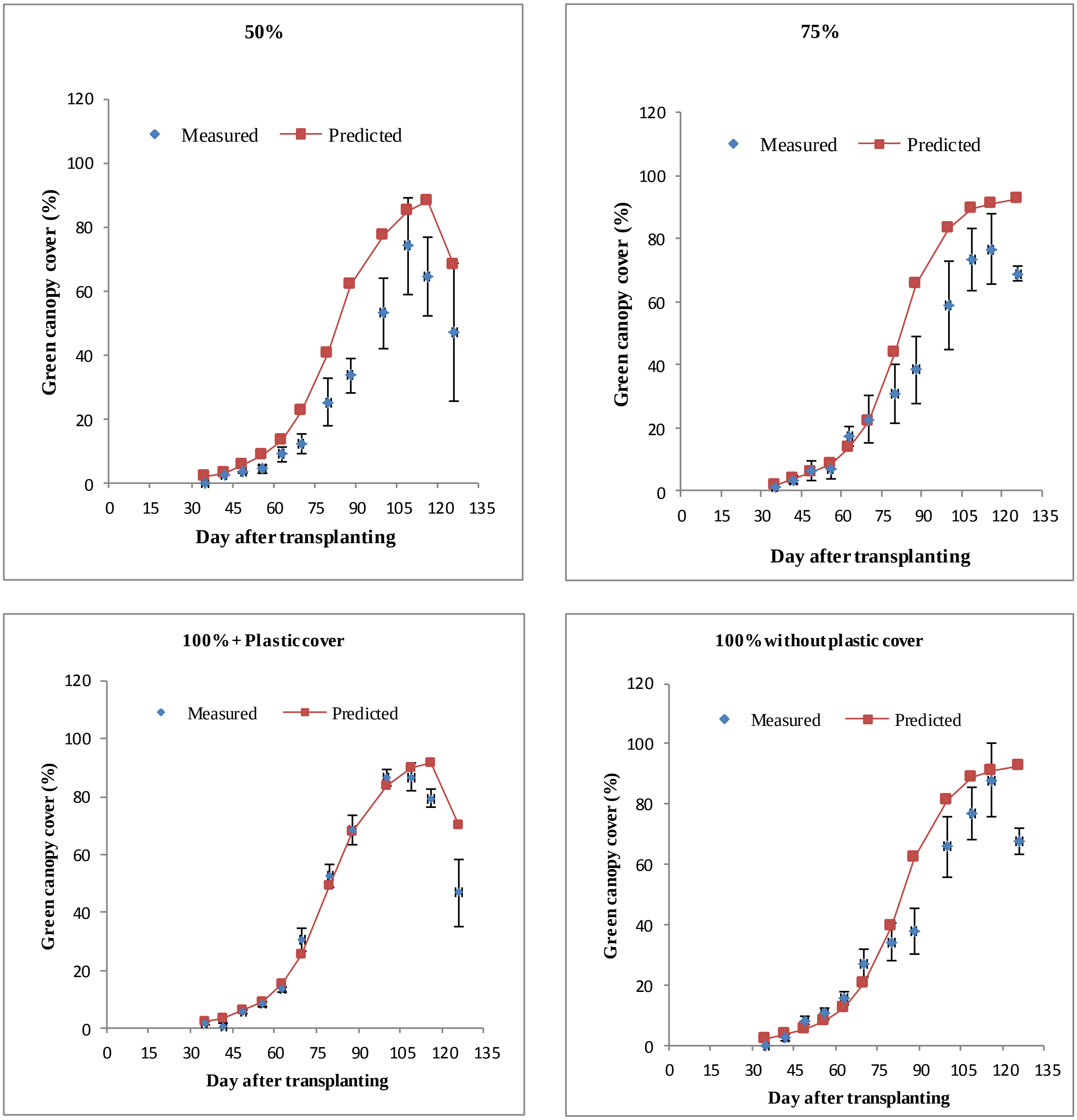


Figure 12: Comparison of predicted with measured eggplant canopy cover as a function water application rate. Vertical bars represent standard error of the mean

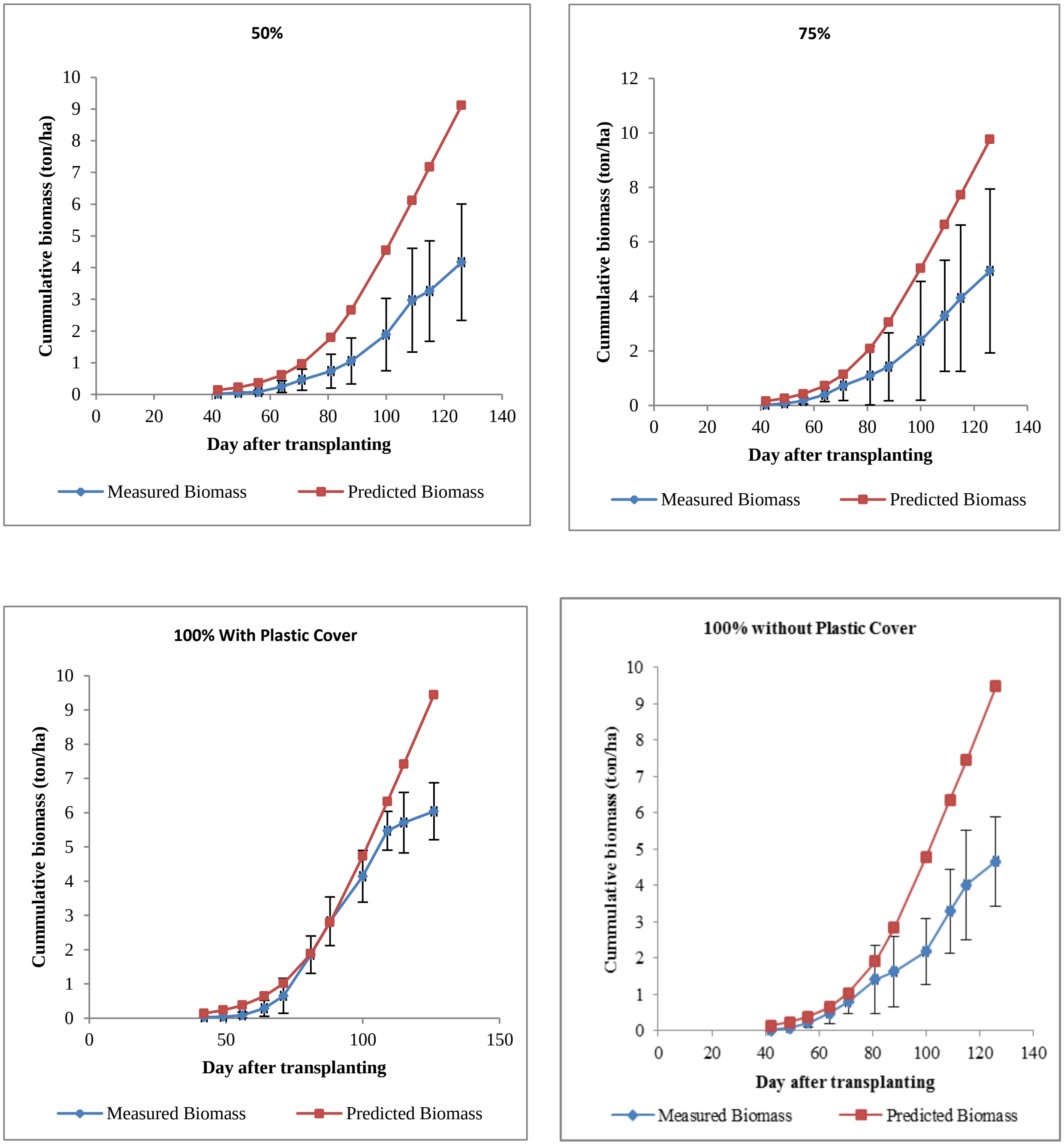


Figure 13: Comparison of predicted with measured biomass accumulation of African eggplant as affected by water application rate. Vertical bars represent standard error of the mean

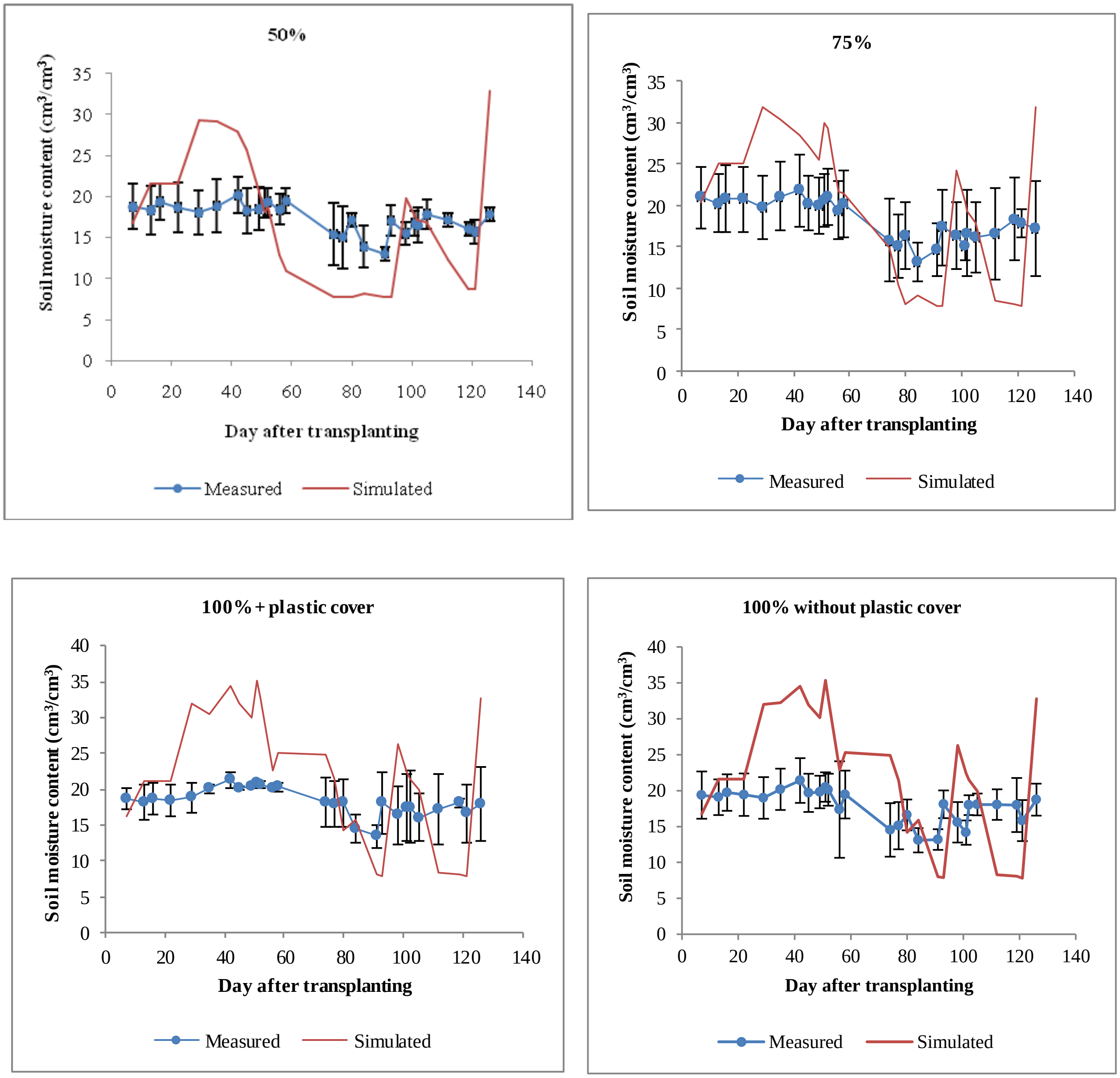


Figure 14: Evolution of measured and predicted soil moisture content at 0.15 m depth. Vertical bars represent standard error of the mean

The deeper soil layers showed some stability in soil moisture content as opposed to the surface soil layer, because soil moisture content varies on the surface of the soil, where the plant roots are active in extracting water. On the other hand, soil moisture content in the deeper soil layer did not vary much due to the fact that the plant roots were only able to extract soil moisture up to about a meter.

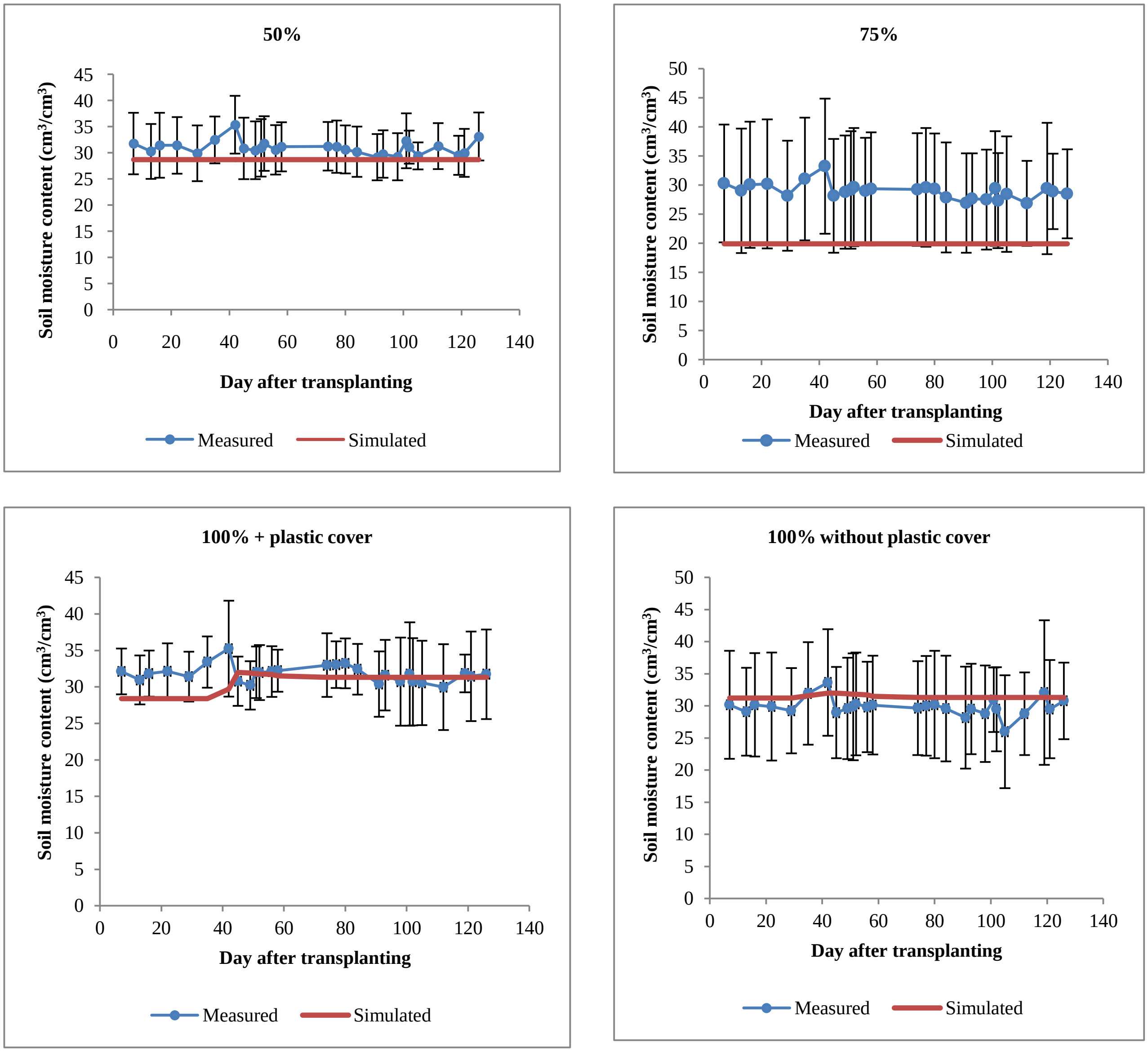


Figure 15: Comparison of measured and predicted soil moisture content at 1.05 m depth. Vertical bars represent standard error of the mean

4.4.3 Comparison of Measured and Predicted Total Biomass

Results on comparison of measured and predicted total biomass are presented in Figure 16. The AquaCrop model over-predicted biomass for treatments, 50 percent of ET and 100 percent of ET plus plastic cover, while treatments with 75 percent of ET and 100 percent of ET without plastic cover were within the prediction accuracy. This may be attributed to the fact that both 75 percent of ET and 100 percent of ET without plastic cover did not experience severe water stress to affect biomass accumulation. However, 50 percent of ET treatment experienced water stress throughout the growing season, while 100 percent of ET plus plastic cover experienced water stress during the maturity period when irrigation was terminated.

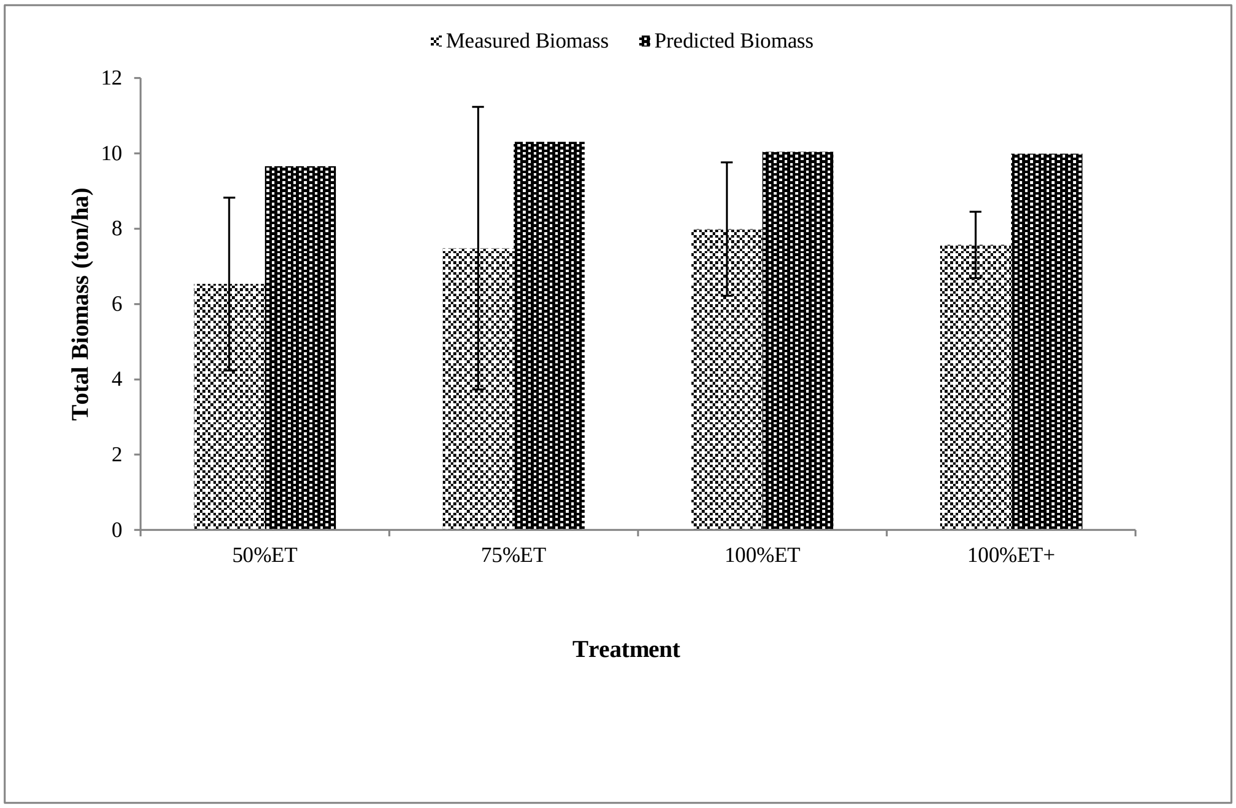


Figure 16: Comparison of measured and Predicted eggplant dry matter biomass. Vertical bars represent standard error of the mean

4.4.4 Comparison of Measured and Predicted Harvest Index

The results on harvest index are presented in Figure 17. In all cases the harvest index was over-estimated and this may be attributed to the overestimation of biomass which is related to HI. The trend in eggplant HI changes due to water deficits were not very well captured by AquaCrop model, as reflected in large differences between simulated and measured HI. This could be as a result of the use of characteristics for the tomato crop in creating a crop file for AquaCrop to calibrate the model. On average, HI for simulated biomass was about 63 percent whilst that of measured biomass was about 15 percent (Figure 17).

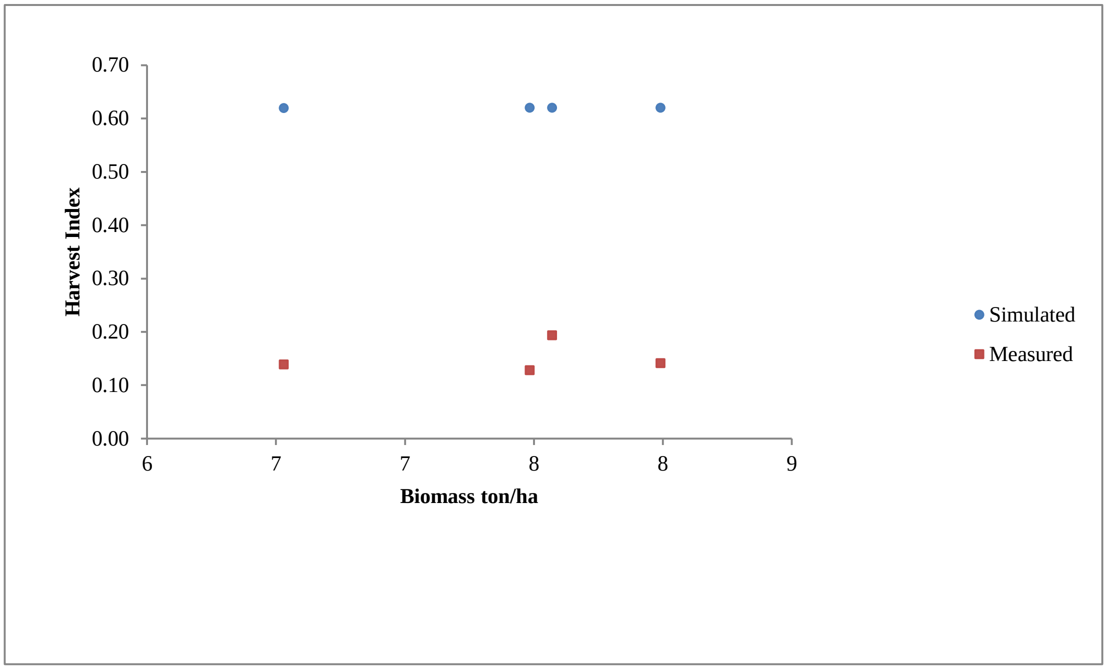


Figure 17: Measured and simulated values of African eggplant harvest index as a function of biomass

As a summary of the outcome of the simulations, the simulated final biomass and grain yield of the different irrigation treatments were compared with the measured values in Table 13 with the deviation of the simulated value from the measured value expressed as a percentage of the measured value. When simulated final biomass was compared with the measured biomass, deviations ranged between 1.89 and 14.07 percent. The smallest deviation recorded of 1.89 percent was observed in the 100 percent of ET with plastic cover followed by 3.09 percent obtained in the 100 percent of ET without plastic cover, then the third largest deviation was 6.40 percent, obtained under 75 percent of ET and the largest deviation of 14.07 percent observed under 50 percent of ET. It was observed that the higher the amount of water application, the higher the accuracy in the predicted versus the measured biomass. As regards fruit yield, the simulated values deviated from the measured by over 100 percent as shown in Table 13.

AquaCrop model did not compare the fruit yield well with the measured yield in all the treatments.

The greater deviations for the simulated yield compared with the simulated biomass are not surprising when considering the difficulties of simulating the final HI (Figure 17). It is particularly difficult to simulate HI for terminal drought conditions where accelerated canopy senescence often has major impact.

The other factor that could have contributed to the high deviation in harvest index between the measured and simulated biomass could be because of the characteristics used for the tomato plant to help with creating a crop file in AquaCrop model. This plant was chosen because it has similar agronomic characteristics and requirements with African eggplant and because these were not known for the African eggplant, tomato plant characteristics were used.

Table 13: Summary of simulated and measured above ground biomass and fruit yield for eggplant

Growing period	irrigation water applied	Final Measured	Biomass Simulated	Deviation	Fruit Measured	yield Simulated	Deviation
	%	t ha^{-1}		%	t ha^{-1}		%
Aug – Dec	50%ET	6.53±10.38	9.65	14.07	0.89 ±1.35	5.98	434
	75%ET	7.48±11.90	10.31	6.40	0.95±1.51	6.39	420
	100%ET	7.99±12.71	10.03	3.09	1.15±1.83	6.22	317
	100%ET+	7.57±12.04	9.99	1.89	1.46±2.32	6.19	228

% deviation = (Simulated – measured) x 100/measured

4.5 Economic Consideration

Results on economic analysis of eggplant production under drip system are presented in Tables 14, 15 and 16. The average fruit yield was observed to be 16,387 kg/ha and the average market price of eggplant per kilogram for the 2011/ 2012 growing season was estimated at US$ 0.5 per kg.

Results on the summary of the fruit and water application and associated deviations from the reference treatment of 100 percent of ET are presented in Tables 14, 15 and 16. The results showed that fruit yield varied from 12.7 ton/ha under 50 percent of ET to 20.9 ton/ha under 100 percent of ET plus plastic cover with reference at 16.4 ton/ha for the 100 percent of ET without plastic cover.

Table 14: Deviations in actual yield and water application with reference to the 100 percent of ET treatment without plastic cover

Level of water applied	Actual yield (kg/ha)	Potential yield (kg/ha)	Yield increase or decrease +/- (%)	Amount of water applied (m^3/ha)	Optimum water application (m^3/ha)	Deviation from optimum water application +/- (%)
50 %ET	12 690.86	16 387.45	-22.56	3800	7600	-0.50
75 %ET	13 610.29	16 387.45	-16.95	5700	7600	-0.25
100 %ET	16 387.45	16 387.45	+0.00	7600	7600	0.00
100 % ET+	20 925.55	16 387.45	+27.69	7600	7600	0.00

Yield increase = (Actual yield – potential yield)/ potential yield x 100

Deviation from optimum water application = (Amount of water applied – optimum water application)/optimum water application x 100

The data showed decrease of yield (-16.95 percent) with 75 percent of ET, (-22.56 percent) with 50 percent of ET and an increase of +27.69 percent with 100 percent of ET plus plastic cover. Similarly, the amount of water applied varied from 3800 m^3/ha to 7600 m^3/ha resulting in a decrease of water application of -25 percent and -50 percent respectively.

In Table 15, no economic returns were recorded for the 50 percent of ET, 75 percent of ET and 100 percent of ET without plastic cover because the inputs were far much higher than the outputs. Water saving in the 50 percent of ET was higher than in the other two treatments and was recorded as US$ 1299.5. It was also observed that the 75 percent of ET showed a yield reduction much higher than that obtained in the 50 percent of ET and was found to be US$ 2174. There was also no economic return recorded in the 75 percent of ET for the same reason that the input cost much higher than the output. The yield reduction was higher than that in the 50 percent of ET because of the reduced water saving which was found to be US$ 649.7.

The yield decrease in the 100 percent of ET without plastic cover was lower than in the deficit irrigated treatments of 50 and 75 percent of ET and was recorded as US$ 1434. This was probably because there was no water stress subjected to this treatment. However, there was no water saving recorded in this treatment. There was also a record of yield reduction in this treatment because the input was again higher than the output.

The inputs in all treatments but one were different. There was a difference in the input recorded in the 100 percent of ET with plastic cover and the additional cost incurred was attributed to the plastic cover. The 100 percent of ET plus plastic cover gave positive net returns of US$ 834 because of the high yield increase recorded.

Similar studies on economic evaluations of deficit irrigation on vegetable production have been conducted. Field demonstration conducted by Shatanawi and the French agriculture Mission in Jordan (1994) showed that 40 percent reduction in water consumptive from the farmer's practices did not affect yield. Observation and communication with some farmers concluded that reducing water application by 30 - 40 percent during drought years did not reduce yield economically.

Table 15: Yield decrease for 50 percent of ET, 75 percent of ET and 100 percent of ET without plastic cover

Input 1US$=4600	Output 50% level of water applied
US$ 7172 Drip irrigation system Cost/growing season $7172/5years= US$1434	-22.56% Yield decrease = 16 387.45 x -22.56% x US$0.5 = - US$ 1848.5 Water saving: US$ 2599 – (50% x US$ 2599) = US$ 1299.5 Total -US$ 549
-US $ 549 - US$ 1434 = -US $ 1983	
Input 1US$=4600	Output 75% level of water applied
US$ 7172 Drip irrigation system Cost/growing season U$ 7172/5years= US $1434	-17.56% Yield decrease = 16 387.45 x -16.96% x US$ 0.5 = -US$ 1389.7 Water saving: US $ 2599 – (75% x US$ 2599) = US$ 649.7 Total US$ -740
-$ 740 - US $1434 = -US $ 2174	
Input 1US$=4600	Output 100% level of water applied without plastic cover
US$ 7172 Drip irrigation kit Cost/growing season US$ 7172/5years= US $1434	0.00% Yield increase = 16 387.45 x 0% x US$0.5 = US$ 0.0 Water saving: US$ 2599 – (100% x US$ 2599) = US$ 0 Total US$ 0
US$ 0 - US$1434 = - US$1434	

Table 16: Yield increase for 100 percent of ET level of water application with plastic cover

Input 1US$=4600	Output 100% level of water applied with plastic cover
US$ 7172 Drip irrigation kit US$ 925 Black plastic cover Cost/growing season US$ 8097/5years= US$1434	27.69% Yield increase = 16 387.45 x 27.69% x US$ 0.5 = US $2268.8 Water saving: US $ 2599 – (100% x US$ 2599) = US$ 0 Total US$ 2268.8
US$ 2268.8 – US$1434 = US$ 834.8	

CHAPTER 5

5.0 CONCLUSIONS

The study was conducted to validate the AquaCrop model for irrigated African eggplant under deficit and full irrigation regimes at UNZA Field Station, with specific objectives on the growth of eggplant of (i) determining the effect of deficit irrigation on yield production; (ii) determining the optimum water use and water use efficiency for the African eggplant; and calibrating and validating AquaCrop model under local climatic conditions.

5.0.1 Effect of Water Application Rate on Dry Matter Production and Fruit Yield

The results showed that decreasing the amount of water applied through irrigation resulted in decrease in total dry matter production and the final fruit yield. In this study reduction of water application by 25 percent resulted in yield reduction of 17 percent, while reduction of water application by 50 percent resulted in yield reduction of 23 percent. In terms of water use efficiency, it was discovered that water use efficiency increased with decreasing level of water application and vice versa. These results therefore suggest that irrigation water requirements of African eggplant crop can easily be reduced by 25 percent in situations where water supply is limited, without significant yield reduction if the 100 percent of ET and 75 percent of ET deficit irrigation practices are adopted. Full water complement is therefore not needed for optimum yield and so can be a cost saving. Therefore, increasing the irrigated area with the saved water could compensate for any yield loss.

The eggplant yield varied from 0.89 ton/ha to 1.46 ton/ha. Fruit yield with 100 percent of ET plus plastic cover was the highest (1.46 ton/ha), followed by 100 percent of ET without plastic cover (1.15 ton/ha), then 75 percent of ET (0.95 ton/ha) and the lowest yield was at 50 percent of ET (0.89 ton/ha). Statistical differences in fruit yield were observed in all the treatments.

However, fruit yields with 50 percent of ET and 75 percent of ET did not differ significantly. Other measured biomass parameters of girth diameter and plant height were not significantly affected by water application rate. The total amount of water applied through irrigation and rainfall varied from 391 mm to 558 mm.

5.0.2 Components of the Soil Water Balance

The observed results showed no significant differences in drainage below the root zone and in soil water storage. However, there were significant differences in evapotranspiration, evaporation and transpiration, with water application rate.

5.0.3 Calibration of Eggplant for AquaCrop Model

Calibration of AquaCrop for drip-irrigated African eggplant was tested for its performance under deficit and fully irrigated treatments. Calibration was less demanding than other system-wide and mechanistic cropping models, owing to the limited number of key parameters to be adjusted. This study suggests that the most logical pathway for a systematic calibration of AquaCrop is first and foremost to ensure a sound prediction of canopy cover.

Results from this study provide a set of first estimates for the calibration of the AquaCrop model on eggplant in the Zambian local conditions and for further testing and use of the model at other locations. Of particular importance is the realization that parameterization of a new yield response to water model, like AquaCrop, is a continuous process and parameters such as the user-input WP* is only established with time and through exposure to independent data sets.

5.0.4 Validation of AquaCrop

The use of the AquaCrop model was validated. Although the model is simple, it, however, addresses the fundamental processes involved in crop productivity and in response to water from physiological and agronomic background. Good agreement was obtained by the AquaCrop model in simulating water content in the soil profile. Model predictions of total biomass, yield and soil water in the 75 percent of ETc and fully irrigated treatments, are particularly promising considering the simplicity of the model and the limited parameterization. Therefore, the parameterized variables need to be further tested under differing climate, soil variety, irrigation methods, and field management.

After calibration, AquaCrop predicted well, the cumulative green canopy cover and cumulative biomass production in the 100 percent of ET with plastic cover and also predicted total biomass well under the 75 percent of ET. The results have practical applications. The model was, however, less satisfactory in predicting yields in severely water stressed treatments. This needs further studies to consider different African eggplant genotypes with different crop canopies. The model, perhaps, needs to incorporate C-13 isotope discrimination to better account for the physiological aspects in CO_2 assimilation. Eggplant is an indeterminate crop of complex behaviour and previous modeling efforts have produced models which are much more complex and sophisticated than AquaCrop. It is therefore encouraging that this model was capable of predicting eggplant yield responses to water.

5.0.5 Economic Optimization Analysis

Economic optimization analysis gave positive net returns to investment and was cost effective for the 100 percent of ET with plastic cover, owing to the high yield increase obtained, but negative net profit was recorded for the 50 percent of ET, 75 percent of ET and 100 percent of ET without plastic cover.

The simulations are very useful in that they could be used to achieve a certain target yield, or to develop a deficit irrigation strategy when irrigation water is scarce. The economic optimization analysis illustrated the fact that the system is quite sensitive to water costs for the range of irrigation treatments used. The combination of AquaCrop with the economic optimization is a powerful tool to assist farmers and irrigation district managers in making decisions in situations where irrigation water supply will be restricted.

By running the model for different planting dates and hence growing periods of different evaporative demand, AquaCrop provides the means to optimize biomass production while maximizing WUE for a particular climate. By running the model for different plant density and irrigation timing during the canopy development phase, soil evaporation can be minimized to allow more water being productively used. By scheduling irrigation at different times with different amounts of water, AquaCrop provides the means to develop deficit irrigation schedules to save water while minimizing reduction in yield, mostly by saving unnecessary runoff, drainage, and soil evaporation and by enhancing HI. Taken as a whole then, AquaCrop, when properly calibrated for a crop species, should prove to be a powerful tool in the analysis of crop WUE and in developing strategies for improvement. This technology should be applied to high value irrigated crops.

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