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LIST OF SYMBOLS AND ABBREVIATIONS

ΔS	Change in soil water storage
Δt	Time step
°C d	Day degrees Celsius
°C	Degree Celsius
25D	Irrigation to field capacity at 20-25% depletion of plant available water
55D	Irrigation to field capacity at 50-55% depletion of plant available water
75D	Irrigation to field capacity at 70-75% depletion of plant available water
a_n	Leaf absorptance of near infrared radiation
a_p	Leaf absorptance of PAR
a_s	Leaf absorptance of solar radiation
CAI	Controlled alternative irrigation
CDM	Canopy dry matter
cm	Centimetre
CO_2	Carbon dioxide
CV	Coefficient of variation
D	Drainage
d	Willmott's index of agreement
DDF	Day degrees to 50% flowering
DDM	Day degrees to maturity
DM	Dry matter
DPAW	Depletion of plant available water
DWR	Vapour pressure deficit-corrected dry matter/water ratio
E	East

e_a	Actual vapour pressure
E_c	Radiation use efficiency
Eq.	Equation
e_s	Saturated vapour pressure
Es	Soil evaporation
E_{sim}	Simulated seasonal soil evaporation
E_{sTmax}	Saturated vapour pressure at maximum air temperature
E_{sTmin}	Saturated vapour pressure at minimum air temperature
ET	Evapotranspiration
ETc	Crop evapotranspiration
ET_{meas}	Measured seasonal evapotranspiration
ETo	FAO reference evapotranspiration
ET_{sim}	Simulated seasonal evapotranspiration
FAO	Food and agriculture Organization of the United Nations
FC	Field capacity
FI	Fractional canopy cover
FI_{PAR}	Fractional interception for PAR
FI_S	Fractional interception for total solar radiation
g	Gram
GDD	Growing day degrees
GLM	General linear model
H_2O	Water
ha	Hectare
Hc	Crop height

Hc_{max}	Maximum crop height
HDM	Harvestable dry matter
HI	Harvest index
I	Irrigation
K	Potassium
K_{bd}	Canopy radiation extinction coefficient for ‘black’ leaves
Kc	Crop coefficients
Kcb	Basal crop coefficients
Kc_{max}	The maximum value for Kc following rain or irrigation
Ke	Soil evaporation coefficient
kg	Kilogram
kPa	Kilopascal
K_{PAR}	Canopy radiation extinction coefficient for PAR
K_s	Canopy radiation extinction coefficient for total solar radiation
l	Litre
LAI	Leaf area index
LDM	Leaf dry matter
ln	Natural logarithm
LSD	Least square differences
m	Meter
m.a.s.l.	Meter above sea level
MAE	Mean absolute error
mg	Milligram

MJ	Mega joule
mm	millimeter
N	Nitrogen
n	Number of observation
NIR	Near infrared
NR	Narrow row
NS	Not significant
p	Leaf-stem partitioning parameter
P	Phosphorous
p	Probability level
Pa	Pascal
PAR	Photosynthetically active radiation
PAW	Plant available water
PE	Potential evaporation
PET	Potential evapotranspiration
PRD	Partial root zone drying
PT	Potential transpiration
PWP	Permanent wilting point
R	Runoff
r^2	Coefficient of determination
RCBD	Randomized complete block design
RDI	Regulated deficit irrigation
RD_{max}	Maximum rooting depth
RF	Precipitation (rainfall)

RH_{max}	Daily maximum relative humidity
RH_{min}	Daily minimum relative humidity
RMSE	Root mean square error
R_s	Daily total incident solar radiation
S	South
SDM	Stem dry matter
SE	Standard errors of means
SLA	Specific leaf area
SPAC	Soil-plant-atmosphere continuum
SWB	Soil Water Balance model
SWC	Soil water content
t	Ton
T	Transpiration
Ta_{max}	Maximum air temperature
Ta_{min}	Minimum air temperature
T_{avg}	Average air temperature
T_b	Base temperature
TDM	Top dry matter
TDMP	Top dry matter production
TE	Transpiration efficiency
T_m	Optimum temperature for crop growth
T_{max}	Maximum transpiration rate
T_{sim}	Simulated seasonal crop transpiration
T_x	Cut-off temperature

U	Wind speed
U_2	Mean daily wind speed at 2 m height
UN	United Nations
VPD	Vapour pressure deficit
WR	Wide row
WUE	Water-use efficiency
Y	Yield
µm	Micrometer
ψ_{lm}	Leaf water potential at maximum transpiration

CHAPTER 1

GENERAL INTRODUCTION

1.1 Botany and ecology of hot pepper

Hot pepper (*Capsicum* spp.), commonly known as chili, is the world's third most important vegetable after potatoes and tomatoes in terms of quantity of production. World production of chili and pepper is 28.4 million tons both dry and green fruit from 3.3 million ha, with an annual growth rate of 0.5% (FAO, 2007). Authorities generally agree that *Capsicum* originated in the new world tropics and subtropics (Mexico, Central America, and Andes of South America) over 2000 years ago (Walter, 1986). Chili belongs to the family *Solanaceae* and genus *Capsicum*. The genus *Capsicum* comprises 20-30 species (Lovelock, 1973). The species *annuum,* however, is the most commonly cultivated (Smith *et al*., 1998).

As a food, pepper has little energy value but it is an excellent source of vitamins A and C and a good source of vitamin B2, potassium, phosphorus, and calcium. The high nutritive value of pepper results in a high market demand year round. Pepper fruits are used in salads, pickles, stuffing, spices, sauce, and as a dried powder. The leaves are used in salads, soups, or eaten with rice (Lovelock, 1973).

Hot peppers are adapted to hot weather conditions. Day temperatures of 24 to 30 °C and night temperatures about 10 to 15 °C are ideal for growth. They are sensitive to freezing temperatures, while temperatures above 32 °C can reduce pollination, fruit set and yield (Smith *et al*., 1998). They are considered to be quantitative short day plants (Demers & Gosselin, 2002).

The crop is grown extensively under rainfed conditions and high yields are obtained with rainfalls of 600 to 1250 mm that are well distributed over the growing season (Doorenbos & Kassam, 1979; Smith *et al*., 1998). Hot pepper production in semi-arid and arid regions, however, depends on irrigation because of unreliability of rainfall, both in terms of quantity and distribution (Wein, 1998). The shallow root system (Dimitrov &

Ovtcharrov, 1995), high stomatal density, large transpiring leaf surface and the elevated stomata opening further make hot pepper plants susceptible to water stress and make irrigation an essential component in hot pepper production (Wein, 1998; Delfine *et al*., 2000). Furthermore, hot peppers, being a labour-intensive high value cash crop, necessitate the use of irrigation.

1.2 Irrigation, irrigation scheduling and deficit irrigation

A rise in the demand for agricultural products due to population growth in many parts of the world and the need to optimize productivity and overcome yield reduction or crop failure due to low and/or erratic rainfall distribution are the main reasons necessitating irrigation agriculture (Hillel & Vlek, 2005). At present approximately 80% of all the available fresh water supply in the world is used for agriculture and food production (Howell, 2001). In many countries where agriculture is the primary economic activity, agriculture accounts for over 95% of the water-use (UN-Water, 2007). However, the amount of water available for irrigation is consistently declining as a result of pressure from other competing demands (domestic, recreation and industrial uses).

Excess water application in irrigation is one of the main reasons for degradation of agricultural land. Huge areas of land become unusable for agriculture due to the rise of water tables and high concentrations of salts in the soil profile as a result of inappropriate irrigation (Ali *et al*., 2001; Smedema & Shiati, 2002; Hillel & Vlek, 2005). Rapid spread of diseases that infect human beings such as malaria (Jumba & Lindsay, 2001) and rift valley fever (Morse, 1995), as well as environmental degradation are the likely result of poorly planned and implemented irrigation projects. This calls for optimization of irrigation project planning and optimum use of the water available for irrigation. Generally, optimization of irrigation water management is necessary for structural (irrigation system design), economic (saving water and energy), and environmental reasons (salt accumulation in soil surface and agro-chemicals leaching into ground water) (Annandale *et al*., 1999).

Irrigation improves yield, not only by direct effect on mitigating water stress, but also by encouraging farmers to invest in inputs like fertilizers and improved cultivars, in which they are otherwise reluctant to invest due to uncertainty of crop production under rainfed conditions (Smith, 2000; Hillel & Vlek, 2005). Irrigation can also prolong the effective crop-growing period in areas with extended dry seasons, thus permitting multiple cropping per year where only a single crop would otherwise be possible (Hillel & Vlek, 2005).

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 & 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. Currently, several methods of irrigation scheduling are available. The different irrigation scheduling approaches employ soil, plant or atmosphere or the combination of two or three components of the soil-plant-atmosphere continuum (SPAC) as their basic framework. Examples of the soil-based approach are monitoring soil water by means of tensiometers (Cassel & Klute, 1986), electrical resistance and heat dissipation soil water sensors (Campbell & Gee, 1986; Jovanovic & Annandale, 1997), or neutron water meters (Gardner, 1986). Crop water requirements can also be determined by monitoring atmospheric conditions (Doorenbos & Pruitt, 1992). Pan evaporation, which incorporates the climatic factors that influence evapotranspiration into a single measurement, has been used to schedule irrigation for several crops (Elliades, 1988; Sezen *et al*., 2006).

Plant water status is also often used as an indicator of when to irrigate (Bordovsky *et al*., 1974; O'Toole *et al*., 1984). However, most physiological indices of plant water stress (leaf water potential, leaf water content, diffusion resistance, canopy temperature) involve measurements that are complex, time consuming and difficult to integrate, and are also subject to errors (Jones, 2004).

Alternatively, a system that integrates our understanding of the SPAC as mechanistically as possible can rather give the best estimates of plant water requirements. According to this concept, the soil water availability is not only governed by the soil water status, but also by plant and climate attributes (Hillel, 1990). Currently the use of this approach is expanding because of better understanding of the SPAC and the ready availability of computer facilities to compute huge amounts of data that would have been difficult to analyze by hand. To this end, various computer software programs are available that utilize soil, plant, atmosphere and/or management data to estimate plant water requirements (Smith, 1992; Crosby, 1996; Annandale *et al.*, 1999; Crosby & Crosby, 1999; Rinaldi, 2001).

Annandale *et al*. (1999) showed, the Soil Water Balance (SWB) model could realistically predict plant water requirements for many field, vegetable and fruit crops. The SWB model is a mechanistic, user friendly, daily time step, and generic crop growth model. It is capable of simulating yield, different growth processes, stress days, field water balance components, etc. However, before one can use the SWB model, there is a need to determine crop-specific model parameters and calibrate the model, and evaluate it, using independent data sets to ensure the adaptability of the model to diverse crop species or cultivars and growing conditions if this has not already been done for the crop of interest. In the absence of such detailed and expensive crop-specific model parameters, an FAO crop factor approach can be utilized to calculate water requirements and schedule irrigation of crops (Allen *et al*., 1998).

Deficit irrigation, the deliberate and systematic under-irrigation of crops, is one of the water-saving strategies widely applied (English & Raja, 1996; Nautiyal *et al*., 2002; Zhang *et al*., 2002). It can increase water-use efficiency of a crop by reducing evapotranspiration whilst maintaining yield comparable to that of a fully irrigated crop. Deficit irrigation could help not only in reducing production costs, but also in conserving water and minimizing leaching of nutrients and pesticides into groundwater. However, before implementing such a strategy across all crops, there is a need to investigate the disadvantages and benefits of deficit irrigation, especially for water stress sensitive crops like *Capsicum* species. Other agronomic factors such as planting density and cultivar to be grown should also be considered to improve water-use efficiency.

Concomitantly, other cultural practices that enhance water-use efficiency needs to be considered. Correct cultivar selection, tillage, mulching, crop residue management, optimum plant spacing, proper fertilization and disease protection are among the cultural practices that are at our disposal to select the best combination of conditions to ensure maximum yield and thereby improve water-use efficiency (Wallace & Batchelor, 1997 as cited by Howell, 2001). Furthermore, collecting and analyzing long-term climatic data of a region helps to understand the evaporative demand of the atmosphere and the water supply and its distribution in a given growing season. This information, coupled with crop data can enable us to generate irrigation calendars using irrigation scheduling computer software.

An irrigation calendar is a simple chart or guideline that indicates when and how much to irrigate. It can be generated by software using data of long term climatic, soil, irrigation type and crop species, and management. It can be made flexible by including real-time soil water and rainfall measurements in the calculation of water requirements of a crop. Work by Hill & Allen (1996) in Pakistan and USA, and by Raes *et al.* (2000) in Tunisia have shown a semi-flexible irrigation calendar facilitated the adoption of irrigation scheduling due to minimum technical knowledge required in understanding and employing irrigation scheduling.

In this regard, the SWB model is equipped with the necessary functionality to generate irrigation calendars from climatic and crop data. Finally by adopting improved cultural practices, proper irrigation and improved use of precipitation, the water-use efficiency of hot pepper can be improved and environmental degradation due to over-irrigation can be reduced.

1.3 Justification of the study

Despite the fact that more than 80% of the world's fresh water resources are used for agriculture, a lack of water is still one of the most limiting environmental factors to crop production worldwide. This is partly because the population distribution and the amount of available fresh water distribution do not correspond (UN-Water, 2007). The intensity of the problem is felt more in arid and semi-arid regions of the world, where water is a scare resource than in other more humid areas.

Hot pepper is a warm season, high value cash crop. Generally, its production is confined to areas where available water is limited and, therefore, irrigation is standard practice in hot pepper production (Wein, 1998). A multitude of rainfall and irrigation management and cultural practices are available for the purpose of increasing water-use efficiency of crop production (Smith, 2000; Wallace & Batchelor, 1997 as cited by Howell, 2001; Passioura, 2006). Cultivar selection and optimum planting density are some of the cultural practices that can be exploited to increase the efficiency of water use.

The efficiency of water use could also be improved by adopting appropriate irrigation scheduling and the practice of deficit irrigation. Various methods of irrigation scheduling are available, but a system that combines the soil-plant-atmosphere continuum usually gives best estimates of the water requirements of plants (Jones, 2008). The SWB model is a computer program that is used to schedule irrigation and simulate crop growth (Annandale *et al*., 1999). To use this software, it is required that crop-specific model parameters be determined. The software also needs to be evaluated and calibrated before applying it to schedule irrigation for a particular crop under specific growing conditions. Where computer accessibility is a problem for irrigation scheduling and the know-how to use computers is lacking, the SWB model can be used to generate site-specific irrigation calendars, for a crop in a particular region based on long-term climatic data. Furthermore, as hot pepper is a very sensitive crop to water stress, a thorough investigation is imperative to ascertain the applicability of deficit irrigation in hot pepper production.

1.4 Objectives of the study

The study was conducted with the following objectives:

- to assess yield of hot pepper cultivars under varying irrigation regimes,
- to assess yield of hot pepper cultivars under different plant populations,
- to understand whether varying row spacing affects hot pepper response to different irrigation regimes,
- to understand whether cultivar differences affects hot pepper response to irrigation regimes,
- to evaluate growth and development of hot pepper under different irrigation regimes,
- to establish an FAO-type crop factor database for hot pepper cultivars
- to determine crop-specific model parameters under contrasting irrigation regimes

and plant populations,

- to calibrate and validate the SWB model for hot pepper cultivars,
- to determine the cardinal temperatures of hot pepper and to calculate the thermal time requirements for various developmental stages of hot pepper, and
- to determine the water requirements of one popular hot pepper cultivar from Ethiopia and generate irrigation calendars for hot pepper growing regions of Ethiopia.

CHAPTER 2

LITERATURE REVIEW

2.1 The role of water in plants

Water is one of the most common and most important substances on the earth's surface. It is essential for the existence of life, and the kinds and amounts of vegetation occurring in various parts of the earth's surface depend more on the quantity of water available than on any other single environmental variable (Kramer & Boyer, 1995).

Water constitutes 80-90% of the fresh mass of most herbaceous plant material and over 50% of the fresh mass of woody plants. Physiological activities of plants are closely related to the plant tissue water content (Kriedemann & Downton, 1981). Water is the solvent in which gasses, minerals, and other solutes enter plant cells and move from organ to organ. It is a reactant in many important biochemical processes, including photosynthesis and hydrolytic processes. Another role of water is in the maintenance of turgor, which is essential for cell enlargement and growth and for maintaining the form of herbaceous plants (Kramer & Boyer, 1995).

Water stress at physiological level causes loss of turgor, and resulting in setting of wilting. It also leads to cessation of cell enlargement, closure of stomata, reduction in photosynthesis, and interference with many other basic metabolic processes. Sub-lethal water stress usually results in the reduction of biomass production and economic yield in plants (McIntyre, 1987). The order in which physiological processes are serially affected by water stress seems to be growth, stomatal movement, transpiration, photosynthesis and translocation. Eventually, continued dehydration causes disorganization of the protoplasm and death of most organisms (Deng *et al*., 2000).

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

Arid and semi-arid regions comprise almost 40% of the world's land area (Parr *et al*., 1990; Gamo, 1999). Aridity is commonly expressed as a function of rainfall and temperature. A climatic aridity index, which is a ratio of precipitation to potential evapotranspiration, is a term coined to describe the degree of aridity. The evapotransipration is calculated following Penman procedure, which takes into account atmospheric humidity, solar radiation, temperature and wind. Arid zone has aridity index of 0.03 to 0.2 and semi-arid has 0.2 to 0.5 (FAO, 1989). A simple dictionary definition expresses aridity in terms of rainfall amount and vegetation types. According to Freedictionary (2008), semi-arid is defined as: "land that is characterized by relatively low annual rainfall of 250 mm to 500 mm and having scrubby vegetation with short, coarse, grasses and not completely arid." Arid is defined as: "land lacking water, especially having insufficient rainfall to support trees or woody plants."

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

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

2.3 Increasing water-use efficiency

Water availability is generally the most important natural factor limiting productivity and expansion of agriculture in arid and semi-arid regions of the world. To satisfy future food demands and growing competition for water, more efficient use of water in both rainfed 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).

2.3.1 Breeding crops for improved water-use efficiency

Genetic improvement in water-use efficiency (WUE) may lead to increased productivity under water-limited conditions. Genetic variability in WUE has been documented for many plant species and cultivars within a species (Turner *et al*., 2001; Condon *et al*., 2004). Physiologists have identified a wide range of morphological, physiological and biochemical traits that contribute to yield improvement of crops in drought-prone environments. Plant selection for shorter time to flowering has been successful for environments in which terminal drought is likely (Thomson *et al*., 1997; Siddique *et al*., 1999). In environments where the timing of drought is persistent or unpredictable, plants with high capacity of abscisic acid accumulation (Innes *et al*., 1984) and/or with high heat tolerance (Srinivasan *et al*., 1996) traits are reported to perform well as opposed to plants lacking such characteristics.

According to Fisher (1981) in water limited environments, yield (Y) is a function of the amount of water passing through transpiration (T), the efficiency with which transpiration water is utilized to produce dry matter (TE), and the partitioning of dry matter into the reproductive component (HI), such that:

$$Y = T \times TE \times HI \qquad (2.1)$$

Increasing the amount of water transpired (T) by a genotype can be achieved by two major strategies, which are under genetic control and can therefore be manipulated by breeding. The first involves increasing T relative to soil evaporation (E_s), while the other involves more efficient extraction of soil water, especially from deep in the soil profile (Turner *et al*., 2001).

In environments where evaporative demand is high and water supply is low, any strategy that increases canopy cover early in the life of the crop should increase the proportion of T relative to ET and thereby increase Y. Increased canopy cover can be achieved genetically as has been discussed by Rebetzke & Richards (1999), which would contribute to the reduction of E_s in relation to T.

The ability of roots to exploit water reserves in the subsoil strongly influences productivity of crops by the direct effect on increasing the amount of T and also indirectly by influencing the timing of supply (Passioura, 1977). A positive correlation between rooting depth and yield has been reported in peanut (Ketring, 1984) and in soybean (Cortes & Sinclair, 1986). This is attributed to the fact that increased root depth allows better water capture and increased T.

A number of research results indicated the presence of considerable genotypic variation in TE among cultivars (Hammer *et al*., 1997; Byrd & May II, 2000; Passioura, 2006; Ullah *et al*., 2008). Genotypic variations in TE can be assessed with accurate estimates of both T and top dry matter (TDM) and this trait can be utilized as a selection criterion. However, in the glasshouse the procedure is extremely time consuming and tedious and in the field it requires elaborate minilysimeter facilities for accurate measurement of T and TDM, after accounting for E_s and root biomass (Turner *et al*, 2001). Work in peanut by Nageswara Roa & Wright (1994) demonstrated the possibility of using correlated traits like specific leaf area as surrogate measure of TE. Leaf ash content and its elements have also been shown to be significantly correlated with TE in a number of species (Mayland *et al*., 1993).

The last variable of the equation that relates to yield and yield components, which is amenable to genetic manipulation for increasing water-use efficiency, is harvest index. This simple ratio varies on the ability of a genotype to partition current assimilates and the reallocation of stored or structural assimilates to the seed and/or fruit. Yield stability in terminal drought environments has been attributed to crops' ability to redistribute assimilates accumulated prior to flowering and immediately post-flowering to the seed during the postflowering period (Turner *et al*., 2001). Genotypic variation in the extent of partitioning and reallocation of assimilates to the seed have been reported in soybean (Westgate *et al*., 1989), in peanut (Wright *et al*., 1991) and in chickpea (Singh, 1991) under water deficit growing conditions.

Thus, by genetically improving one or more variables of the equation that describes the relationship between yield and yield components, water-use efficiency could be improved in water limited environments.

2.3.2 Water-saving agriculture

Water-saving agriculture refers a comprehensive exercise using every possible water-saving measure in whole-farm production, including the full use of natural precipitation as well as the efficient management of an irrigation network (Wang *et al*., 2002; Deng *et al*., 2006). The following are the major strategies to achieve water-saving agriculture.

2.3.2.1 Increasing precipitation use efficiency

Rainfed agriculture remains the dominant crop and forage production system throughout the world, and hence the improvement of food and fibre production requires that we increase precipitation use efficiency (Smith, 2000; Hatfield *et al*., 2001). Furthermore, rainfed agriculture is characterized by seasonal variation in rainfall distribution and amount, which calls for improvement in precipitation use efficiency (Smith, 2000). Precipitation use efficiency is a measure of the biomass or grain yield produced per increment of precipitation (Hatfield *et al*., 2001). Various practices are employed to improve precipitation use efficiency, among which timely planting, minimum tillage, new cultivars, mulching and soil nutrient management are the principal ones (Turner, 2004).

The term water harvesting is defined as the collection of surface runoff and its use for irrigated crop production under dry and arid conditions. In some cases special measures are taken to increase the runoff to water harvesting areas. These measures generally improve precipitation use efficiency as they allow holding back, collecting, and hence rendering useful the fast running-off fraction of precipitation water that otherwise would have been lost (Wolff & Stein, 1999).

The effect of tillage on the soil water profile, infiltration, soil evaporation and runoff varies depending on the type of tillage and mulch management. Burns *et al*. (1971) showed that tillage disturbance of the soil surface increased soil water evaporation compared with untilled areas. Cresswell *et al*. (1993) observed that tillage of bare soils increased saturated hydraulic conductivity, while excessive tillage caused the lowest conductivities because of the increase in air-filled pores. In contrast to Cresswell *et al*. (1993), Christensen *et al*. (1994) found that more soil water was conserved during fallow periods with no tillage than clean till. Pikul & Aase (1995) stated that no tillage has advantage over tillage because surface cover is maintained, and this reduces the potential for soil crusting and erosion. Furthermore, they found that decreasing tillage showed a trend towards improving WUE because of improved soil water availability through reduced evaporation losses.

Crop residue and mulches are known to reduce soil water evaporation by reducing soil temperature, impeding vapour diffusion, absorbing water vapour onto mulch tissue, and reducing the wind speed gradient at the soil-atmosphere interface (Hatfield *et al*., 2001). Azooz & Arshad (1998) found higher soil water contents under no tillage as compared with moldboard plough in British Columbia. Johnson *et al*. (1984) reported that more water was available in the upper 1 m under no-tillage compared with other tillage practices in Wisconsin. This increase was attributed to the fact that the crop residue provided a barrier to soil water evaporation and the absence of tillage operations limited the extent of soil disturbance. A study conducted in Jordan by Abu-Awwad (1999) on onion revealed that covering the soil surface significantly increased transpiration compared with an open soil surface treatment, because of the elimination of wet soil surface evaporation, which increased the water available for transpiration. He reported that covering the soil surface reduced the amount of irrigation water required by an onion crop by about 70% for all irrigation treatments as compared with the amount of irrigation water required by the bare soil surface treatment.

2.3.2.2 Increasing irrigation use efficiency

This refers to the use of irrigated farming practices with the most economical exploitation of the water resources. Irrigation management that enables reduced water supply to the crop, while still achieving a high yield forms the pillar of the system. Irrigation management that also minimizes leakage and evaporation from storage facilities and in transport contributes positively towards efficient exploitation of water resources.

Irrigation scheduling

Water-use efficiency can be improved through practicing irrigation scheduling (Itier *et al*., 1996; Howell, 2001; Home *et al*., 2002). Irrigation scheduling is the practice of applying the right amount of water at the right time for crop production. Irrigation scheduling is conventionally based on soil water measurement, where the soil water status is measured directly to determine the need for irrigation. Examples are the monitoring of soil water by means of tensiometers (Cassel & Klute, 1986), electrical resistance and heat dissipation soil water sensors (Campbell & Gee, 1986), or neutron water meters (Gardner, 1986). A potential problem with soil water based approaches is that many features of the plant's physiology respond directly to changes in water status in the plant tissues, rather than to changes in the bulk soil water content. The actual tissue water potential at any time, therefore, depends both on the soil water status and on the rate of water flow through the plant and the corresponding hydraulic flow resistance between the bulk soil and the appropriate plant tissues. The plant response to a given amount of soil water, therefore, varies as a complex function of evaporative demand. Other disadvantages of using soil water measurement for irrigation scheduling include soil heterogeneity. This requires many sensors and selecting positions that are representative of the root zone is difficult (Jones, 2004).

The second approach is the use of plant stress sensing apparatus, where irrigation scheduling decisions are based on plant responses rather than on direct measurements of soil water status (Bordovsky *et al*., 1974; O'Toole *et al*., 1984). Examples are visual observation of the plant leaf, leaf water potential, stomata resistance, canopy temperature, cell enlargement, relative leaf water content, plant organ diameter, photosynthesis rate, abscisic acid hormone levels, leaf osmotic potential, and sap flow. However, due to a multitude of shortcomings related to this approach, the feasibility thereof, especially on large scale, becomes questionable. The majority of the system requires instruments beyond the reach of ordinary farmers, as well as complex technical know-how. Time required to use these instruments also discourages their ready application. On top of this, if our measurement target is on one aspect (plant) of the soil-plant-atmosphere continuum, it will be difficult to estimate realistically the plant water requirement. This is because the plant system involves many complex and intricate processes (Jones, 2004).

The third option is calculation of the soil water balance components, where the soil water status is estimated by calculating the change in soil water over a period. This is given by the difference between the inputs (irrigation plus precipitation) and losses (runoff plus drainage plus evapotranspiration). The input parameters are easy to measure, using conventional instruments like rain gauges for rainfall and irrigation, and water meters for irrigation. Runoff and drainage could either be estimated from soil physical properties or directly measured *in situ* or could be assumed negligible based on soil conditions and water supply. Evapotranspiration can be estimated by monitoring atmospheric conditions (Doorenbos & Pruitt, 1992; Allen *et al*., 1998). Pan evaporation, which incorporates the climatic factors influencing evapotranspiration into a single measurement, has often been used to estimate evapotranspiration of several crops (Elliades, 1988; Sezen *et al*., 2006).

Currently the use of the soil water balance approach is on the increase because of better understanding of the soil-plant-atmosphere continuum and the availability of computer facilities to compute complex equations. Various computer software programs are available that utilize soil, plant, atmosphere and management data to estimate plant water requirements. Annandale *et al*. (1999) showed, on many fruit, vegetable and field crops, the Soil Water Balance (SWB) model to realistically predict plant water requirements. The SWB model is a mechanistic, user friendly, daily time step, and generic crop growth model. It is capable of simulating yield, different physiological processes, stress days, and field water balance components. Elsewhere, different authors (Smith, 1992; Crosby & Crosby, 1999; Rinaldi, 2001) employing similar principles and working on different crops under different conditions showed the practicality of using computer software in irrigation scheduling. Furthermore, collecting and analyzing the long-term climatic data can help to understand typical evaporative demand of the atmosphere and the water requirements in a growing season for better water management (Smith, 2000). This information, coupled with crop data, can enable the generation of irrigation calendars, using computer software.

An irrigation calendar is a simple chart or guideline that indicates when and how much to irrigate. It can be made flexible by including real-time soil water and rainfall measurements in the calculation of water requirements of a crop. Work by Hill & Allen (1996) in Pakistan and USA, and by Raes *et al.* (2000) in Tunisia have shown a semi-flexible irrigation calendar facilitated the adoption of irrigation scheduling due to less technical knowledge required in understanding and employing the irrigation scheduling.

In this regard, the SWB model is equipped with the necessary capability to enable the development of irrigation calendars and estimation of water requirements of plants from climatic, soil, crop and management data (Annandale *et al*., 1999, Geremew, 2008).

Deficit irrigation

Deficit irrigation, the deliberate and systematic under-irrigation of crops, is a common practice in many areas of the world (English & Raja, 1996; Nautiyal *et al*., 2002; Zhang *et al*., 2002). Fereres & Soriano (2007) defined deficit irrigation as the application of water below the evapotranspiration (ET) requirements. Therefore, irrigation supply under deficit irrigation is reduced relative to that needed to meet maximum ET. Government agencies in water deficit countries such as India and South Africa have endorsed the concept of deficit irrigation by recommending that irrigation planning be based on '50% dependable' supply of water (Chitale, 1987). Thus, the main driving reason for adoption of deficit irrigation is limited and reliable availability of the water supply.

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 & 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 & 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 & 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 rainfed conditions (Oweis *et al*., 1998). Another form of deficit irrigation is called sustained deficit 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). The theoretical basis of RDI is crop physiology and biochemistry. RDI is conducted on crops according to their characteristics and water requirements. In this type of deficit irrigation, 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).

A deficit irrigation form recently developed, called controlled alternative irrigation or partial root zone drying (PRD) is an irrigation system where alternate sides of the root system are irrigated during alternate periods (Wang *et al*., 2002; Chaves & Oliveira, 2004). In PRD the maintenance of the plant water status is ensured by the wet part of the root system, whereas the decrease in water-use derives from the closure of stomata promoted by dehydrating roots. The principle of this deficit irrigation 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.

Another example of deficit irrigation is where irrigation is planned in such a way that "room for rain" is left. In this method, irrigation is applied to refill part of the depletion field capacity, while the remaining portion of the soil water depletion is expected to be refilled by rain (Jovanovic *et al*., 2004). The deficit level imposed in this system depends on the level of sensitivity of a crop grown to water deficit and the rainfall distribution of an area.

Deficit irrigation has been successful in most cases in tree crops for a number of reasons. First, economic return in tree crops is often associated with factors such as crop quality, and second the yield determining processes in many fruit trees are not sensitive to water deprivation at some developmental stages (Johnson & Handley, 2000). Experiments with deficit irrigation have been successful in many fruit and nut tree species such as almond (Goldhamer & Viveros, 2000), citrus (Domingo *et al*., 1996), apple (Mpelasoka *et al*., 2001), mango (Spreer *et al*., 2007) and wine grapes (Bravdo & Naor, 1996; MacCarthy *et al*., 2002; Fereres & Evans, 2006), almost always with positive results.

Conflicting results were reported on the effects of deficit irrigation on annual crops, probably depending upon 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 % 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% increment in total soluble solids and better colour development with deficit irrigation as compared to partial rootzone drying and full irrigation. However, Shock & Feibert (2002) reported a reduction in potato tuber yield of as much as 17% 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 & Soriano, 2007). Whenever irrigation is applied, salts are transported from a water source to a root zone (soil surface) and the salts accumulate there as evapotransipration usually removes the water, leaving the precipitated salts. This salinization becomes serious in arid and semi-arid areas where water is scarce (Smedema & Shiati, 2002). This is because the rainfall in these areas is not adequate to provide the leaching requirement to remove excess salts accumulated periodically. Deficit irrigation if taken as an option to overcome scarcity of water in these areas, salinization could become a problem, as it does not provide the extra water that is required to leach the accumulated salts in the soil surface. Thus, adoption of deficit irrigation without precautionary measures to periodically perform leaching of concentrated salts poses a problem for sustainability of irrigation.

2.4 A brief description of the Soil Water Balance model

The Soil Water Balance (SWB) model is a multi-soil layer, daily time step, generic crop, mechanistic, user-friendly, irrigation scheduling model (Annandale *et al*., 1999). It simulates the soil water balance and crop growth using crop-specific model parameters. It is based on the improved version of the soil water balance model described by Campbell & Diaz (1988). The SWB model contains three units, namely the weather unit, soil unit and crop unit. The weather unit of SWB calculates Penman-Monteith grass reference daily evapotranspiration (ETo) as a function of daily average temperature, vapour pressure deficit, radiation and wind speed, according to the recommendations of the Food and Agriculture Organization of the United Nations (Allen *et al*., 1998). The soil unit simulates the dynamics of soil water movement in the soil profile in order to quantify transpiration and evaporation. In the crop unit, the SWB model calculates crop dry matter accumulation in direct proportion to the vapour pressure deficit-corrected dry matter/water ratio (Tanner & Sinclair, 1983). The crop unit also calculates radiation-limited growth (Monteith, 1977) and takes the lesser of the two. This dry matter is partitioned to the roots, stems, leaves and grains or fruits. Partitioning depends on phenology, calculated with thermal time and modified by water stress.

Site specific input data to run the model includes daily weather data, altitude, latitude, and hemisphere. In the absence of measured data on total solar radiation, average wind speed, and average vapour pressure; the model is equipped with functions for estimating these parameters from available weather data according to the FAO 56 recommendation (Allen *et al*., 1998).

Soil input data such as the runoff curve number, drainage fraction and maximum drainage rate, soil layer characteristics (thickness, volumetric soil water content at field capacity and permanent wilting point, initial volumetric water content, and bulk density) are also required to run the model.

Since SWB is a generic crop growth model, model parameters specific for each crop have to be determined. The following are the crop-specific model parameters that are required to run the growth model of SWB: canopy extinction coefficient for total solar radiation (Ks), vapour pressure deficit-corrected dry matter/water ratio (DWR), radiation use efficiency (E_c), base temperature (T_b), optimum temperature for crop growth (T_m), cut-off temperature (T_x), maximum crop height (Hc_{max}), day degrees at the end of vegetative growth, day degrees for maturity, transition period day degrees, day degrees for leaf senescence, maximum root depth (RD_{max}), fraction of total dry matter translocated to heads, canopy water storage, leaf water potential at maximum transpiration (ψ_{lm}), maximum transpiration rate (T_{max}), specific leaf area (SLA), leaf-stem partitioning parameter (p), total dry matter at emergence, fraction of total dry matter partitioned to roots, root growth rate and stress index (Annandale *et al*., 1999).

2.5 Water requirements of peppers and water stress effects on peppers crops

The water requirements of peppers vary between 600 and 1250 mm per season, depending on regional climate and cultivar (Doorenbos & Kassam, 1979). The wide variation in water requirements of pepper is attributed to the broad genetic variation within the species and the wide range of environments the crop is adapted to.

The hot pepper plant (*Capsicum annuum* L.) has a shallow root system, which extracts 70 to 80 % of its water from the top 0.3 m soil layer (Dimitrov & Dvtcharrom, 1995). This, together with high stomatal density, a large transpiring leaf surface and an elevated stomatal opening, predispose the pepper crop to be vulnerable to water stress (Delfine *et al*., 2000).

Like other crops, optimum supply of water throughout the growing season is essential for optimum production of hot peppers. Water supply that is below or above optimum levels leads to deterioration in both quantity and quality of the pepper yield.

Mild water stresses in plants usually directly affect growth (cell elongation), whereas photosynthesis and translocation are less sensitive to water stress (Kramer & Boyer, 1995). The biochemistry of photosynthesis (namely, Rubisco characteristics) was not affected in sweet pepper by mild water stress; rather the observed reduction in photosynthesis was caused by limitation of carbon dioxide (CO_2) conductance due to partial closure of stomata (Delfine *et al*., 2000) as stomata serve for both CO_2 conduction and transpiration.

Pepper plants are most sensitive to water stress during flowering and fruit development (Katerji *et al*., 1993). According to Costa & Gaianquito (2002), the increased fruit dry yields due to the effect of increased water supply or irrigation was mainly attributed to a significant increment in fruit number. Improvement of average diameters and lengths of fruits, and pericarp thickness were also observed as more water was applied (Costa & Gaianquito, 2002). The reduction in fruit number due to water stress was attributed to flower abortion (Dorji *et al*., 2005), which results in a reduction of fruit number. Dorji *et al*. (2005), however, reported no significant differences in dry mass distribution among plant organs due to irrigation treatments. Stressing the pepper plant at the beginning of fruit set resulted in lower fruit number per plant and a high proportion of undersized fruits. Furthermore, the percentage of non-marketable fruits showed a significant share of blossom-end rot when plants are stressed at the beginning of fruit set or if continuously exposed to acute water stress throughout the growing season (Costa & Gaianquito, 2002).

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

Conflicting results have been reported regarding the practicality of deficit irrigation for water conservation in hot pepper. Kang *et al*. (2001) and Dorji *et al*. (2005) suggest the use of deficit irrigation in hot pepper. However, others confirmed the sensitivity of pepper to water stress and the beneficial effects of abundant irrigation. Costa & Gianquinto (2002) and Beese *et al*. (1982) observed significant yield increases with water levels above 100 % evapotranspiration, indicating yield increases with additional water beyond the well-watered control. The inconsistency of the results reported may be attributed to differences in the cultivars used (Ismail & Davies, 1997; Jaimez *et al*., 1999) and in the growing conditions (Pellitero *et al*., 1993).

2.6 Planting density effect on growth, yield and water-use of plants

In modern crop production, crops are planted in a wide range of inter- and intra-row spacings giving different plant arrangements and plant population densities. The choice of a particular plant arrangement and plant population is dictated by crop species (cultivars), inputs used, irrigation system employed, machinery used for cultural practices, the method of harvesting employed, the end use of the produce, etc. It is usually a matter of compromise between convenience and productivity.

Knowledge of crop response to population density is useful for management decisions and it provides the basis for assessing the effects of intra-species competition (Jolliffe, 1988). Crops (cultivars) with vigorous growth habit are usually planted at a wider row spacing to avoid competition among neighbouring plants and also to prevent mutual shading in plant canopies. Disease prevalence and severity are also important considerations for a wider row planting option (Castilla & Fereres, 1990).

Plant population primarily affects the amount of radiation intercepted per plant (Villalobos *et al*., 1994). Light quality as modified by different plant populations may also play an important role on early plant growth and partitioning responses (Ballare *et al*., 1987). The yield advantage due to narrow spacing is usually attributed to the development of a full canopy in early development stages (Fukai *et al*., 1990). These full canopies, in turn, intercept more radiation and have a greater photosynthetic production than the partial canopy development that is usually observed in wider row spacings.

Plant densities beyond certain thresholds can adversely affect fruit quality and encourage disease development in pepper plants. Inadequate fruit colour development was also observed in over densely planted hot pepper (Stoffella & Bryan, 1988). This may be due to the inability of some of the fruit to be in direct sunlight, which is important for the development of carotenoid pigments. Poor ventilation is responsible for high disease incidence associated with high planting density in tomato, especially under greenhouse conditions (Castilla & Fereres, 1990).

Plant efficiency was suggested to increase with increasing plant population for bell pepper (Stoffella & Bryan, 1988; Lorezo & Catilla, 1995) and pepperoncini (Motsenbocker, 1996). Lorezo & Catilla (1995) reported a significantly higher yield due to high density planting. This higher yield is attributed to increased leaf area index (LAI), which in turn improved radiation interception (Lorezo & Catilla, 1995). Higher values of LAI in high density treatments led to an improved radiation interception and subsequently, to higher biomass and yield than in the low density treatment. Jolliffe & Gaye (1995) reported that as much as 47% variation in total fruit dry yield of pepper can be attributed to population density effects at 103 days after transplanting. At the end of the growing season, plant population density treatments accounted for 35% of the variation in the final cumulative fruit dry mass. Similarly, high density populations have been reported desirable for maximum yields in cayenne (Decoteau & Graham, 1994) and bell pepper (Russo, 1991; Locascio & Stall, 1994).

Plant spacing can also influence morphological development of peppers. Pepper and other plants grown in denser populations tend to be taller (Karlen *et al.*, 1987; Stoffella & Bryan, 1988) and may set fruit higher on the plant than those grown in less-dense plantings. Narrow row spacing (higher population density) resulted in plants that were smaller (less leaf and plant mass), more upright, and produced less fruit yield per plant but higher fruit yield (tons ha^{-1}) and number ha^{-1}. This suggests that the high yield with narrow row spacing is attributed to higher plant population and fruit production per area, rather than higher pepper yield per plant or fruit size. Similar results were reported for cayenne pepper (Decoteau & Graham, 1994), bell pepper (Stoffella & Bryan, 1988) and Tabasco pepper (Sundstorm *et al.*, 1984). Further benefit of narrow spacing are increased ease of harvesting in closely spaced plant due to plant's upright position with lower leaf area, which make locating fruits for hand removal easier (Motsenbocker, 1996).

Growing conditions and genotypes influence the relationship between planting density and crop yield (Taylor, 1980; Johnson *et al*., 1982; Tan *et al*., 1983). High yields as a result of high plant population are achieved under optimal water supply condition (Cantliffe & Phatak, 1975; O'Sullivan, 1980; Taylor, 1980; Taylor *et al*., 1982; Tan *et al*., 1983; Gan *et al*., 2002). Tan *et al*. (1983) reported similar cucumber yield for high and low plant populations when grown without irrigation, but they observed a significant plant population effects under irrigated conditions. Taylor (1980), working on soybean, observed no difference in yield among 0.25-, 0.5-, 0.75- and 1-m wide row spacings in a sub normal rainfall year, whereas, although not significant, yield tended to increase as row spacing decreased in normal rainfall seasons. For a growing season with rainfall above normal, soybeans in 0.25 m row spacing out-yielded those in 1.0 m rows by 17%.

The growing length dictates plant response to plant population (Villalobos *et al*., 1994). Accordingly, high potential sunflower yields under non-limiting conditions can be achieved by using short-cycle cultivars if plant population is high enough, whereas to exploit the yield potential of long-cycle sunflower, improvement in harvest index rather than plant population deserves attention. This is explained by the fact that in short-cycle cultivars optimum biomass per unit area is achieved as the density of planting is increased. In case of the long-cycle cultivars, within acceptable ranges of plant populations, optimum biomass per unit area tends to remain unchanged over longer growing seasons.

CHAPTER 3

THE EFFECT OF DIFFERENT IRRIGATION REGIMES ON GROWTH AND YIELD OF THREE HOT PEPPER (*Capsicum annuum* L.) CULTIVARS

Abstract

A field trial was conducted in the 2004/2005 growing season at the Hatfield Experimental Farm (Pretoria) to investigate the effect of different irrigation regimes on the growth, yield and water-use efficiency of different hot pepper cultivars. The aim was to select cultivars that are efficient in water utilization. Treatments were arranged in a randomized complete block strip plot design, with irrigation regime assigned to main plots and cultivars to sub-plots. The three cultivars were Mareko Fana, Jalapeno and Malaga and the three irrigation regimes, based on the percentage depletion of plant available water (DPAW) to 0.6 m soil depth were 25D: 20-25% DPAW; 55D: 50-55% DPAW; and 75D: 70-75% DPAW. Treatments were replicated three times and drip irrigation was utilized. Growth analysis, soil water content and yield measurements were performed.

Fresh fruit yield increased by 77 % and dry fruit yield increased by 64 % by irrigating at 25D as compared to 75D. The significantly higher yield obtained by the 25D irrigation tratment is attributed to its positive effect on fruit number and top dry biomass production. Cultivar Mareko Fana (3.63 t ha^{-1}) out-yielded Jalapeno (3.44 t ha^{-1}) and Malaga (2.11 t ha^{-1}) by 5 and 71 %, respectively in dry fruit yield. Higher fruit fresh yield was recorded for Jalapeno (29.28 t ha^{-1}), followed by Mareko Fana (21.49 t ha^{-1}) and Malaga (6.90 t ha^{-1}). The significant yield differences among the varieties, despite the fact that comparable top dry matter yields were produced by all varieties, may be explained by the fact that the variety with highest yield (Mareko Fana) partitioned more

of its assimilates (55%) to fruits, while the variety with lowest yield (Malaga) accumulated only 37% of its assimilates in fruit on average. Average dry fruit mass and succulence were significantly affected by cultivar differences, but not by irrigation regime. Fruit number per plant was significantly affected by irrigation regime and cultivar differences. Jalapeno, a cultivar that matured early and with high harvest index, gave higher water-use efficiency in terms of fresh- (40.4 kg ha^{-1} mm^{-1}) and dry- (4.9 kg ha^{-1} mm^{-1}) fruit yield. Specific leaf area (SLA), leaf area index (LAI) and fractional interception (FI) were significantly affected by the effect of the variety. Irrigation regime significantly affected FI, but did not affect SLA and LAI.

It was concluded that irrigating between 25D and 55D is necessary for optimum yields. Furthermore, the absence of interactions between irrigation regime and cultivars for most parameters suggests that the optimum irrigation regime for best hot pepper productivity could be applied across all varieties.

Key words: Hot pepper, irrigation regime, soil water depletion, water-use efficiency

3. 1 INTRODUCTION

Hot pepper (*Capsicum annuum* L.) is a high value cash crop, of which cultivation is confined to warm and semi-arid regions of the world, where water is often a limiting factor for crop production (Kramer & Boyer, 1995). A shallow root system (Dimitrov & Ovtcharrova, 1995), high stomatal density, a large transpiring leaf surface and elevated stomata openings, make hot pepper plants susceptible to water stress (Wein, 1998; Delfine *et al*., 2000). The conventional solution to water shortages has been irrigation. However, due to competing demands for water from other sectors and increasing investment cost for irrigation, the rate of irrigation expansion is constantly decreasing (Hillel & Vlek, 2005). Therefore, adoption of land, crop and water management practices that enhance water-use efficiency of a crop are indispensable (Howell, 2001; Passioura, 2006).

Currently, irrigation techniques like water-saving irrigation and deficit irrigation are being used to increase the efficiency of irrigation (Wang et al., 2002; Deng *et al*., 2006; Fereres & Soriano, 2007). The application of drip irrigation has enhanced the water-use efficiency (WUE) of crops as compared to the more traditional irrigation methods (Xie *et al*., 1999; Antony & Singandhupe, 2004). Furthermore, other cultural practices such as cultivar selection (Ismail & Davies, 1997; Steyn, 1997; Jaimez *et al*., 1999; Collino *et al*., 2000), plant population density (Tan *et al*., 1983; Taylor *et al*., 1982), and fertilization (Ogola *et al*., 2002; Rockström, 2003) are reported to influence plant responses to irrigation water application. For instance, treatments like N fertilization (Ogola *et al*., 2002), high planting density (Ogola *et al*., 2005), and cultivars with a rapid early growth habit (Lewis & Thurling, 1994) were reported to contribute to increased WUE of plants by reducing water loss through evaporation, while increasing the water loss through transpiration. Species or cultivar differences in physiological adaptation to water shortages can also be exploited to make informed decisions on what to plant, where to plant, when to plant and what irrigation and other cultural management to use. Generally, studies demonstrated that growth and production were positively correlated with water-use due to its effects on leaf area, harvest index, mean fruit size and fruit number per plant (Chartzoulakis & Drosos, 1997; Sezen *et al*., 2006).

Hot pepper cultivars show considerable biodiversity. Cultivars differ vastly in attributes such as growth habit, length of the growing season, cultural requirements, fruit size, pigmentation and pungency (Bosland, 1992). Most experiments on C*apsicum* species have been conducted in controlled glasshouse conditions (Chartzoulakis & Drosos, 1997; Kang *et al*., 2001; Costa & Gianquinto, 2002; Dorji *et al*., 2005). Field studies on the effects of water deficit on growth, yield and water-use of hot peppers are few and inconclusive with regard to the optimum irrigation amount, due to variation in cultivars and growing conditions (Ismail & Davies, 1997; Jaimez *et al*., 1999; Delfine *et al*., 2000). Furthermore, literature on the water requirements of different hot pepper cultivars under local conditions is lacking. It is also important to understand the response of hot pepper to different levels of water deficit in order to determine the extent to which hot peppers can withstand water deficits, while maintaining acceptable yield. The objective of this study was, therefore, to establish whether hot pepper response to irrigation regime is influenced by cultivar differences. The effect of different irrigation regimes on growth, yield and water-use efficiency was evaluated in the field, with the aim of selecting the cultivars that are more efficient in water utilization.

3.2 MATERIALS AND METHODS

3.2.1 Experimental site and treatments

A field experiment was conducted on the Hatfield Experimental Farm, Pretoria, South Africa (latitude $25^0$45' S, longitude $28^0$16' E, and an altitude of 1327 m.a.s.l.) during the 2004/05 growing season. The area has an average annual rainfall of 670 mm, mainly from October to March (Annandale *et al*., 1999). The average annual maximum air temperature for the area is 25 °C and the average annual minimum air temperature is 12 °C. The hottest month of the year is January, with an average maximum air temperature of 29 °C, while the coldest months are June and July, with an average minimum air temperature of 5 °C. The soil characteristics to 30 cm soil depth are predominately sandy clay loam with permanent wilting point of 128 mm m^{-1}, field capacity of 240 mm m^{-1} and pH (H_2O) of 6.5. The soil contained 572 mg kg^{-1} Ca, 79 mg kg^{-1} K, 188 mg kg^{-1} Mg and 60.5 mg kg^{-1} Na.

Treatments were arranged in a randomized complete block strip plot design, with irrigation regime assigned to main plots and cultivars to sub-plots. The three cultivars were Mareko Fana, Jalapeno and Malaga. The three irrigation regimes were: high irrigation regime (25D, maximum of 20-25 % depletion of plant available water, DPAW), a medium irrigation regime (55D, maximum of 50-55 % DPAW) and a low irrigation regime (75D, maximum of 70-75 % DPAW). The plant available water was determined to 0.6 m soil depth. The profile was refilled to field capacity each time the predetermined soil water deficit per treatment was reached for all treatments. Subplots were 5 rows wide and 2.4 m long, with inter-row spacing of 0.7 m and intra-row spacing of 0.4 m.

3.2.2 Crop management

Six-week-old hot pepper seedlings of the respective cultivars were transplanted on November 11, 2004. Plants were irrigated using drip irrigation for 1 hour (12.5-15.5 mm) every other day for the first three weeks until plants were well established. Thereafter, plants were irrigated to field capacity, every time the predetermined soil water deficit per treatment was reached. Based on soil analysis and target yeild, 150 kg ha^{-1} N, 75 kg ha^{-1}

P and 50 kg ha^{-1} K were applied to all plots. The N application was split, with 50 kg ha^{-1} at planting, followed by a 100 kg ha^{-1} top dressing eight weeks after transplanting. Weeds were controlled manually. Preventive sprays of Benomyl® (1H – benzimidazole) and Bravo® (chlorothalonil) were applied to control fungal diseases, while red spider mites were controlled with Metasystox® (oxydemeton–methyl) applied at the recommended doses.

3.2.3 Measurements

Soil water deficit measurements were made using a model 503DR CPN Hydro probe neutron water meter (Campbell Pacific Nuclear, California, USA), which was calibrated for the site. Readings were taken twice a week, at 0.2 m increments to a depth of 1.0 m, from access tubes installed in the middle of each plot (one access tube per plot) and positioned between rows.

Data on plant growth were collected at 15 to 25 day intervals. The fractional canopy interception (FI) of photosynthetically active radiation (PAR) was measured using a sunfleck ceptometer (Decagon Devices, Pullman, Washington, USA) a day before harvest. The PAR measurement for a plot consisted of three series of measurements in rapid succession. A series of measurements consisted of one reference reading above the canopy and ten readings below the canopy. The difference between the above canopy and below canopy PAR measurements was used to calculate the fractional interception (FI) of PAR using the following equation (Jovanovic & Annandale, 1999):

$$FI_{PAR} = 1 - \left(\frac{PAR\ below\ canopy}{PAR\ above\ canopy} \right) \quad (3.1)$$

Eight plants from the central two rows were reserved for yield measurement. Fruits were harvested three times in a season. On the final day of harvest, the whole aboveground part of plants was removed and separated into fruits, stems and leaves. Samples were then oven dried at 75 °C for 72 hours to constant mass and the dry mass determined. Leaf area was measured with an LI 3100 belt driven leaf area meter (Li-Cor, Lincoln, Nebraska, USA) and leaf area index was calculated from the leaf area and ground area from which the samples were taken. Specific leaf area was calculated as the ratio of leaf area to leaf dry mass.

Total crop evapotranspiration (ETc) was estimated using the soil water balance equation,

$$ETc = I + RF + \Delta S - D - R \tag{3.2}$$

where I is irrigation, RF is precipitation, ΔS is the change in soil water storage, D is drainage and R is runoff. Drainage was estimated using SWB model, runoff was assumed negligible as the experiment setting doses not allow free runoff.

Water-use efficiency was calculated for top dry matter, fresh fruit mass and fruit dry mass from the ratio of the respective parameter mass to calculated total evapotranspiration using eq. (3.2). Succulence, a quality measure for fresh market peppers, was calculated as the ratio of fresh fruit mass to the dry fruit mass.

3.2.4 Data analysis

Data were analyzed by using the Mixed Procedure of SAS software Version 9.1 (SAS, 2003). Treatment means were separated by the least significance difference (LSD) test at $P \leq 0.05$.

3.3 RESULTS AND DISCUSSION

3.3.1 Specific leaf area, leaf area index and canopy development

Table 3.1 presents the effect of cultivar and irrigation regime on fractional interception of photosynthetically active radiation ($FI_{(PAR)}$), leaf area index (LAI) and specific leaf area (SLA) at harvest. SLA, LAI and $FI_{(PAR)}$ were significantly affected by cultivar. Malaga gave the highest average SLA (21.14 m^2 kg^{-1}), followed by Mareko Fana (17.17 m^2 kg^{-1}) and Jalapeno (16.05 m^2 kg^{-1}). Malaga produced the highest average LAI (2.31m^2 m^{-2}) and $FI_{(PAR)}$ (0.80), while Mareko Fana produced LAI of 1.67m^2 m^{-2} and $FI_{(PAR)}$ of 0.68. The lowest average LAI (1.56 m^2 m^{-2}) and $FI_{(PAR)}$ (0.60) were recorded for Jalapeno. This shows that Malaga used less assimilate per unit leaf area as it produced more leaf area per unit of leaf dry mass as compared to the other two cultivars.

Irrigation regime affected $FI_{(PAR)}$, but did not affect SLA and LAI. $FI_{(PAR)}$ was improved by 16 % by irrigating at 25D as compared to irrigating at 75D. The irrigation regime effect between 25D and 55D, and between 55D and 75D were not significant for FI. Tesfaye *et al.* (2006) working on chickpea, cowpea and common bean observed a reduction in both $FI_{(PAR)}$ and LAI due to water stress. Joel *et al.* (1997) indicated that $FI_{(PAR)}$ could be reduced as much as 70 % due to water stress in sunflower. They attributed the reduction in $FI_{(PAR)}$ to the corresponding reduction in LAI caused by water stress. LAI decline caused by water stress was also reported for potato (Kashyap & Panda, 2003). Absence of significant effects of irrigation regime on LAI in the present study may be explained by the fact that late leaf data collection (data was collected on final harvest date) and rainfall interference during the growing season may have confounded the effect of irrigation treatment on LAI.

The SLA remained unaffected by irrigation treatment but significant cultivar differences occurred. The robustness of SLA across different irrigation treatments for the same cultivar highlights the scientific merit of using this crop-specific parameter in modelling of hot pepper under varied growing conditions (Annandale *et al*., 1999).

Table 3.1 Specific leaf area (SLA), leaf area index (LAI) and fractional interception of photosynthetically active radiation ($FI_{(PAR)}$) as affected by different irrigation regimes and hot pepper cultivars

Irrigation	Cultivar	SLA ($m^2\ kg^{-1}$)	LAI ($m^2\ m^{-2}$)	$FI_{(PAR)}$
25D	Mareko Fana	17.16	1.81	0.77
	Jalapeno	16.02	1.70	0.63
	Malaga	21.25	2.42	0.84
55D	Mareko Fana	17.20	1.79	0.66
	Jalapeno	16.07	1.50	0.60
	Malaga	21.28	2.71	0.82
75D	Mareko Fana	17.15	1.41	0.60
	Jalapeno	16.05	1.46	0.57
	Malaga	21.17	1.77	0.76
LSD	Irrigation	NS	NS	0.09*
	Cultivar	0.10**	0.51*	0.13*
	Irrigation x Cultivar	NS	NS	NS

Notes: 25D, 55D, & 75D: Irrigation at 20-25, 50-55, and 70-75 % depletion of plant available water, respectively; LSD: least significant difference ($P \leq 0.05$); NS: not significant ($P>0.05$); *: significant at $P \leq 0.05$; **: significant at $P \leq 0.01$.

3.3.2 Dry matter production and distribution

Irrigation regime significantly affected top dry matter but not leaf and stem dry matter (Figure 3.1). There were significant differences among the cultivars in stem dry matter, but not in top and leaf dry matter. Interactions between cultivars and irrigation treatments for top and leaf dry matters were not significant, but the interaction was significant for stem dry matter. Irrigating at 25D increased top dry matter by 46 % as compared to irrigating at 75D. The irrigation regime effects between 25D and 55D, and between 55D and 75D were not significant. Higher stem dry matter was produced by Malaga (2.99 t ha^{-1}) by irrigation treatment of 25D, and the lowest stem dry matter was produced by Jalapeno (1.11 t ha^{-1}) by irrigation regime of 75D. The absence of a significant effect due to irrigation regime and cultivars on leaf dry mass may be explained by the fact that leaves were harvested late into the season, after a significant proportion of the leaves had already been shed. High rainfall in the growing season may also have interfered with the irrigation regime and confounded the effects of irrigation regime on leaf dry mass.

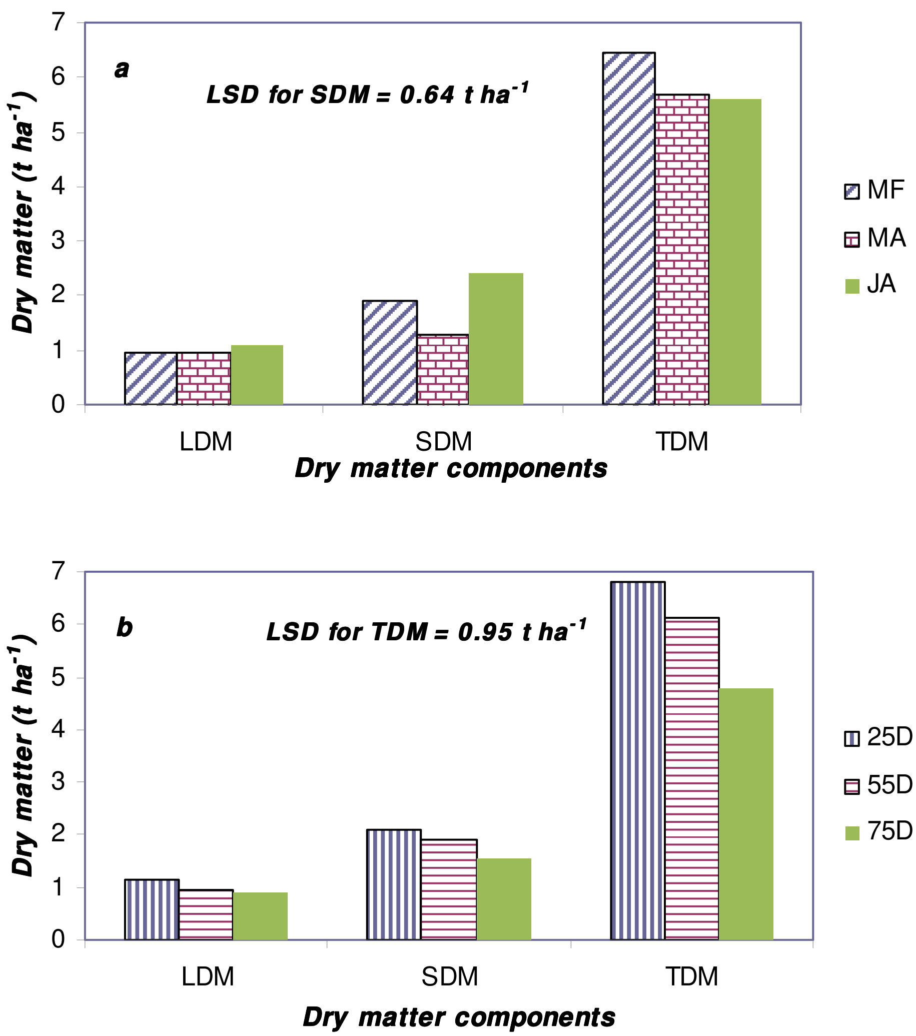


Figure 3.1 Top (TDM), leaf (LDM) and stem (SDM) dry matter as affected by cultivar (a) and irrigation regime (b). MF: Mareko Fana, MA: Malaga, JA: Jalapeno. 25D, 55D, & 75D: irrigation at 20-25, 50-55, and 70-75 % depletion of plant available water, respectively. LSD: least significant difference (P ≤ 0.05).

Data on dry matter partitioning to fruits, leaves and stems are presented in Table 3.2. Assimilate partitioned to fruits and stems were significantly increased due to irrigating at a low soil water depletion level. Dorji *et al*. (2005), however, reported no significant differences in dry mass distribution among plant organs due to irrigation treatments. Marked differences in assimilate partitioning to fruits, leaves and stems were observed due to cultivar differences. Cultivar and irrigation regime interactions for assimilate partitioning to fruits were significant, but it was not significant for stems and leaves.

Table 3.2 Dry matters partitioning to fruits, leaves and stems as affected by different irrigation regimes and cultivars

Cultivar	Irrigation	Harvest Index	Leaf Fraction	Stem Fraction
Mareko Fana	25D	0.59 bA	0.14	0.27
	55D	0.58 aA	0.12	0.30
	75D	0.49 bB	0.19	0.32
Jalapeno	25D	0.63 aA	0.16	0.21
	55D	0.61 aA	0.16	0.23
	75D	0.58 aA	0.19	0.23
Malaga	25D	0.41 cA	0.18	0.41
	55D	0.35 bB	0.20	0.45
	75D	0.35 cB	0.21	0.44
LSD	Irrigation	0.05*	NS	0.02**
	Cultivar	0.04**	0.04*	0.03**
	Irrigation x Cultivar	0.14*	NS	NS

Notes: 25D, 55D, & 75D: irrigation at 20-25, 50-55, and 70-75 % depletion of plant available water, respectively; LSD: least significant difference ($P \leq 0.05$); NS: not significant ($P>0.05$); *: significant at $P \leq 0.05$; **: significant at $P \leq 0.01$. Column means within the same irrigation regime followed by the same lower case letter or column means within the same cultivar followed by the same upper case letter are not significantly different ($P>0.05$).

Harvest index was significantly affected by interactions between irrigation regime and cultivars. Irrigating at lower depletion level of plant available water in Mareko Fana and Malaga resulted in a significant improvement in harvest index, while in Jalapeno the effect was not significant. The highest harvest index (0.63) was observed for Jalapeno under the 25D treatment, while the lowest harvest index was observed for Malaga (55D and 75D).

Sixty percent of assimilate was portioned to fruits in Jalapeno, while it was 55 % in Mareko Fana and 37 % by Malaga. Assimilate partitioned to leaves and stems were, respectively, 17% and 22 % for Jalapeno, 15 % and 30% for Mareko Fana, and 20 % and 43 % for Malaga. Overall, fruits remained the major sink; accounting for more than 51 % of the top plant dry matter mass, followed by stems (32 %) and then leaves (17%). This result further indicated that the harvest index was significantly affected by irrigation regime, but the effect of irrigation regime is modified by cultivar differences. The harvest index reported here is higher than that of the 39% reported from split-root experiments with pot grown pepper (Cantore *et al*., 2000), whereas it closely approaches that of the 56 % reported from a deficit irrigation and partial root drying experiment on pepper (Dorji *et al*., 2005).

The significant fruit dry yield differences among the cultivars (Table 3.3), despite the fact that comparable top dry matters were produced by all cultivars, may be explained by the fact that the variety with highest yields (Mareko Fana) partitioned more of its assimilates (55%) to fruits, while the variety with lowest yield (Malaga) partitioned only 37% of its assimilates to fruits. Moreover, the cultivar with lowest yield accumulated more than 40 % of its assimilate in stems, whose contribution to photosynthesis or fruit yield is insignificant.

3.3.3 Yield, yield components and selected quality measures

Table 3.3 shows yield, yield components and selected quality traits as a function of cultivar and irrigation regime. Fresh and dry fruit yields were significantly affected by cultivar differences, and also high irrigation regime (25D) significantly increased both fresh and dry fruit yields (Table 3.3). Cultivar and irrigation regime interactions were not significant for both fresh and dry fruit yields, indicating that these parameters responded to soil water level, independent of cultivar differences When dry fruit yield of the respective cultivars are averaged over-irrigation regimes, cultivar Mareko Fana (3.60 t ha^{-1}) out-yielded Jalapeno (3.44 t ha^{-1}) and Malaga (2.11 t ha^{-1}) by 5 and 71 %, respectively. When fresh fruit yield of the respective cultivars are averaged over-irrigation regimes, higher fresh fruit yield was recorded for Jalapeno (29.28 t ha^{-1}), followed by Mareko Fana (21.49 t ha^{-1}) and Malaga (6.90 t ha^{-1}). When fresh and dry fruit yields are averaged over the cultivars, a 77 and 64 % improvement in fresh and dry yields, respectively, were observed by irrigating at 25D as compared to irrigating at 75D.

Table 3.3 Fruit yield, yield components and selected quality measures as affected by different irrigation regimes and cultivars

Irrigation	Cultivar	Fresh fruit yield (t ha^{-1})	Dry fruit yield (t ha^{-1})	Fruit (number $plant^{-1}$)	Mean fruit mass (g)	Succulence[a]
25D	Mareko Fana	28.02	4.37	67 bA	1.82	6.01 bA
	Jalapeno	38.22	4.03	46 bA	2.45	9.44 a A
	Malaga	9.71	2.96	377 aA	0.23	3.27 cA
55D	Mareko Fana	21.65	3.76	57 bA	1.87	5.91 bA
	Jalapeno	28.66	3.55	40 bA	2.46	8.01 a B
	Malaga	6.39	1.95	252 aB	0.22	3.25 cA
75D	Mareko Fana	16.36	2.76	45 bA	1.71	5.77 bA
	Jalapeno	20.97	2.75	35 bA	2.19	7.61 a B
	Malaga	4.61	1.42	183 aC	0.22	3.25 cA
LSD	Irrigation	6.526*	0.704*	41.494*	NS	NS
	Cultivar	6.430*	0.720*	37.479**	0.122**	0.416**
	Irrigation x Cultivar	NS	NS	141.250**	NS	1.637**

Notes: a: ratio of total fresh fruit mass to top dry fruit mass; 25D, 55D, & 75D: 20-25, 50-55, and 70-75 % depletion of plant available water, respectively; LSD: least significant difference ($P \leq 0.05$); NS: not significant ($P > 0.05$); *: significant at $P \leq 0.05$; **: significant at $P \leq 0.01$. Column means within the same irrigation regime followed by the same lower case letter or column means within the same cultivar followed by the same upper case letter are not significantly different ($P > 0.05$).

There were no significant differences in fresh and dry fruit yields between 25D and 55D suggesting the possibility of employing water-saving tactics. Similarly, results elsewhere reported the applicability of deficit irrigation in hot pepper production without compromising yields (Kang *et al*., 2001; Dorji *et al*., 2005). However, others confirmed the sensitivity of pepper to water stress and the beneficial effects of abundant irrigation. Costa & Gianquinto (2002) and Beese *et al*. (1982) observed significant yield increases with water rates above 100 % evapotranspiration, indicating that yield increases with more water than the well-water control. The inconsistency of the results reported may be attributed to differences in the cultivars (Ismail & Davies, 1997; Jaimez *et al*., 1999) and in the growing conditions (Pellitero *et al*., 1993).

Average dry fruit mass and succulence were significantly affected by cultivar differences, but not by irrigation regime. Cultivar and irrigation regime interactions were significant for succulence, but not for average dry fruit mass. Fruit number per plant was significantly affected by irrigation regime, cultivar differences and their interaction effect. When mean dry fruit mass was averaged across irrigation regimes, Jalapeno (2.27 g) gave higher mean dry fruit mass, followed by Mareko Fana (1.80 g) and Malaga (0.22 g). However, the number of fruits produced by respective cultivars followed the reverse order as that of mean dry fruit mass, where Malaga produced 271 fruits per plant on average, while Mareko Fana and Jalapeno produced 56 and 41 fruits per plant, respectively.

Although plants were irrigated at less frequent intervals under 55D and 75D than 25D, the mean fruit mass was not affected by irrigation regime. This may be attributed to low crop load due to high degree of flower abortion in 55D and 75D plants, compared to those plants receiving the 25D irrigation treatment (Dorji *et al*., 2005). Reduction in fruit number due to low level of soil water in 55D and 75D may have enhanced accumulation of available assimilates in the remaining fewer fruits, maintaining the final fruit mass comparable to 25D. Pepper plants are most sensitive to water stress during flowering and fruit development (Katerji *et al*., 1993). Furthermore, the existence of a consistent inverse relationship between mean dry fruit mass and fruit number per plant among the cultivars confirms the difficulty of achieving improvement in these two parameters simultaneously.

Jalapeno (8.4) was on average more succulent at harvest than Mareko Fana (5.9) and Malaga (3.3). Irrigation at a low level of soil water depletion (25D) resulted in greater succulence than when irrigating at a medium (55D) or high (75D) level of soil water depletion. Thus Jalapeno fruits harvested from plants irrigated at 25D are recommended for the fresh market, as these fruit exhibit highest succulence, which directly relates to hot pepper fruit quality.

3.3.4 Soil water content, water-use and water-use efficiency

Soil water content to 0.6 m soil depth during the growing season is shown in Figure 3.2. Soil water content within the 0.60 m soil profile decreased gradually towards the end of the season in plots irrigated at 55D and 75D. However, soil water remained higher in the plots irrigated at 25D. From the commencement of stress imposition (December 13) the soil water deficit level reached below 55D on only four occasions, whereas it never dropped below D75 due to high rainfall in the growing season. The depletion level for the 75D was higher than for 55D, and that of 55D was higher than 25D throughout the growing season, indicating that water availability was higher for 25D than 55D, followed by 75D.

Table 3.4 presents the components of soil water balance. The irrigation and rain in the different irrigation treatments, i.e., 25D, 55D and 75D was 830 mm, 731 mm and 673 mm for Mareko Fana, 740 mm, 655 mm and 616 mm for Jalapeno, and 902 mm, 792 mm and 710 mm for Malaga. The water consumption (evapotranspiration) ranged from 430 mm to 675 mm, and the observed differences in evapotranspiration among the cultivars were as a result of the differences in the length of the growing season. The water saved by irrigating at 75D as compared to 25D was 23 % for Mareko Fana, 20 % for Jalapeno, and 27 % for Malaga. Similarly, by irrigating at 55D as opposed to irrigating at 25D, on average across the cultivars, 14% of water was saved. The total irrigation events corresponding to the different irrigation treatments, i.e., 25D, 55D and 75D were 20, 11 and 9 days in Jalapeno and 26, 13 and 9 days in Malaga and Mareko Fana.

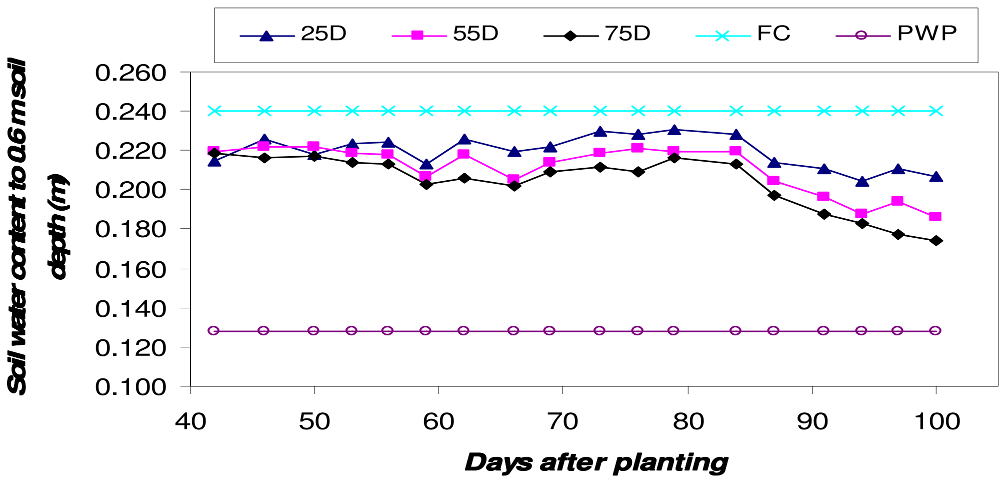


Figure 3.2 Soil water content to 0.6 m soil depth during growing season as influenced by irrigation regime. 25D, 55D, & 75D: 20-25, 50-55, and 70-75 % depletion of plant available water, respectively. FC: Field capacity, PWP: Permanent wilting point.

Table 3.4 Components of soil water balance as affected by different cultivars and irrigation regimes

Irrigation	Mm					
	Cultivar	Rainfall	Irrigation	Drainage	ΔS	ETc
25D	Mareko F.	520	310	247	3	586
	Jalapeno	463	277	236	12	516
	Malaga	557	355	243	6	675
55D	Mareko F.	520	211	220	2	513
	Jalapeno	463	192	211	11	455
	Malaga	557	235	215	4	581
75D	Mareko F.	520	153	176	-3	494
	Jalapeno	463	153	191	5	430
	Malaga	557	153	181	3	532

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

Table 3.5 summarizes the water-use efficiency (WUE) in terms of fresh and dry fruit yields and top dry matter yields for all the treatments. The WUE in terms of fresh and dry fruit yields were significantly influenced by cultivars, but WUE for top dry matter was not affected by cultivar (Table 3.5). Irrigation regime did not affect any of the WUE considered. The cultivar and irrigation regime interaction effects for the three WUE considered were also not significant. Similarly, Katerji *et al*. (1993) using trickle irrigation, observed no significant differences in WUE between stressed and well-irrigated treatments. However, Kang *et al*. (2001) and Dorji *et al*. (2005) reported significant improvement in WUE due to water stress applied. In the present study, reduction in water application did not contribute to improvement in WUE. This is because yield and biomass were significantly reduced due to the reduction in irrigation. On average, the cultivar Jalapeno exhibited higher WUE in terms of fresh and dry fruit yields, followed by Mareko Fana and Malaga. The cultivars Jalapeno and Mareko Fana had comparable WUE in terms of top dry matter yield. The difference in WUE among the cultivars can be explained by the fact that cultivars with high WUE reached maturity earlier, with relatively high fresh as well as dry fruit yield. The absence of significant differences in WUE for top dry matter production is because all three cultivars produced comparable top dry matter yields.

Table 3.5 Water-use efficiency (WUE) as affected by different cultivars and irrigation regimes

Irrigation	Cultivar	WUE fresh fruit (kg ha^{-1} mm^{-1})	WUE dry Fruit (kg ha^{-1} mm^{-1})	WUE top dry matter (kg ha^{-1} mm^{-1})
25D	Mareko Fana	45.2	5.3	13.2
	Jalapeno	74.1	5.4	12.5
	Malaga	14.4	3.3	10.7
55D	Mareko Fana	42.2	5.2	12.7
	Jalapeno	63.0	5.4	12.7
	Malaga	11.0	2.5	9.7
75D	Mareko Fana	33.1	4.1	11.3
	Jalapeno	48.8	4.5	11.1
	Malaga	8.7	2.0	7.6
LSD	Irrigation	NS	NS	NS
	Cultivar	12.57**	1.50**	NS
	Irrigation X Cultivar	NS	NS	NS

Notes: 25D, 55D, & 75D: irrigation at 20-25, 50-55, and 70-75 % depletion of plant available water, respectively; LSD: least significant difference ($P \leq 0.05$); NS: not significant ($P>0.05$); *: significant at $P \leq 0.05$; **: significant at $P \leq 0.01$.

3.4 CONCLUSIONS

This study demonstrated that highest yield under rainfed conditions with supplemental irrigation in Pretoria would be obtained by maintaining the depletion of soil water level between 20 and 55%. The absence of significant differences in fresh and dry fruit yields between 25D and 55D, suggests the potential of practicing deficit irrigation.

Despite comparable top dry biomass yields, the cultivars produced significantly different dry and fresh fruit yields. This is due to the fact that the dry yield differences among the cultivars were more attributed to differences in harvest index and average fruit mass, than leaf area, top biomass or fruit number differences. The WUE did not improve by irrigating at higher level of plant water depletion, as the corresponding yield reduction per unit water saved outweighed the yield gain per unit water applied. Significant differences in WUE for fresh and dry fruit yields were observed among the cultivars. This is attributed to early maturity, high harvest index and high succulence by those cultivars with high WUE for fresh and dry fruit yields. There were no significant interaction effects observed for most parameters which revealed that hot pepper response to irrigation regime was the same for all cultivars. It appears that an appropriate irrigation regime that maximizes production of hot pepper can be devised across cultivars.

Finally, where the cost of fresh water is high, further research is recommended to establish an irrigation regime involving deficit irrigation by quantifying the trade-off between the yield loss that would be incurred because of irrigation at levels that are below the optimum and the economical and ecological advantage that would be achieved by practicing deficit irrigation.

CHAPTER 4

RESPONSE OF HOT PEPPER (*Capsicum annuum* L.) CULTIVARS TO DIFFERENT ROW SPACINGS

Abstract

A field trial was conducted in the 2004/2005 growing season at the Hatfield Experimental Farm, University of Pretoria, to investigate the effect of different row spacings and cultivars on growth, yield and water-use efficiency with the aim of selecting the cultivars that are more efficient in resource utilization. Treatments were arranged in a randomized complete block strip plot design, where the row spacings and cultivars were assigned to main plots and sub plots, respectively. The three cultivars were Jalapeno, Malaga and Serrano, and the two row spacings 0.45 m and 0.70 m. Treatments were replicated three times and drip irrigation was utilized. Growth analysis, soil water content and yield measurements were performed.

Cultivar Jalapeno (4.24 t ha^{-1}) out-yielded Serrano (2.67 t ha^{-1}) and Malaga (2.50 t ha^{-1}) in dry fruit yield. Higher fresh yield was also recorded for Jalapeno (38.61 t ha^{-1}), followed by Serrano (15.62 t ha^{-1}) and Malaga (8.05 t ha^{-1}). A 25% and 22% improvement in fresh fruit and dry fruit yields, respectively, was observed by planting at a row spacing of 0.45 m, as compared to planting at a row spacing of 0.70 m. Fruit number per plant increased from 112 to 127 as row spacing increased from 0.45 m to 0.70 m, indicating a compensatory growth response by individual plants to offset yield reduction due to wide row spacing. The high fruit dry mass recorded in Jalapeno (4.24 t ha^{-1}), in spite of low fruit number per plant, is attributed to its high harvest index (0.64) and high average fruit dry mass (2.44 g). Malaga produced the highest fruit number per plant (245), but yielded the lowest dry and fresh fruit yield due to its relatively low harvest index (0.40) and low average fruit dry mass (0.23 g). The existence of a consistent inverse relationship between average dry fruit mass and fruit number per plant among the cultivars confirms the difficulty of achieving improvement in those two parameters concomitantly.

No significant interaction effect was observed for most parameters studied; revealing that hot pepper response to row spacing did not depend on cultivar differences. Thus, it appears that appropriate row spacing that maximizes production of hot pepper can be devised across cultivars having similar growth habit to ones studied here.

Key words: Hot pepper, plant density, row spacing, water-use efficiency

4.1 INTRODUCTION

Hot pepper cultivars show considerable biodiversity: cultivars differ vastly in attributes such as growth habit, length of growing season, cultural requirements, fruit size, pigmentation and pungency (Bosland, 1992). Production and harvesting costs are high in hot pepper, as the crop is capital- (irrigation & other inputs) and labour-intensive. Managing production inputs and minimizing production costs are increasingly important for profitable hot pepper production. Row spacing is one of the cultural practices that influence productivity of a crop (Kelley & Boyhan, 2006).

Optimum plant population or in-row plant spacing studies have been conducted on bell (Russo, 1991; Locascio & Stall, 1994), cayenne (Decoteau & Graham, 1994), pepperoncini (Motsenbocker, 1996), paprika (Kahn *et al*., 1997; Cavero *et al*., 2001), and pimiento peppers (Ortega *et al*., 2004). However, recommendations suggested by each investigator vary widely. For instance, Decoteau & Graham (1994) reported 44 400 plants ha^{-1} for optimum cayenne pepper production, while Ortega *et al*. (2004) recommended plant densities in the range of 100 000 to 120 000 plants ha^{-1} for pimiento pepper. This is because optimum plant population density for a given species varies depending on cultivar, input level, harvesting techniques and other cultural practices.

Generally, high density planting is associated with high yields. High density planting also aids mechanical harvesting, as more fruits set on higher plant canopy (Decoteau & Graham, 1994). However, disease incidence due to reduced ventilation (Karlen *et al*., 1987; Stofella & Bryan, 1988) and poor colour development of fruits due to reduced light exposure (Stofella & Bryan, 1988; Cavero *et al*., 2001) are some of the limitations of high density planting. Thus, it appears that a compromise is made between yield, quality and ease of performing cultural practices when the producer has to decide the best planting density.

Literature reviewed so far indicated that most researchers considered only one or two cultivars in their studies, and little information is available on how the different growth components of pepper are affected by row spacing to ultimately determine the performance of hot pepper cultivars. Information on how row spacing affects yield and growth of different hot pepper cultivars has not been well elucidated under field conditions in the Pretoria area. Furthermore, literature on the impact of varying the plant population of hot pepper on canopy growth is inadequate. Cognizant of the diversity of hot peppers and the sparse information available on plant population effects on performance of hot pepper, a field experiment was conducted with the objective to investigate effects of different row spacings on yield, quality and growth of hot pepper cultivars.

4.2 MATERIALS AND METHODS

4.2.1 Experimental site and treatments

A field experiment was conducted at the Hatfield Experimental Farm, Pretoria, South Africa (latitude $25^0$45' S, longitude $28^0$16' E, altitude 1327 m.a.s.l.). The area has an average annual rainfall of 670 mm, mainly from October to March (Annandale *et al*., 1999). The average annual maximum air temperature for the area is 25 °C and the average annual minimum air temperature is 12 °C. The hottest month of the year is January, with an average maximum air temperature of 29 °C, while the coldest months are June and July, with an average minimum air temperature of 5 °C. The soil characteristics to 30 cm soil depth are predominately sandy clay loam with permanent wilting point of 128 mm m^{-1}, field capacity of 240 mm m^{-1} and pH of 6.5. The soil contained 572 mg Ca, 79 mg K, 188mg Mg and 60.5 mg Na per one kg of dry soil.

Treatments were arranged in randomized complete block strip plot design, where the row spacings and cultivars were assigned to main plot and sub plots, respectively. The two row spacings were 0.7 x 0.4 m and 0.45 x 0.4 m, which corresponded to 35714 and 55555 plants ha^{-1}, respectively. The three cultivars were Serrano, Jalapeno and Malaga.

4.2.2 Crop management

Six-week-old hot pepper transplants of the respective cultivars were transplanted on 11 November, 2004. Plants were irrigated using drip irrigation for 1 hour (12.5-15.5 mm) every other day for three weeks until plants were well established. Thereafter, the soil profile was refilled to field capacity, every time when the measured soil water deficit level reached 50-55% depletion of plant available water. Based on soil analysis results and target yield, 150 kg ha^{-1} N, 75 kg ha^{-1} P and 50 kg ha^{-1} K were applied to all plots. The N application was split, with 50 kg ha^{-1} at planting, followed by a 100 kg ha^{-1} top dressing eight weeks after transplanting. Weeds were controlled manually. Fungal diseases were controlled using Benomyl® (1H – benzimidazole) and Bravo® (chlorothalonil) sprays, while red spider mites were controlled with Metasystox® (oxydemeton–methyl) applied at the recommended doses.

4.2.3 Measurements

Eight plants from the central two rows of each plot were marked for yield measurement. Fruits were harvested three times during the season. On the final day of harvest, all aboveground plant parts were harvested and separated into fruits, stems and leaves and whereafter they were oven dried at 75 °C for 72 hours to constant mass, and dry mass was determined. Leaf area was measured with an LI 3100 belt driven leaf area meter (Li-Cor, Lincoln, Nebraska, USA). Leaf area index was calculated from the leaf area and ground area from which the samples were taken. Specific leaf area was calculated as the ratio of leaf area to leaf dry mass.

The fraction of photosynthetically active radiation intercepted (FI_{PAR}) by the canopy was measured using a sunfleck ceptometer (Decagon Devices, Pullman, Washington, USA) a day before harvest. The photosynthetically active radiation (PAR) measurement for a plot consisted of three series of measurements in rapid succession. A series of measurements consisted of one reference reading above the canopy and ten readings below the canopy. The difference between the above canopy and below canopy PAR measurements was used to calculate the fractional interception (FI) of PAR using the following equation (Jovanovic & Annandale, 1999).

$$FI_{PAR} = 1 - \left(\frac{PAR\ below\ canopy}{PAR\ above\ canopy} \right) \quad (4.1)$$

Total crop evapotranspiration (ETc) was estimated using the soil water balance equation,

$$ETc = I + RF + \Delta S - D - R \quad (4.2)$$

where I is irrigation, RF is precipitation, ΔS is the change in soil water storage, D is drainage and R is runoff. Drainage was estimated using SWB model, runoff was assumed negligible as the experiment setting doses not allow free runoff.

Water-use efficiency was calculated for top dry matter, fresh fruit mass and fruit dry mass from the ratio of the respective parameter mass to calculated total evapotranspiration using eq. (3.2). Succulence, a quality measure for fresh market peppers, was calculated as the ratio of fresh fruit mass to the dry fruit mass.

4.2.4 Data analysis

Data was analyzed using the Mixed Procedure of SAS software Version 9.1 (SAS, 2003). Treatment means were separated by the least significance difference (LSD) test at $P \leq 0.05$.

4.3 RESULTS AND DISCUSSION

4.3.1 Specific leaf area, leaf area index and canopy development

Table 4.1 presents the results of the effect of row spacing and cultivar differences on specific leaf area (SLA), leaf area index (LAI) and fractional interception (FI). The main effect of cultivar was highly significant (P≤0.01) for SLA, LAI and FI. Row spacing highly significantly (P≤0.01) affected LAI and FI, but not SLA. Decreasing row spacing increased FI on average from 0.66 to 0.77. The FI measured was significantly different between Serrano (0.73) and Jalapeno (0.64), and between Malaga (0.78) and Jalapeno (0.64), while FI of Serrano (0.73) and that of Malaga (0.78) did not differ significantly. A significant difference in SLA was observed among the three cultivars, with Serrano being the highest and Jalapeno the lowest.

Table 4.1 Specific leaf area (SLA), leaf area index (LAI) and fractional interception (FI) as affected by different row spacings and cultivars

Row spacing	Cultivar	SLA (m^2 kg^{-1})	LAI (m^2 m^{-2})	FI
0.45 m	Serrano	20.55	1.84 Aa	0.77
	Jalapeno	16.08	1.80 Aa	0.73
	Malaga	18.15	2.48 aB	0.83
0.70 m	Serrano	20.43	1.10 Ba	0.70
	Jalapeno	15.79	1.54 bB	0.55
	Malaga	18.09	1.78 bB	0.72
LSD	Row spacing	NS	0.141**	0.048**
	Cultivar	0.533**	0.394**	0.111**
	Row spacing x Cultivar	NS	0.401**	NS

Notes: LSD: least significant difference (P ≤ 0.05); NS: not significant (P>0.05); *: significant at P ≤ 0.05; **: significant at P ≤ 0.01. Column means within the same cultivar followed by the same lower case letter or column means within the same row spacing followed by the same upper case letter are not significantly different (P>0.05).

The cultivar and row spacing interaction effect was significant for LAI, but not for SLA and FI. Highest LAI (2.48 m^2 m^{-2}) was recorded in Malaga at a row spacing of 0.45 m, while the lowest LAI (1.10 m^2 m^{-2}) was observed in Jalapeno at a row spacing of 0.7 m.

The relationship between LAI and FI, or SLA and LAI is not usually direct. For instance, on average the relatively high LAI recorded for Jalapeno (1.67 m^2 m^{-2}) in relation to Serrano (1.47 m^2 m^{-2}) did not result in higher FI for Jalapeno (0.64) as compared to Serrano (0.73). Furthermore, the high mean SLA observed in Serrano (20.49 m^2 kg^{-1}) as compared to Jalapeno (15.94 m^2 kg^{-1}) did not result in higher LAI for Serrano (1.47 m^2 m^{-2}) as compared to Jalapeno (1.67 m^2 m^{-2}). This is because FI is affected not only by the size of the canopy but also by the way in which the leaves are configured in a canopy (Russell *et al*., 1990). Similarly, SLA reflects the dry leaves mass contained in a unit of leaf area. Thus depending on cultivars' difference, cultivars with thin leaves with similar leaf area would have a high SLA, which is an indicator of high productivity (Wilson *et al*., 1999).

The present study has shown an improved light interception as row spacing decreased from 0.70 m to 0.45 m. Lorezo & Catilla (1995) reported also higher LAI and a marked improvement in radiation interception as plant populations increased in hot pepper. Flénet *et al*. (1996), working on four different crop species (maize, sorghum, soybean and sunflower), reported an improvement in light interception ability as row spacing decreased and attributed it to the even distribution of plants and hence foliage in narrower row spacing. Taylor *et al*. (1982) observed no significant increase in LAI of soybean due to higher density planting. However, light interception was consistently greater in 0.25 m row spacing than 1.0 m row spacing, which they attributed to a more even leaf distribution in the narrow row spacing. The robustness of SLA across different row spacings highlights the reliability of using this crop-specific parameter in modelling of hot pepper under varied growing conditions (Annandale *et al*., 1999).

4.3.2 Dry matter production and partitioning

Dry matter production as affected by row spacing and cultivar is presented in Table 4.2. Top dry matter, leaf dry matter and stem dry matter were significantly improved as a result of increasing planting density. A significant difference in leaf dry matter and stem dry matter were observed among the cultivars, but the top dry matter production was not affected by cultivar. The cultivar and row spacing interaction effect was significant for leaf dry matter, but there was no interaction between top dry matter and stem dry matter.

An increase of 27.8 % in top dry matter, 33.6 % in leaf dry matter and 33.7 % in stem dry matter was observed as the row spacing decreased from 0.70 to 0.45 m. Cultivar Malaga produced the highest leaf dry matter (1.176 t ha^{-1}) and stem dry matter (2.649 t ha^{-1}), whereas the lowest leaf dry matter and stem dry matter was recorded in Serrano (0.717 t ha^{-1}) and Jalapeno (1.358 t ha^{-1}), respectively.

Table 4.2 Top dry matter (TDM), leaf dry matter (LDM) and stem dry matter (SDM) as affected by different row spacings and cultivars

Row spacing	Cultivar	TDM (t ha^{-1})	LDM (t ha^{-1})	SDM (t ha^{-1})
0.45 m	Serrano	6.476	0.896 aA	2.580
	Jalapeno	7.076	1.109 aB	1.480
	Malaga	7.313	1.358 aC	3.092
0.70 m	Serrano	4.782	0.538 bA	1.908
	Jalapeno	6.211	0.986 bB	1.236
	Malaga	5.539	0.993 aB	2.206
LSD	Row spacing	1.13**	0.07**	0.59**
	Cultivar	NS	0.23**	0.87**
	Row spacing x Cultivar	NS	0.23**	NS

Notes: LSD: least significant difference (P≤ 0.05); NS: not significant (P>0.05); *: significant at P ≤ 0.05; **: significant at P ≤ 0.01. Column means within the same cultivar followed by the same lower case letter or column means within the same row spacing followed by the same upper case letter are not significantly different (P>0.05).

Data on dry matter partitioning to fruit, leaf and stem as affected by row spacing and cultivar difference is presented in Table 4.3. Marked differences in assimilate partitioning to fruit, leaf and stem was observed due to cultivar differences. The proportion of assimilate portioned to fruit in Jalapeno was 64 %, while in Serrano it was 47 % and in Malaga it was 40 %. Assimilate partitioned to leaf and stem were, respectively, 16% and 20 % for Jalapeno, 13% and 40% for Serrano and 19% and 41% for Malaga. Overall, fruits remained the major sink, accounting for more than 50 % of the top plant dry matter mass, followed by stem (34 %) and then leaf (16%). The average harvest index reported

Table 4.3 Dry matter partitioning to fruits, leaves and stems as affected by different row spacings and cultivars

Row spacing	Cultivar	Harvest Index	Leaf Fraction	Stem Fraction
0.45 m	Serrano	0.46	0.14	0.30
	Jalapeno	0.63	0.16	0.21
	Malaga	0.39	0.19	0.42
0.70 m	Serrano	0.48	0.11	0.41
	Jalapeno	0.64	0.16	0.20
	Malaga	0.40	0.19	0.41
LSD	Row spacing	NS	NS	NS
	Cultivar	0.08**	0.03**	0.06**
	Row spacing x Cultivar	NS	NS	NS

Notes: LSD: least significant difference ($P \leq 0.05$); NS: not significant ($P > 0.05$); *: significant at $P \leq 0.05$; **: significant at $P \leq 0.01$.

for the cultivars is higher than the 39% reported for a split-root experiment on pot-grown pepper (Cantore *et al*., 2000), whereas it closely approaches that of 56 % reported from a deficit irrigation and partial root drying experiment on pepper (Dorji *et al*., 2005). In agreement with the present finding, Jolliffe & Gaye (1995) also reported no significant effect on harvest index as plant population changed from 1.4 to 11.1 plants m^{-2} in bell pepper. The result of the present study confirmed that dry matter partitioning is a cultivar trait and is hardly affected by growing conditions. Neither row spacing nor the interaction between row spacing and cultivar were significant for assimilates partitioning.

The significant fruit yield differences (Table 4.4) among the cultivars, despite the fact that comparable top dry matter yields (Table 4.2) have been produced by all cultivars, may be explained by the fact that top yielding cultivar (Jalapeno) partitioned more of its assimilates (64%) to fruit, while cultivar with lowest fruit yield (Malaga) accumulated only 40% of its assimilates in fruits (Table 4.3). Moreover, cultivar Malaga, with lowest yield, accumulated more than 41% of assimilates in stems, which contributed insignificantly to photosynthesis or fruit yield.

4.3.3 Fruit yield, yield components and selected quality measures

Table 4.4 shows yield, yield components and selected quality measures as a function of row spacing and cultivar difference. Fresh and dry fruit yields were significantly affected by cultivar differences. High planting density significantly increased both fresh and dry fruit yields (Table 4.4). Cultivar and row spacing interaction was not significant for both fresh and dry fruit yields, indicating that these parameters responded to row spacing treatment independent of cultivar differences.

Cultivar Jalapeno (4.24 t ha^{-1}) out-yielded Serrano (2.67 t ha^{-1}) and Malaga (2.50 t ha^{-1}) by 59 % and 69 %, respectively, in dry fruit yield. Higher fresh fruit yield was recorded for Jalapeno (38.61 t ha^{-1}), followed by Serrano (15.62 t ha^{-1}) and Malaga (8.05 t ha^{-1}). A 25% improvement in fresh fruit and 22% dry fruit yields were observed by planting at row a spacing of 0.45 m, as compared to row spacing of 0.70 m.

Fruit number per plant was significantly affected by row spacing and cultivar. Average dry fruit mass and succulence were significantly affected by cultivar differences, but not by row spacing. Cultivar and row spacing interaction effect was not significant for fruit number per plant, average fruit mass and succulence.

Fruit number per plant increased from 112 to 127 as row spacing increased from 0.45 m to 0.70 m, indicating a compensatory growth response by individual plants to offset the yield reduction due to wider row spacing. The higher productivity observed due to narrow row spacing as compared to wide row spacing is attributed to higher top dry mass and fruit dry mass per unit area of land. The cumulative compensatory growths effects (fruit number per plant, average fruit mass, individual plant dry matter production) observed for wide row spacing were not adequate enough to offset the yield reduction incurred as a result of the wider row spacing. Fruit number per plant and average fruit mass exhibited an inverse relationship across all three cultivars.

Table 4.4 Fruit yield, yield components and selected quality measures as affected by different row spacings and cultivars

Row spacing	Cultivar	Fresh fruit Yield (t ha^{-1})	Dry fruit yield (t ha^{-1})	Fruit number plant^{-1}	Average fruit mass (g)	Succulence
0.45 m	Serrano	17.83	3.00	68	0.80	5.95
	Jalapeno	41.99	4.49	33	2.45	9.10
	Malaga	9.44	2.86	235	0.22	3.31
0.70 m	Serrano	13.41	2.34	79	0.81	5.81
	Jalapeno	35.24	3.99	46	2.42	9.11
	Malaga	6.760	2.14	255	0.24	3.12
LSD	Row spacing	6.01*	0.83**	16.51*	NS	NS
	Cultivar	8.14**	1.11**	38.83**	0.19**	0.45**
	Row spacing x Cultivar	NS	NS	NS	NS	NS

Notes: LSD: least significant difference ($P \leq 0.05$); NS: not significant ($P>0.05$); *: significant at $P \leq 0.05$; **: significant at $P \leq 0.01$.

The high fruit dry mass recorded in Jalapeno (4.24 t ha^{-1}), in spite of low fruit number per plant, is attributed to its high harvest index (0.64) and high average fruit mass (2.44 g). Malaga produced the highest fruit number per plant (245), but yielded the lowest dry and fresh fruit yield due to its relatively low harvest index (0.40) and low average fruit mass (0.23 g). The existence of a consistent inverse relationship between average dry fruit mass and fruit number per plant among the cultivars confirms the difficulty of achieving improvement in those two parameters concomitantly.

Jalapeno exhibited a higher degree of succulence (9.11) at harvest than Serrano (5.89) or Malaga (3.21). The high variation in fresh fruit yield per unit of land observed among the cultivars is partly attributable to the marked difference in the degree of succulence among the cultivars (Table 4.4).

In agreement with the present findings, Lorezo & Catilla (1995) observed an increase in yield of bell pepper as planting density was increased. They attributed the effect to increased LAI, which in turn improved radiation interception. Jolliffe & Gaye (1995) reported as much as a 47% variation in total fruit dry yield of pepper that was harvested 103 days after transplanting and attributed this to population density effects. At the end of the growing season plant population density treatments accounted for 35% of the variation in the final cumulative fruit dry mass. Similarly, the increase in plant productivity was considered to result from the increase in plant population for Tabasco pepper (Sundstorm *et al*., 1984); bell pepper (Stoffella & Bryan, 1988); cayenne pepper (Decoteau & Graham, 1994) and pepperoncini (Motsenbocker, 1996) until optimum plant population is reached, beyond which yield reported to decrease due to intra-species competition.

4.3.4 Water-use and water-use efficiency

Table 4.5 presents the components of soil water balance. The water consumption (evapotranspiration) ranged from 451 mm to 552 mm, and the observed differences in evapotranspiration among the cultivars were as a result of the differences in the length of the growing season. Table 4.6 the water-use efficiency (WUE) in terms of fresh and dry fruit yields and top dry matter, as influenced by cultivar and row spacing. WUE in terms of top dry matter and fresh and dry fruit yields were significantly influenced by cultivars and row spacing (Table 4.6). The cultivar and row spacing interaction effect for the three WUE considered was not significant. In the present study, reducing the row spacing from 0.7 to 0.45 m increased the WUE. This is because yield and biomass were significantly improved due to decreasing the row spacing, but the water supply (irrigation plus rain) was the same for the two row spacings. The cultivar Jalapeno exhibited higher WUE, followed by Serrano and Malaga. The difference in WUE among the cultivars can be explained by the fact that cultivars with high WUE mature earlier, with relatively high fresh and dry fruit yield.

Table 4.5 Components of soil water balance as affected by different cultivars and row spacing

Row spacing	Cultivar	Rainfall (mm)	Irrigation (mm)	Drainage (mm)	ΔS (mm)	ETc (mm)
0.45 m	Serrano	521	220	247	-5	521
	Jalapeno	458	190	236	6	458
	Malaga	552	233	243	4	552
0.70 m	Serrano	521	220	220	2	523
	Jalapeno	458	190	211	11	451
	Malaga	552	233	215	2	538

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

Table 4.6 Water-use efficiency as affected by different hot pepper cultivars and row spacings

Row spacing	Cultivar	WUE fresh fruit kg ha^{-1} mm^{-1})	WUE dry fruit (kg ha^{-1} mm^{-1})	WUE top dry matter yield (kg ha^{-1} mm^{-1})
0.45 m	Serrano	34.2	5.8	12.4
	Jalapeno	91.7	9.8	15.5
	Malaga	17.1	5.2	13.2
0.70 m	Serrano	25.6	4.5	9.1
	Jalapeno	78.1	8.8	13.8
	Malaga	12.4	4.0	9.9
LSD	Row spacing	8.3*	1.0*	1.53**
	Cultivar	17.4**	1.65**	2.0**
	Row spacing x Cultivar	NS	NS	NS

Notes: LSD: least significant difference (P≤ 0.05); NS: not significant (P>0.05); *: significant at P ≤ 0.05; **: significant at P ≤ 0.01.

4.4. CONCLUSIONS

Results from the present study indicate that high density planting markedly increased growth and yield per unit area. Except fruit number per plant, yield components such as average fruit mass and harvest index were unaffected by row spacing. This indicates that the change in those important yield compensation processes were not adequate to offset the yield reduction due to wide row spacing planting. Thus, the yield increment recorded in the narrow row spacing is due to high biomass production per unit area, which in turn is attributable to the improved light interception in those plants planted in narrow row spacing.

Although all cultivars produced comparable top dry biomass, dry and fresh fruit yields were significantly different among the cultivars. Malaga, a cultivar with the highest leaf area, leaf mass and fruit number per plant, yielded the least. Jalapeno, a cultivar with the highest harvest index and average fruit mass, produced the highest fresh and dry fruit yields. Thus, the yield difference among the cultivars was more attributable to differences in harvest index and average fruit mass rather than leaf area, top biomass or fruit number differences. Hot pepper breeders working on yield improvement should target harvest index and average fruit mass in their effort to breed high yielding cultivars. The wide gap in fresh fruit yield per unit land among the cultivars is attributed to the marked difference among the cultivar in their succulence at harvest. High density planting by virtue of its high yield per unit area resulted in improved water-use efficiency. Cultivars with high water-use efficiency can be obtained by selecting those that mature earlier with relatively high fresh and dry fruit yield.

No significant interaction effects were observed for most parameters studied; revealing that hot pepper response to row spacing did not depend on cultivar differences. Thus, it appears that appropriate row spacing, which maximizes production of hot pepper, can be devised across cultivars having similar growth habit with the ones considered in this study.

CHAPTER 5

EFFECTS OF ROW SPACINGS AND IRRIGATION REGIMES ON GROWTH AND YIELD OF HOT PEPPER (*Capsicum annuum* L. CV 'CAYENNE LONG SLIM')

Abstract

A rainshelter trial was conducted in the 2004/2005 growing season at the Hatfield experimental farm, Pretoria, to investigate the effect of row spacings and irrigation regimes on yield, dry matter production and partitioning, and water-use efficiency of hot pepper. A factorial combination of two row spacings (0.45 m and 0.7 m) and three irrigation regimes, based on the measure of depletion of plant available water (PAW) (25D: 20-25% depletion of PAW; 55D: 50-55% depletion of PAW; and 75D: 70-75% depletion of PAW) constituted the treatments. The trial was arranged in a randomized complete block design with three replications. Drip irrigation was utilized. Growth analysis, soil water content and yield measurements were made.

Fresh fruit yield increased by 66 % and dry fruit yield increased by 51 % when planting at 0.45 m row spacing compared to 0.7 m row spacing. Similarly, fresh fruit yield increased by 49 % and dry fruit yield increased by 46 % by irrigating at 25D, as compared to 75D. Fruit number per plant significantly increased from 70 to 100 as irrigation regimes changed from 75D to 25D. Planting at 0.45 m row spacing significantly improved water-use efficiency (WUE) for both fresh and dry fruit yields. Higher WUE (16.4 kg ha^{-1} mm^{-1}) in terms of top dry matter was observed for the 0.45 m row spacing irrigated at 75D, while the least WUE (8.5 kg ha^{-1} mm^{-1}) was found for 0.7 m row spacing irrigated at 55D. Irrigating at 25D as compared to 75D significantly increased the assimilate partitioned to fruit, while the assimilate partitioned to leaf was significantly decreased. Row spacing did not markedly affect assimilate partitioning, and there was also no interaction effect of row spacing and irrigation regime. The extent of LAI reduction due to water stress was expressed more in the 0.7 m row spacing than with the 0.45 m row spacing. Average fruit mass, succulence and specific leaf area were not affected by row spacing or irrigation regime.

It was concluded that yield loss could be prevented by irrigating at 25D, confirming the sensitivity of the crop to even mild water stress. Furthermore, the absence of interaction effects for most parameters suggested that appropriate irrigation regime to maximize hot pepper productivity can be devised across row spacing.

Key words: Hot pepper, irrigation regime, row spacing, water-use efficiency

5.1 INTRODUCTION

Many countries of the arid and semi-arid regions of the world are becoming more prone to water deficit in crop production and their future agricultural industry is at stake, unless judicious use of water in agriculture is implemented. Deficit irrigation, the deliberate and systematic under-irrigation of crops, is one of the possible water-saving strategies (English & Raja, 1996). It usually increases the water-use efficiency of a crop by reducing evapotranspiration, but produces yields that are comparable to that of a fully irrigated crop. Deficit irrigation could also help to minimize leaching of nutrients and pesticides into groundwater (Home *et al*., 2002). South Africa has endorsed the concept of deficit irrigation in such a way that irrigation planning be based on a '50% dependable' supply of water (Chitale, 1987). However, before implementing such recommendations for all crops there is a need to justify the losses and benefits from deficit irrigation, especially for water deficit sensitive crops like *Capsicum* species.

Hot pepper (*Capsicum annuum* L.) is a high value cash crop of which cultivation is confined to warm and semi-arid regions of the world. A shallow root system (Dimitrov & Ovtcharrova, 1995), high stomatal density, a large transpiring leaf surface and the elevated stomata opening, predisposes the pepper plant to water stress (Wein, 1998; Delfine *et al*., 2000). Therefore, before employing deficit irrigation as a water-saving strategy, an intensive study should be made to ascertain the practicality of such a strategy.

Deficit irrigation has been studied on hot pepper with varied responses. Research findings documented by various researchers indicated a marked variability in pepper response to water stress, although overall, irrigation increased yield substantially (Batal & Smittle, 1981; Beese *et al*., 1982; Pellitero *et al*., 1993; Costa & Gianquinto, 2002). Deficit irrigation has been investigated mainly for C*apsicum* species without considering other factors that would affect growth and development of plants. However, water requirements of plants vary for different cultivars (Ismail & Davies, 1997; Jaimez *et al*., 1999; Collino *et al*., 2000), nitrogen fertilization (Ogola *et al*., 2002; Rockström, 2003), and irrigation methods (Xie *et al*., 1999; Antony & Singandhupe, 2004). Likewise, plant population density was reported to impact the water consumption behaviour of plants (Taylor, 1980; Tan *et al*., 1983; Ritchie & Basso, 2008). Under low water supply, high plant population did not affect yield per unit area, whereas when water availability was not limited, high plant population is produced optimum yield (Taylor *et al*., 1982; Tan *et al*., 1983; Ritchie & Basso, 2008).

Information on frequency and quantity of irrigation water and the effects of deficit irrigation on yield and growth of the hot pepper plant has not been well investigated under field conditions in Pretoria. Furthermore, literature on the impact of varying the plant population of hot pepper and its interaction with different irrigation regimes is lacking. Irrigating at appropriate depletion of plant available soil water coupled with the optimum row spacing contributes to water-saving without scarifying yield. Thus, it was hypothesized that the correct combination of row spacing and irrigation regime would improve hot pepper yield and water-use efficiency. Therefore, this experiment was conducted with the objective to investigate the effect of plant density and irrigation regime on yield, dry mass production and water-use efficiency.

5.2 MATERIALS AND METHODS

5.2.1 Experimental site and treatments

An experiment was conducted under a rain shelter at the Hatfield Experimental Farm, University of Pretoria, South Africa (latitude 25^{0}45' S, longitude 28^{0}16' E, altitude 1327 m.a.s.l.). The area has an average annual rainfall of 670 mm, mainly from October to March (Annandale *et al*., 1999). The average annual maximum air temperature for the area is 25 °C and the average annual minimum air temperature is 12 °C. The hottest month of the year is January, with an average maximum air temperature of 29 °C, while the coldest months are June and July, with an average minimum air temperature of 5 °C. The top 30 cm soil layer has a sandy clay loam texture, with permanent wilting point of 151 mm m^{-1}, a field capacity of 270 mm m^{-1} and pH (H_2O) of 6.4. The soil contained 2340 mg kg^{-1} Ca, 155 mg kg^{-1} K, 967 mg kg^{-1} Mg and 196 mg kg^{-1} Na.

Treatment consisted of a factorial combination of two row spacings and three irrigation regimes. The two inter-row spacings were 0.7 m and 0.45 m, with intra-row spacing of 0.4 m, which corresponded to population of 35714 and 55555 plants ha^{-1}. The three irrigation regimes were: High irrigation regime (25D, irrigated when 20-25 % depletion of plant available water (DPAW) was reached), medium irrigation regime (55D, irrigated when 50-55 % DPAW was reached) and low irrigation regime (75D, irrigated when 70-75 % DPAW was reached). The plant available water was measured to 0.6 m soil profile. Treatments were arranged in a randomized complete block design with three replicates. Plots consisted of five rows of 2.4 m in length.

5.2.2 Crop management

Seven-week-old hot pepper transplants of cultivar 'Cayenne Long Slim' were transplanted on 19 November 2004. The plants were irrigated for one hour (12.5-15.5 mm) every other day for three weeks until plants were well established. Thereafter, plants were irrigated to field capacity each time the predetermined soil water deficit was reached. Weeds were controlled manually. Benomyl® (1H – benzimidazole) and Bravo® (chlorothalonil) were applied as preventive sprays for fungal diseases, while red spider mites were controlled using Metasystox® (oxydemeton–methyl) applied at the recommended doses. The N application was split, with 50 kg ha^{-1} at planting, followed by a 100 kg ha^{-1} top dressing eight weeks after transplanting. No P was applied, as the soil analysis showed sufficient P in the soil, while 50 kg ha^{-1} K was applied at planting. The rain shelter was left open day and night until 24 days after transplanting (until the plants were well established) where-after it was closed at nighttime and daytime only during periods of rainfall.

5.2.3 Measurements

Soil water deficit measurements were made using a neutron water meter model 503DR CPN Hydroprobe (Campbell Pacific Nuclear, California, USA). The neutron water meter was calibrated for the site. Readings were taken twice a week from access tubes installed at the middle of each plot and positioned between rows, for 0 .2 m soil layers to 1.0 m depth.

Eight plants from the central two rows were marked for yield measurement. Fruits were harvested three times during the season. On the final day of harvest all aboveground plant parts were removed and separated into fruits, stems and leaves, and then oven dried at 75 °C for 72 hours to constant mass. Leaf area index was calculated from the leaf area and ground area from which the samples were taken. Leaf area was measured with an LI 3100 belt driven leaf meter (Li-Cor, Lincoln, Nebraska, USA) on fresh leaf samples. Specific leaf area was calculated as the ratio of leaf area to leaf dry mass. Water-use efficiency was calculated for top dry matter, fresh fruit mass and fruit dry mass yields by calculating the ratio between the respective parameter yields and total water-use (rainfall and irrigation during the season).

The fraction of photosynthetically active radiation (FI_{PAR}) intercepted by the canopy was measured using a sunfleck ceptometer (Decagon Devices, Pullman, Washington, USA). The PAR measurement for a plot consisted of three series of measurements in rapid succession. A series of measurements consisted of one reference reading above the canopy and ten readings below the canopy. The difference between the above canopy and below canopy PAR measurements was used to calculate the fractional interception (FI) of PAR using the following equation:

$$FI_{PAR} = 1 - \left(\frac{PAR\, below\ canopy}{PAR\ above\ canopy} \right) \tag{5.1}$$

Total crop evapotranspiration (ETc) was estimated using the soil water balance equation,

$$ETc = I + RF + \Delta S - D - R \tag{5.2}$$

where I is irrigation, RF is precipitation, ΔS is the change in soil water storage, D is drainage and R is runoff. Drainage and runoff were assumed negligible as the irrigation amount was to refill deficit to field capacity.

Water-use efficiency was calculated for top dry matter, fresh fruit mass and fruit dry mass from the ratio of the respective parameter mass to calculated total evapotranspiration using eq. (5.2). Succulence, a quality measure for fresh market peppers, was calculated as the ratio of fresh fruit mass to the dry fruit mass.

5.2.4 Data analysis

The data were analyzed using the GLM procedure of SAS software Version 9.1 (SAS, 2003). Treatment means were separated by the least significance difference (LSD) test at $P \leq 0.05$.

5.3 RESULTS AND DISCUSSION

5.3.1 Specific leaf area, leaf area index and canopy development

Table 5.1 presents results on the effect of row spacings and irrigation regimes on fractional interception of photosynthetically active radiation (FI_{PAR}), leaf area index (LAI) and specific leaf area (SLA). Both row spacing and irrigation regime significantly affected FI and LAI, but not SLA. The interaction effect was significant for FI, but not for LAI and SLA. The lack of variability of SLA across different row spacings and irrigation regimes highlights the reliability of using this crop-specific parameter in modelling of hot pepper under varied growing conditions (Annandale *et al*., 1999). Decreasing row spacing (increasing planting density) increased mean FI from 0.69 to 0.79, while it increased mean LAI from 1.48 to 2.29 m^2 m^{-2}. Similarly, irrigating at 25D relative to irrigating at 75D, increased mean FI from 0.63 to 0.83, while mean LAI increased from 1.37 to 2.11m^2 m^{-2}. The highest FI (0.86) and LAI (2.63 m^2 m^{-2}) values were achieved for plants irrigated at 25D and planted at 0.45 m row spacing. On the other hand, the lowest FI (0.60) and LAI (1.39 m^2 m^{-2}) values were observed for plants irrigated at 75D and planted at 0.7 m row spacing.

High irrigation regime increased FI and LAI by improving the canopy size of individual plants as evidenced from high leaf dry mass produced due to frequent irrigation (Figure 5.1). In agreement with the present results, Tesfaye *et al*. (2006), working on chickpea, cowpea and common bean, also observed a reduction in both FI and LAI due to water stress. Joel *et al*. (1997) indicated that FI could be reduced as much as 70 % due to water stress in sunflower. They attributed the reduction in FI to the corresponding reduction in LAI caused by water stress. LAI decline caused by water stress was also reported for potato (Kashyap & Panda, 2003).

Lorenzo & Castilla, (1995) also reported high LAI and marked improvement in radiation interception as plant population increased in hot pepper. Working on four different species (maize, sorghum, soybean and sunflower), Flénet *et al*. (1996) reported improvement in light interception ability of these crops in narrow rows and attributed it to a more even distribution of plants and hence foliage. Taylor *et al*. (1982) observed a significant increment in LAI of soybean due to high irrigation, but not from high density planting. However, light interception was consistently greater in 0.25 m row spacing than 1.0 m row spacing, which they attributed to a more even leaf distribution in the narrow row spacing.

Table 5.1 Specific leaf area (SLA), leaf area index (LAI) and fractional interception of photosynthetically active radiation (FI_{PAR}) as affected by different row spacings and irrigation regimes

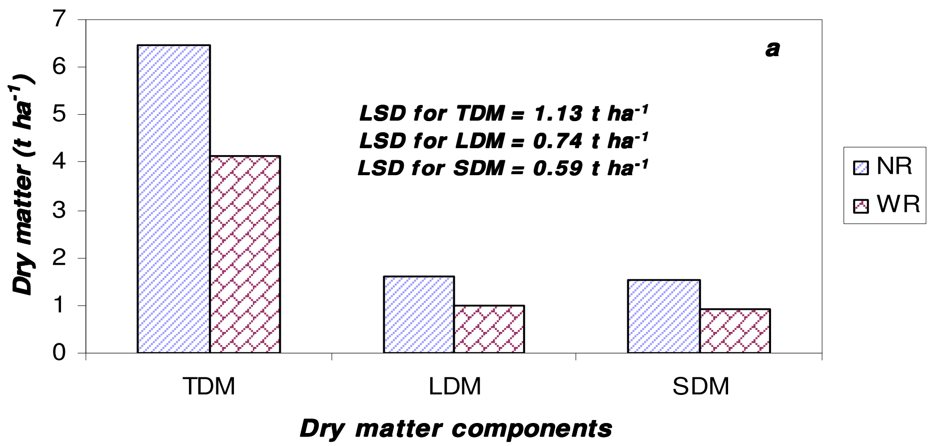
Row Spacing	Irrigation regimes	SLA (m^2 kg^{-1})	LAI (m^2 m^{-2})	FI_{PAR}
0.45 m	25D	14.98	2.63	0.86 aA
	55D	14.94	2.28	0.84 aA
	75D	15.09	1.54	0.66 aB
0.7 m	25D	14.96	1.59	0.81 aA
	55D	14.97	1.46	0.65 bB
	75D	14.98	1.39	0.60 aB
LSD	Row spacing	NS	0.30**	0.04**
	Irrigation regime	NS	0.30**	0.05**
	Row spacing x Irrigation regime	NS	NS	0.10*

Notes: 25D, 55D, & 75D: 20-25, 50-55, and 70-75 % depletion of plant available water, respectively; LSD: least significant difference ($P \leq 0.05$); NS: not significant ($P > 0.05$); *: significant at $P \leq 0.05$; * *: significant at $P \leq 0.01$. Column means within the same irrigation regime followed by the same lower case letter or column means within the same row spacing followed by the same upper case letter are not significantly different ($P>0.05$).

5.3.2 Dry matter production and partitioning

Figure 5.1 presents top (TDM), leaf (LDM) and stem (SDM) dry matter as affected by row spacings and irrigation regimes. Top dry matter and stem dry matter were significantly improved due to increasing planting density and irrigating at 25D (Figure 5.1). Leaf dry matter was significantly increased by high density planting, but it was not affected by irrigation regime. The interaction effect between row spacing and irrigation regime for top, stem and leaf dry matter was not significant.

High density planting increased top, stem and leaf dry matter on average by 56, 63, and 59 %, respectively. Similarly, irrigating at 25D increased mean top, stem and leaf dry matter by 29, 19 and 7 %, respectively compared to the 75D irrigation treatment. The 25D treatment had 1.38, 0.21, and 0.08 t ha^{-1} higher top, stem and leaf dry matter yields, respectively, relative to 75D, while the differences between 25D and 55D, and 55D and 75D were minimal.



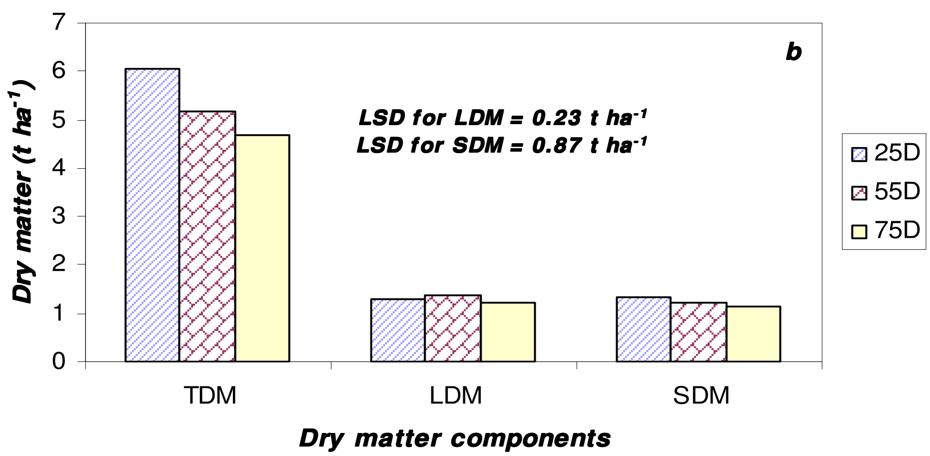


Figure 5.1 Top (TDM), leaf (LDM) and stem (SDM) dry matter as affected by row spacings (a) and irrigation regimes (b). NR: narrow row (0.45 m) and WR: wide row (0.7 m). 25D, 55D, & 75D: irrigation at 20-25, 50-55, and 70-75 % depletion of plant available water, respectively. LSD: least significant difference ($P \leq 0.05$).

Row spacing and irrigation regime effects on dry matter partitioning to different plant parts are shown in Table 5.2. High irrigation regime resulted in significant increase in the proportion of assimilate partitioned to fruit (harvest index), while it resulted in a significant decrease in the proportion of assimilate partitioned to leaves. However, assimilate partitioned to stem was not significantly affected by the irrigation regime. Neither planting density nor the interaction effect of planting density and irrigation regime markedly affected assimilate partitioning. Jolliffe & Gaye (1995) reported no significant effect on harvest index as plant population changed from 1.4 to 11.1 m^{-2} in bell pepper. Dorji *et al*. (2005) reported no significant difference in dry mass distribution among plant organs due to irrigation treatments. Irrespective of the treatments, fruits remained the major sink (Table 5.2) accounting on average for more than 49 % of the top

Table 5.2 Dry matter partitioning to fruits, leaves and stems as affected by different row spacings and irrigation regimes

Row spacing	Irrigation Regimes	Harvest Index	Leaf Fraction	Stem Fraction
0.45 m	25D	0.57	0.22	0.22
	55D	0.49	0.27	0.24
	75D	0.50	0.25	0.25
0.7 m	25D	0.58	0.20	0.22
	55D	0.53	0.25	0.22
	75D	0.48	0.29	0.23
LSD	Row spacing	NS	NS	NS
	Irrigation regime	0.05*	0.03*	NS
	Row spacing x Irrigation regime	NS	NS	NS

Notes: 25D, 55D, & 75D: 20-25, 50-55, and 70-75 % depletion of plant available water, respectively; LSD: least significant difference ($P \leq 0.05$); NS: not significant ($P>0.05$); *: significant at $P \leq 0.05$, **: significant at $P \leq 0.01$.

plant dry mass in the present study. This value is higher than the 39% reported from a split-root pot experiment with pepper (Cantore *et al*., 2000), whereas it is lower than the 56 % harvest index reported for a deficit irrigation and partial root drying pepper experiment by Dorji *et al*. (2005). The strength of stem and leaf sinks were more or less equal across all treatments (Table 5.2).

5.3.3 Yield, yield components and selected quality measures

Table 5.3 shows yield, yield components and selected quality measures as a function of row spacing and irrigation regime. Fresh and dry fruit yields at the 0.45 m row spacings were significantly higher than in 0.7 m row spacing. Irrigating at 25D also significantly increased both fresh and dry fruit yields (Table 5.3). Mean fresh and dry fruit yields increased by 66 and 51 %, respectively, by planting at 0.45 m than at 0.7 m row spacing. Similarly, a 49% increase in fresh fruit yield and a 46% increase in dry fruit yields were observed by irrigating at 25D as compared to 75D. Row spacing and irrigation regime interaction was not significant for both fresh and dry fruit yields, indicating that soil water level response did not depend on hot pepper row spacing.

Table 5.3 Fruit yield, yield components and selected quality measures of hot pepper as affected by different row spacings and irrigation regimes

Row Spacings	Irrigation Regimes	Fresh fruit yield (t ha^{-1})	Dry fruit yield (t ha^{-1})	Fruit (number $plant^{-1}$)	Average fruit dry mass (g)	Succulence
0.45 m	25D	28.02	3.77	90	0.75	7.34
	55D	21.10	3.17	83	0.69	6.88
	75D	19.34	3.13	80	0.70	6.43
0.7 m	25D	18.62	3.08	109	0.79	6.09
	55D	13.76	2.02	75	0.76	6.77
	75D	10.17	1.56	60	0.75	6.58
LSD	Row spacing	4.69**	0.41**	NS	NS	NS
	Irrigation regime	6.21*	0.54**	18.68*	NS	NS
	Row spacing x Irrigation regime	NS	NS	NS	NS	NS

Notes: 25D, 55D, & 75D: 20-25, 50-55, and 70-75 % depletion of plant available water, respectively; LSD: least significant difference ($P \leq 0.05$); NS: not significant ($P>0.05$); *: significant at $P \leq 0.05$; **: significant at $P \leq 0.01$.

Average fruit mass and fruit number per plant were not affected by row spacing. Irrigating at 25D significantly increased the number of fruit per plant, whereas average fruit mass was not affected by irrigation regime. Fruit succulence (ratio of total fresh fruit mass to total dry fruit mass) was neither affected by row spacing nor by irrigation regime. The marked improvement in dry fruit yield by irrigating at 25D is attributed to the corresponding significant increase in harvest index, fruit number per plant and top dry mass observed at high irrigation regime (Table 5.2, 5.3 and Figure 5.1). The yield increment due to narrow row spacing is mainly attributed to the increment in the plant population per unit area, as the yield from individual plants was not affected by row spacing.

Flowering and fruit development are the most sensitive developmental stages for water stress in hot pepper (Katerji *et al*., 1993). The observed marked reduction in fruit number per plant and average fruit mass, although statistically not significant, due to irrigating at 75D confirmed the sensitivity of the reproductive stages to water stress. Similarly, high floral abortion was observed due to deficit irrigation and partial root drying treatments in an experiment carried out by Dorji *et al*. (2005) showing the mechanism of fruit yield reduction due to water stress.

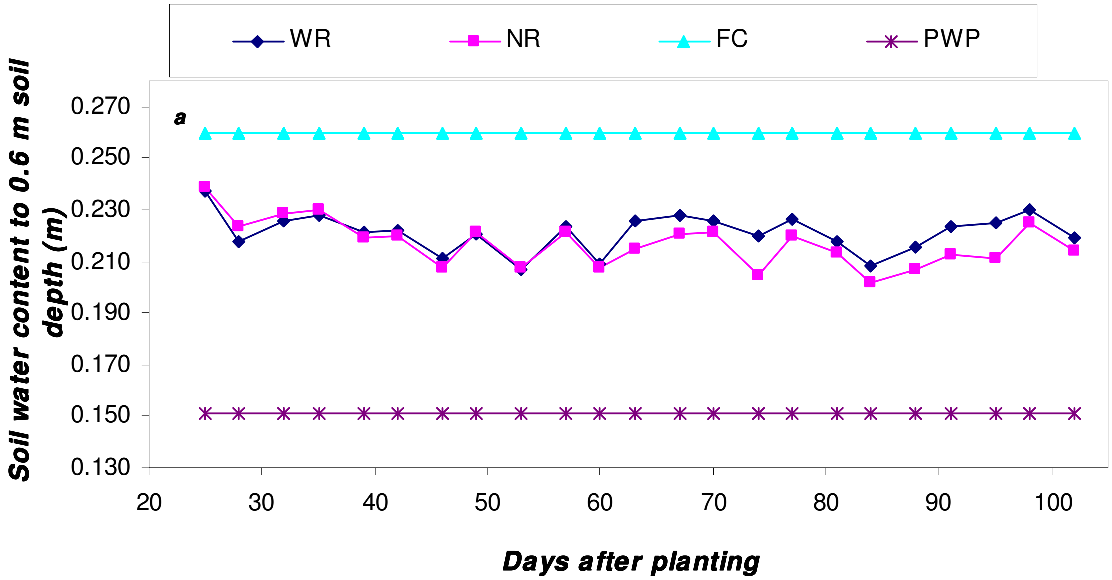
The water requirements of peppers vary between 600 to 1250 mm, depending on the region, climate and cultivar (Doorenbos & Kassam, 1979). Kang *et al*. (2001) and Dorji *et al*. (2005) reported no significant differences in yield of hot pepper between low and high irrigation regimes. Others confirmed the sensitivity of pepper to water stress and the beneficial effects of abundant irrigation. Beese *et al*. (1982) and Costa & Gianquinto (2002) observed significant yield increases with water levels above 100 % evapotranspiration, indicating that yield increases with additional water beyond the well-water control. A possible explanation is that plants supplied with full evapotranspiration requirement can actually still undergo mild undetectable stress, which prevents them from achieving highest yields (Tardieu, 1996). However, results elsewhere reported the practicality of deficit irrigation for water conservation in hot pepper (Kang *et al*., 2001; Dorji *et al*., 2005) and the importance of considering cultivar variability before adopting a deficit irrigation practice (Jaimez *et al*., 1999). Further, Pellitero *et al*. (1993) reported significantly higher total yield at 75% available soil water (ASW) in one season and at 65 to 85% ASW in another season, while no significant differences occurred between treatments in the third season. The inconsistency of results across cultivar, locations and over years confirms the variability of pepper response to irrigation regime, depending on climate, cultivar and management conditions.

5.3.4 Soil water content, water-use and water-use efficiency

Soil water content variation during the growing season is shown in Figure 5.2. Soil water content within the 0.6 m soil depth decreased gradually towards the end of the season in medium irrigated (55D) and low irrigated (75D) treatments. However, soil water remained higher in the frequently irrigated treatment (25D) (Figure 5.2a). The soil water content to 0.6 m soil depth shows relatively a slight difference for narrow row (NR) and wide row (WR) spacing during the early stage of growth (Figure 5.2b). This is because in the early growth stage, more water is lost through evaporation than transpiration, since a small canopy contributes less to the evapotranspiration (Villalobos & Fereres, 1990). However, as the season progress the size of canopy increases, hence more water is transpired by high plant density resulting in a lower soil water content under NR spacing (high plant density) than at WR spacing (low plant density).

The total water-use (irrigation plus 94 mm rainfall) and water-use efficiency (WUE) on the basis of fresh fruit, dry fruit and top dry matter yields are presented in Table 5.4. The irrigation amounts (plus 94 mm rainfall) were 539, 456, and 369 mm for 25D, 55D and 75D, respectively. The 75D treatment reduced total water consumption on average by 18 % for 55D and 46 % for 75D compared to 25D, where 539 mm of water applied. The irrigation frequency was 28, 16 and 12 times for 25D, 55D and 75D. The average irrigation interval following treatment imposition was three for 25D, seven for 55D and 10 days for 75D.

Narrow row spacing (0.45 m) significantly increased the WUE for fresh fruit, dry fruit and top dry matter. However, irrigation regime did not affect the WUE for all yield components considered. Narrow row spacing increased the WUE for the fresh fruit, dry fruit and top dry matter yields by 69, 56 and 59 %, respectively. Interaction between row spacing and irrigation regime on WUE was significant for top dry matter yield. Highest WUE (16.4 kg ha^{-1} mm^{-1}) in terms of top dry matter yield was observed for the 0.45 m row spacing for plots irrigated at 75D, while the lowest WUE (8.5 kg ha^{-1} mm^{-1}) was found under 0.7 m row spacing for plots irrigated at 55D.



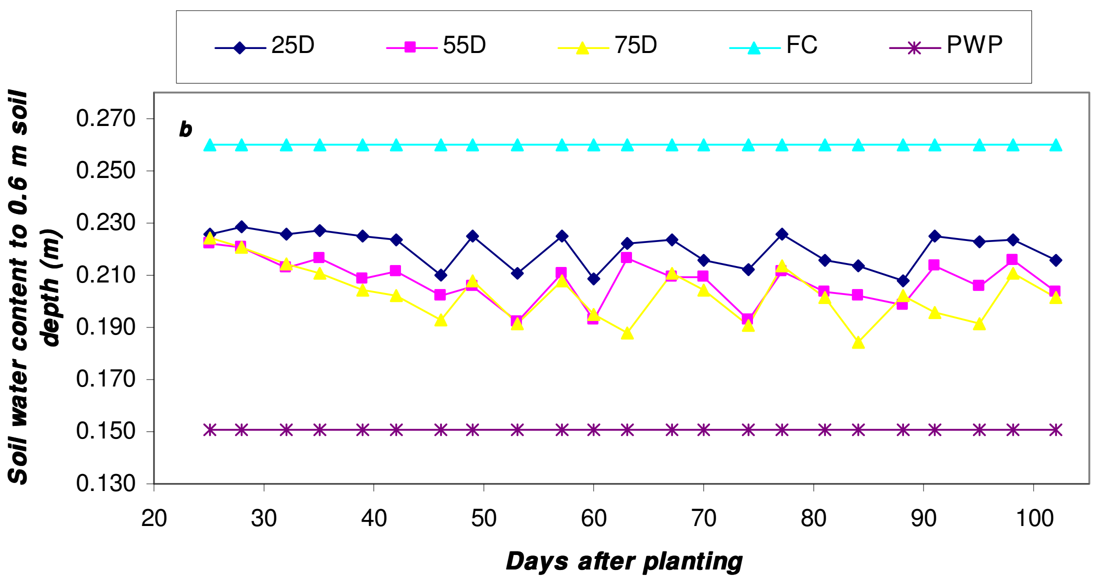


Figure 5.2 Soil water content to 0.6 m soil depth during the growing season as influenced by plant density (a) and irrigation regime (b). HD: high plant density, LD: low plant density. 25D, 55D, & 75D: 20-25, 50-55, and 70-75 % depletion of plant available water, respectively. FC: Field capacity, PWP: Permanent wilting point.

Table 5.4 Water-use and water-use efficiency (WUE) of hot pepper as affected by different row spacings and irrigation regimes

Row spacing	Irrigation Regimes	Irrigation plus Rainfall (94 mm)	WUE - fresh fruit (kg ha^{-1} mm^{-1})	WUE - dry fruit (kg ha^{-1} mm^{-1})	WUE - top dry matter (kg ha^{-1} mm^{-1})
0.45 m	25D	539	52.0	7.0	12.3 bA
	55D	456	46.3	7.0	14.2 aA
	75D	369	55.3	8.4	16.4 aA
0.7 m	25D	539	34.6	5.7	9.9 aB
	55D	456	30.2	4.4	8.5 aB
	75D	369	27.5	4.2	8.8 aB
LSD	Row spacings		10.4**	0.83**	1.31**
	Irrigation		NS	NS	NS
	Row spacings x Irrigation		NS	NS	3.74*

Notes: 25D, 55D, & 75D: 20-25, 50-55, and 70-75 % depletion of plant available water, respectively; Irrigation: irrigation regime; LSD: least significant difference ($P \leq 0.05$); NS: not significant ($P>0.05$); *: significant at $P \leq 0.05$; **: significant at $P \leq 0.01$. Column means within the same irrigation regime followed by the same lower case letter or column means within the same row spacing followed by the same upper case letter are not significantly different ($P>0.05$).

Elsewhere variable WUE results were determined for pepper as the irrigation regime changed. Kang *et al*. (2001) and Dorji *et al*. (2005) reported significant differences in WUE, while Katerji *et al*. (1993) using trickle irrigation observed no significant differences in WUE between stressed and well-irrigated treatments. In the present study, the absence in the improvement of WUE at low irrigation regime is due to the fact that top dry matter yields as well as both fresh and dry fruit yields were correspondingly reduced as the soil water deficit amount increased (Figure 5.1 & Table 5.3). Highest WUE values observed in the high plant population treatment can be attributed to the significant increase in fresh and dry fruit mass as well as top dry matter yield produced per unit area under the denser populations. Furthermore, high plant density results in lower water loss through soil evaporation, which in turn makes more water to be available for transpiration thereby increasing yield.

5.4 CONCLUSIONS

This study demonstrated that increased yield could be achieved through frequent irrigation. For maximum yield, a maximum plant available water depletion level of 20-25 % and a row spacing of 0.45 m are recommended for Long Slim hot pepper. On average, an irrigation interval of three days was practised to maintain the depletion level of plant available water between 20-25%. The WUE did not improve by low irrigation regime as the corresponding yield reduction outweighed the water-saved. The results indicated that high density planting improved growth and yield per unit area. Yield components like fruit number, average fruit mass and harvest index were unaffected by row spacing. This indicates that important yield compensation processes did not occur as the planting density decreased.

Irrespective of the row spacing used, important parameters like harvest index, leaf fraction, fresh and dry fruit yields, and fruit number were significantly affected as the irrigation regime changed, implying that these parameters are not influenced by the interaction of row spacing and irrigation regime. Therefore, to optimize resource capture and utilization by hot pepper, an optimum irrigation regime can be determined independent of the row spacing. Similarly, appropriate row spacing needs to be worked out, independent of the soil water status, provided that the level of water supply fall within the current treatment range.

Generally, this study revealed that mild to severe water stress could cause substantial yield losses in hot pepper, confirming the sensitivity of this crop to water stress. However, where the cost of fresh water is high, further research is recommended to establish irrigation regime at soil water depletion level of below 55D. Furthermore, research that seeks to quantify the trade-off between the yield loss that would be incurred because of deficit irrigation and the economic and ecological advantage that would be generated by practicing deficit irrigation is recommended.

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CHAPTER 6

FAO-TYPE CROP FACTOR DETERMINATION FOR IRRIGATION SCHEDULING OF HOT PEPPER (*Capsicum annuum* L.) CULTIVARS

Abstract

Hot pepper *(Capsicum annuum L.)* is an irrigated, high value cash crop. Irrigation requirements can be estimated following a FAO crop factor approach, using information on basal crop coefficients (Kcb), crop coefficients (Kc) and duration of crop growth stages. However, this information is lacking for hot pepper cultivars differing in growth habit and length of growing season under South African conditions. Detailed weather, soil and crop data were collected from three field trials conducted in the 2004/05 growing season. A canopy-cover based procedure was used to determine FAO Kcb values and growth periods for different growth stages. A simple soil water balance equation was used to estimate the ETc and Kc values of cultivar Long Slim. In addition, initial and maximum rooting depth and plant heights were determined. A database was generated containing Kcb and Kc values, growing period duration, rooting depth, and crop height for different hot pepper cultivars, from which the seasonal water requirements were determined. The length of different growth stages and the corresponding Kcb values were cultivar and growing condition dependent. The database can be used to estimate Kcb and Kc values for new hot pepper cultivars from canopy characteristics. The Soil Water Balance (SWB) model predicted the soil water deficits to field capacity and fractional canopy cover well, using the FAO crop factor approach.

Keywords: basal crop coefficient, crop coefficient, crop evapotranspiration, crop model, SWB model

6.1 INTRODUCTION

Hot pepper (*Capsicum annuum* L.) is a warm season, high value cash crop. Irrigation is standard practice in hot pepper production (Wein, 1998). Hot pepper cultivars exhibit considerable biodiversity: cultivars differ vastly in attributes such as growth habit, length of growing season, cultural requirements, fruit size, pigmentation and pungency (Bosland, 1992). The water requirements of peppers vary between 600 and 1250 mm per growth cycle, depending on region, climate and variety (Doorenbos & Kassam, 1979).

Various models, from simple empirical equations to complex and mechanistic models, are available to estimate plant water requirements by utilizing soil, plant, climatic and management data. Mechanistic models simulate growth and the canopy size, which enables the simulation of crop water requirements. However, such models require crop-specific growth parameters, which are not readily available for all crops and conditions (Hodges & Ritchie, 1991; Annandale *et al*., 1999).

The FAO approach was used to develop the irrigation scheduling model CROPWAT (Smith, 1992) and, in South Africa, SAPWAT (Crosby, 1996; Crosby & Crosby, 1999). Annandale *et al*. (1999) also integrated the FAO approach into the Soil Water Balance (SWB) irrigation scheduling model to simulate water requirements of crops in the absence of crop-specific growth parameters. Allen *et al*. (1998) presented an updated procedure for calculating ETo from daily climatic data, and crop evapotranspiration (ETc) from ETo and crop coefficients in the FAO 56 report. The FAO 56 report provides two such crop coefficients, a crop coefficient (Kc) and a basal crop coefficient (Kcb). The Kc is used to estimate the crop ETc, while the Kcb is used to calculate the potential transpiration.

The Kc values published in the FAO 56 report represent mean values obtained under standard growing conditions where limitations on crop growth and evapotranspiration, due to water shortage, crop density, pests or salinity, are removed. Furthermore, the Kc values reported by FAO 56 are influenced by the time interval between wetting events, magnitude of the wetting event, evaporative demand of the atmosphere, and soil type. Allen *et al*. (1998) also stressed the need to collect local data on growing seasons and rate of development of irrigated crops to make necessary adjustments to the Kc values to reflect changes in cultivars and growing conditions.

Since Kcb is a function of crop height and canopy development (Allen *et al*., 1998), its value therefore, depends on cultivar, management and climatic conditions (Jagtap & Jones, 1989; Jovanovic & Annandale, 1999). The Kc and Kcb values for only a few of the pepper cultivars grown in South Africa are available. The fact that hot pepper is an irrigated high value cash crop, with wide genetic variability within the species, necessitated the determination of Kc and Kcb values for local hot pepper cultivars, representing different growth habits and growing season lengths. Therefore, three field trials were conducted to determine the seasonal water requirements of hot pepper cultivars for the area, and to generate a database of Kc and Kcb values, growing periods, rooting depths, and crop heights for these different hot pepper cultivars. In addition to the field trials, the SWB model was run using the FAO crop factors generated for cultivar Long Slim to test the model's ability to predict soil water deficit and fractional canopy cover.

6.2 MATERIALS AND METHODS

6.2.1 Experimental site and treatments

Detailed weather, soil and crop data were collected from three field trials conducted in the 2004/2005 growing season at the Hatfield Experimental Farm, University of Pretoria, Pretoria. The site is located at latitude 25° 45' S, longitude 28° 16' E and altitude 1327 m.a.s.l., with an average annual rainfall of 670 mm (Annandale *et al*., 1999). The average annual maximum air temperature for the area is 25 °C and the average annual minimum air temperature is 12 °C. The hottest month of the year is January, with an average maximum air temperature of 29 °C, while the coldest months are June and July, with an average minimum air temperature of 5 °C.

The soil physical and chemical properties of the experimental sites are indicated in Table 6.1. Experimental procedures followed are summarized in Table 6.2. In all three experiments, a plot consisted of five 2.4 m long rows, with an intra-row spacing of 0.4 m. The two row spacing treatments utilized in both open field and rainshelter experiments were low plant density (0.7 m) and high plant density (0.45 m). The three irrigation regime treatments utilized in both open field 1 and rainshelter experiments were high irrigation (25D: irrigated to field capacity when 20-25% of plant available water was depleted from the soil), intermediate irrigation (55D: irrigated to field capacity when 50-55% of plant available water was depleted from the soil), and low irrigation (75D: irrigated to field capacity when 70-75% of plant available water was depleted from the soil). Treatments were replicated three times.

6.2.2 Crop management and measurements

Seven-week-old hot pepper seedlings of the respective cultivars were transplanted into the field. Drip irrigation was used in all three trials. Plants were irrigated for an hour (12.5 to 15.5 mm) every second day for three weeks until plants were well established. Thereafter, plants were irrigated to field capacity, every time the predetermined soil water deficit for each treatment was reached (Table 6.2). Based on soil analysis results and target yield, 150 kg ha^{-1} N and 50 kg ha^{-1} K were applied to all plots. The open field experiment also received 75 kg ha^{-1} P. The N application was split, with 50 kg ha^{-1} at planting, followed by a 100 kg ha^{-1} top dressing eight weeks after transplanting. Weeds were controlled manually. Fungal diseases were controlled using Benomyl® (1H – benzimidazole) and Bravo® (chlorothalonil) sprays, while red spider mites were controlled with Metasystox® (oxydemeton–methyl) applied at the recommended doses.

Table 6.1 Soil chemical and physical properties of experimental plots

Soil chemical properties						
Experiment	pH (H_2O)	Na (mg kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})
Open field 1, 2	6.5	29	60.5	79	572	188
Rainshelter	6.4	196	192.3	155	2340	976
Soil physical properties						
	Particle size distribution (%)				Soil water content (mm m^{-1})*	
	Coarse sand	Fine and medium sand	Silt	Clay	FC	PWP
Open field 1, 2	63.2	6.7	2.0	28.1	240	128
Rainshelter	50.8	11.5	10.7	27.0	270	151

Notes: *FC: field capacity; PWP: permanent wilting point.

Table 6.2 Treatments, experimental design and planting date of experiments

Experiment	Treatment: Factor 1	Treatment: Factor 2	Design	Date of planting	Remarks
Open field 1	3 Cultivars[a]	3 Irrigation regimes[b]	Strip plot in RCBD*	11 November 2004	Irrigation regimes to main- plots and cultivars to sub-plots
Open field 2	3 Cultivars[c]	2 Row spacings[d]	Strip plot in RCBD*	11 November 2004	Row spacings to main-plots and cultivars to sub-plots
Rainshelter[e]	3 Irrigation regimes[b]	2 Row spacings[d]	RCBD*	19 November 2004	

Notes: a: Mareko Fana, Jalapeno and Malaga; b: Irrigated to field capacity when 20-25%, 50-55 % or 70-75 % of plant available water was depleted from the soil; c: Jalapeno, Malaga and Serrano; d: 0.7 m or 0.45 m; e: cultivar Long Slim; *: RCBD = randomized complete block design.

Soil water deficit measurements were made using a model 503DR CPN Hydroprobe neutron water meter (Campbell Pacific Nuclear, California, USA). Readings were taken twice a week, at 0.2 m increments to a depth of 1.0 m, from access tubes installed in the middle of each plot (one access tube per plot) and positioned between rows.

Data on plant growth were collected at 15 to 25 day intervals. The fraction of photosynthetically active radiation (PAR) intercepted by the canopy (FI_{PAR}) was measured using a sunfleck ceptometer (Decagon Devices, Pullman, Washington, USA). PAR measurements for a plot consisted of three series of measurements conducted in rapid succession on cloudless days. A series of measurements consisted of one reference reading above and ten readings beneath the canopy, which were averaged. FI_{PAR} was then calculated as follows:

$$FI_{PAR} = 1 - \left(\frac{PAR\, below\ canopy}{PAR\ above\ canopy} \right) \quad (6.1)$$

Four plants per plot were harvested to measure leaf area using an LI 3100 belt driven leaf area meter (Li-Cor, Lincoln, Nebraska, USA). Leaf area index was calculated from the one-sided leaf area and ground area from which the samples were taken.

Total crop evapotranspiration (ETc) was estimated using the soil water balance equation,

$$ETc = I + RF + \Delta S - D - R \quad (6.2)$$

where I is irrigation, RF is precipitation, ΔS is the change in soil water storage, D is drainage and R is runoff.

Crop coefficients (Kc) were calculated as follows:

$$Kc = \frac{ETc}{ETo} \quad (6.3)$$

where ETo is grass reference evapotranspiration, estimated using the Penman-Monteith method (Allen *et al.*, 1998).

Crop potential evapotranspiration (PET) is calculated as follows:

$$PET = ETo\ Kc_{\max} \quad (6.4)$$

where Kc_{max} represents the maximum value for Kc following rain or irrigation. It is selected as the maximum of the following two expressions (Allen *et al.*, 1998):

$$Kc_{\max} = 1.2 + [0.04\,(U_2 - 2) - 0.004\,(RH_{\min} - 45)]\,(Hc/3)^{0.3} \quad (6.5)$$

or

$$Kc_{max} = Kcb + 0.05 \tag{6.6}$$

where U_2 is mean daily wind speed at 2 m height (m s^{-1}), RH_{min} is daily minimum relative humidity (%), and Hc is crop height (m).

The PET is partitioned into potential crop transpiration (PT) and potential evaporation from the soil surface (PE) (Allen *et al*., 1998):

$$PT = Kcb\ ETo \tag{6.7}$$

FI can also be estimated from PT and PET as follows (Allen *et al*., 1998):

$$FI = \frac{PT}{PET} \tag{6.8}$$

$$PE = PET - PT \tag{6.9}$$

where FI is fractional canopy cover.

Daily Kcb was calculated from FI, PET and ETo using the following equation derived from Eqs. (6.7) and (6.8).

$$Kcb = \frac{FI\ PET}{ETo} \tag{6.10}$$

The procedures described by Allen *et al*. (1998) were used to determine Kc and Kcb values for the initial, mid- and late-season stages, as well as the period of growth stages in days, for all the cultivars. The initial stage runs from planting date to approximately 10 % ground cover (FI = 0.1). The Kcb for the initial growth stage is equal to the daily calculated Kcb at FI = 0.1. Crop development extends from the end of the initial stage until FI is 90% of maximum FI ($0.9FI_{max}$) (Table 3). Allen *et al*. (1998) recommended the beginning of mid-season when the crop has attained 70 to 80% ground cover (FI = 0.7 to 0.8). Since not all cultivars and treatments attained 70% ground cover, the beginning of the mid-season was taken as the day at which FI was $0.9FI_{max}$, following Jovanovic and Annandale (1999). The mid-season stage runs from effective full cover (end of development stage) to the start of maturity. The start of maturity is assumed to be when FI decreases to the same value it had at the beginning of the mid-season stage (Jovanovic & Annandale, 1999). The mid-season stage Kc and Kcb values are equal to the average daily Kc and Kcb values during the mid-season stage. The late-season stage runs from the end of mid-season stage until the end of the growing season. The late-season stage Kc and Kcb values are equal to the average daily calculated Kc and Kcb values at the end of the growing season.

Daily weather data were collected from an automatic weather station located about 100 m from the experimental site. The automatic weather station consisted of an LI 200X pyranometer (Li-Cor, Lincoln, Nebraska, USA) to measure solar radiation, an electronic cup anemometer (MET One, Inc., USA) to measure average wind speed, an electronic tipping bucket rain gauge (RIMCO, R/TBR, Rauchfuss Instruments Division, Australia), an ES500 electronic relative humidity and temperature sensor and a CR10X data-logger (Campbell Scientific, Inc., Logan, Utah, USA).

6.2.3 The Soil Water Balance (SWB) model

The Soil Water Balance (SWB) model is a mechanistic, real-time, user-friendly, generic crop irrigation scheduling model simulating soil water balance and crop growth from crop-specific model parameters (Annandale *et al*., 1999). An FAO approach is embedded into the SWB irrigation scheduling model to simulate water requirements of crops in the absence of crop-specific model parameters. The model allows simulation of field soil water balance, soil water deficit, root depth, fractional canopy cover and crop height and performs statistical analyses to indicate the level of agreement between simulated and measured values.

The FAO based subroutine of the SWB model was run for cultivar Long Slim using FAO crop factors determined from the field experiment and weather data collected. The FAO based SWB model requires the following input parameters to run the model: basal crop coefficient values for initial, mid-season and late season stages, crop growth periods in days and total allowable depletion of soil water (%) for initial, development, mid-season and late season stages, initial and maximum rooting depth (RD) and plant height (Hc), potential yield, stress index, maximum transpiration (T_{max}), leaf water potential at T_{max} and canopy interception water storage. Furthermore date of planting, irrigation water amount and weather data are essential to run the model.

6.3 RESULTS AND DISCUSSION

6.3.1 Canopy development, root depth, leaf area index and plant height

Figure 6.1 shows measured values of canopy cover (FI) and estimated root depth (RD) during the growing season of hot pepper cultivar Long Slim under high density (0.45 m row spacing) and high irrigation (irrigation at 20-25% depletion of plant available water) treatment. RD was estimated from weekly measurements of soil water content (SWC) with the neutron meter following Jovanovic & Annandale (1999). It was assumed to be equal to the depth at which 90% of soil water depletion occurred during weekly periods.

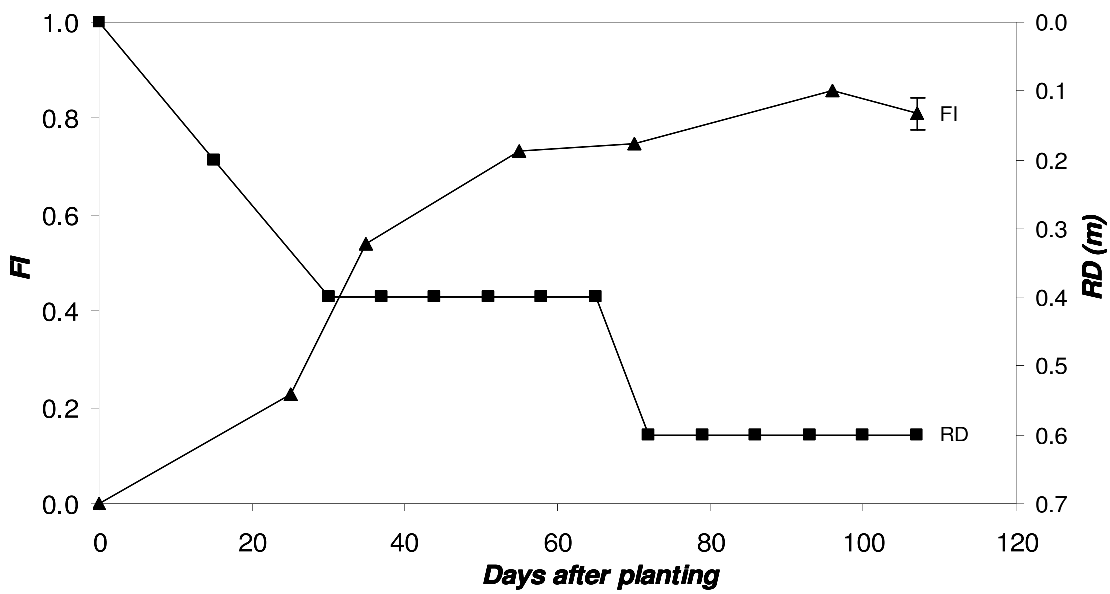


Figure 6.1 Measured values of canopy cover (FI) and estimated root depth (RD) during the growing season of hot pepper cultivar Long Slim. Vertical bar is ± 1 standard error of the measurement.

The trend in estimated RD values was in agreement with that recommended by Jovanovic & Annandale (1999). Maximum RD values estimated from SWC measurements were generally in agreement with those reported by Smith (1992) and Jovanovic & Annandale (1999).

Table 6.3 presents maximum RD, maximum crop height (Hc_{max}), 90% of maximum canopy cover ($0.9FI_{max}$), and leaf area index (LAI) at $0.9FI_{max}$ for five hot pepper cultivars. The Hc_{max} increased significantly due to a higher irrigation regime for cultivar Malaga only. Significant increases in canopy cover ($0.9FI_{max}$) were observed for Serrano in response to narrow row spacing. The higher irrigation regime (25D) significantly increased $0.9FI_{max}$ for Long Slim, Malaga and Mareko Fana, while it also significantly increased LAI at $0.9FI_{max}$ for Long Slim. As is evident from Table 6.3, there exists a very strong correspondence between LAI and FI. The measured seasonal FI values for Long Slim (Figure 6.1), and $0.9FI_{max}$ values (Table 6.3) calculated for all cultivars were greater than those reported by Jovanovic and Annandale (1999) for green and chilli peppers. The wide plant spacing of 1.0 m x 0.5 m used by Jovanovic and Annandale (1999) resulted in a low plant density, compared to the present study, which may have contributed to the low FI values reported for green and chilli peppers in their study. The Hc_{max} values reported here are also markedly greater than those reported by Jovanovic and Annandale (1999) for green and chilli peppers. The Hc_{max} for Mareko Fana and Serrano were in agreement with the value reported by Allen *et al*. (1998) for sweet pepper.

6.3.2 Basal crop coefficients and growth periods

The ETo was calculated from weather data using the FAO Penman-Monteith equation (Allen *et al*., 1998).The ETo was then used to determine potential evapotranspiration (PET) with Eqs. (6.4), (6.5) and (6.6). Daily basal crop coefficients (Kcb) were calculated from FI, PET and ETo, using Eq. (6.10), which was derived from Eqs. (6.8) and (6.9). Daily Hc was estimated by fitting a second-polynomial equation to seven measured data points of Hc as a function of days after planting for all cultivars. The selected function adequately described the relationship between daily Hc and days after planting, as the coefficient of determination was greater than 93% for all cultivars. An initial Hc of 0.05 m was taken for all cultivars, following the recommendation of Jovanovic & Annandale (1999).

Table 6.3 Maximum root depth (RD), maximum crop height (Hc_{max}), 90% of maximum canopy cover ($0.9FI_{max}$) and leaf area index (LAI) at $0.9FI_{max}$ for five hot pepper cultivars

Cultivar	Maximum RD (m)	Hc_{max} (m)	$0.9FI_{max}$	LAI (at $0.9FI_{max}$) (m^2 m^{-2})
Jalapeno (25D)	0.6	0.64a	0.56a	1.16a
Jalapeno (75D)	0.6	0.63a	0.45a	0.98a
SE		0.022	0.038	0.109
Long Slim (0.45[a] & 25D)	0.6	0.82a	0.74a	2.02a
Long Slim (0.45 [a] & 75D)	0.6	0.81a	0.68b	1.54b
SE		0.040	0.015	0.039
Malaga (25D)	0.6	0.84a	0.76a	2.24a
Malaga (75D)	0.6	0.73b	0.58b	1.91a
SE		0.031	0.024	0.200
Mareko Fana (25D)	0.6	0.71a	0.73a	1.74a
Mareko Fana (75D)	0.6	0.69a	0.56b	1.63a
SE		0.021	0.034	0.162
Serrano (0.45)[a]	0.6	0.71a	0.68a	1.34a
Serrano (0.70)[b]	0.6	0.68a	0.59b	1.25a
SE		0.019	0.015	0.105

a: 0.45- m row spacing; b: 0.7- m row spacing; 25D or 75D: Irrigated to field capacity when 20-25% or 70-75 % of plant available water was depleted, respectively. Means within the same cultivar followed by the same letter are not significant different ($P \leq 0.05$). SE: standard error.

Figure 6.2 presents values of FI and Kcb for hot pepper cultivar Long Slim under narrow row spacing and high irrigation regime. The lengths of initial, development and mid-season growth stages are also indicated in Figure 6.2. A third polynomial was fitted through seven measured data points of FI as a function of days after planting. A good fit was observed between the observed and measured FI, which is evident from the high coefficient of determination ($r^2 = 0.98$). Development stage Kcb values increased from 0.14 to a maximum of 1. The Kcb value of 1 reported for the mid-season growth stage indicates that reference evapotranspiration and potential transpiration were approximately equal during this growth stage for cultivar Long Slim. Figure 6.2 does not show the late stage due to the fact that fruits were harvested while still green and thus the experiments were terminated before plant senescence.

Table 6.4 summarizes Kcb values for initial, mid-season and late-season stages, as well as period of the stages in days for all five hot pepper cultivars. Initial Kcb values ranged from 0.12 to 0.14 and were slightly lower than the Kcb value (0.15) recommended by Allen *et al*. (1998) for sweet pepper. The Kcb values calculated for Serrano (high plant density) and Long Slim (high plant density and low irrigation, and low plant density and high irrigation) matched the Kcb value (0.13) reported by Jovanovic & Annandale (1999) for green and chilli peppers.

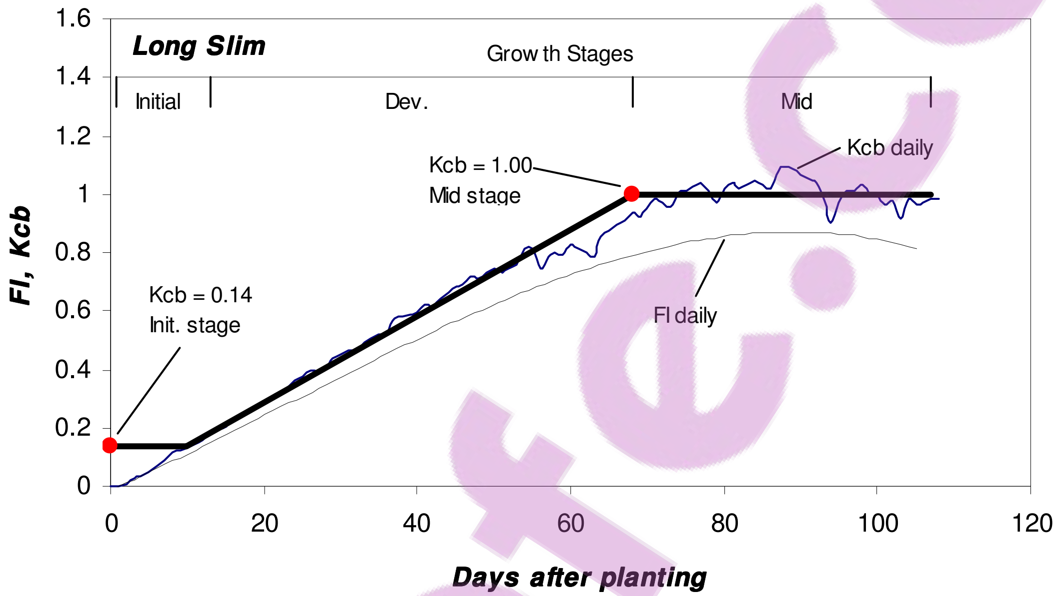


Figure 6.2 Daily values of canopy cover (FI daily) and basal crop coefficient (Kcb daily), and estimated Kcb values for three growth stages of hot pepper cultivar Long Slim under high density and high irrigation treatment (initial, crop development and mid-season stages).

The Kcb value is a reflection of plant height and plant canopy development (Allen *et al*., 1998). The Kcb value, therefore, depends on cultivar, management and climatic conditions (Jagtap & Jones, 1989; Jovanovic & Annandale, 1999). The present study indicated that management factors such as row spacing and irrigation regime, which influence canopy growth and plant height, affected the initial Kcb and period of the initial growth stage. In general, narrow row spacing and high irrigation regime increased the initial Kcb values and decreased the period of the initial growth stage. Furthermore, cultivar variation in attributes such as rate of early canopy development and plant height can influence the initial Kcb value and the period of the initial growth stage. Malaga and Jalapeno, with the lowest initial Kcb and relatively longer initial growth stage, exhibited a slow rate of both canopy growth and height increase during the early stage of growth (data not shown).

Table 6.4 Basal crop coefficients (Kcb), and growth period (initial, development, mid-season and late-season stages) for five hot pepper cultivars

Cultivar &treatment	Kcb			Growth period (days)				
	Initial	Mid	Late	Initial	Dev.	Mid	Late	Total
Jalapeno (25D)	0.12	0.72	-	16	60	30	-	106
Jalapeno (75D)	0.12	0.70	-	19	56	31	-	106
Long Slim (0.45[a] and 25D)	0.14	1.00	-	10	56	41	-	107
Long Slim (0.45[a] and 75D)	0.13	0.86	-	13	53	44	-	107
Long Slim (0.7[b] and 25D)	0.13	0.78	-	16	61	33	-	107
Malaga (25D)	0.12	0.97	0.85	20	63	40	6	129
Malaga (75D)	0.12	0.94	0.84	24	60	41	5	129
Mareko Fana (25D)	0.12	0.93	-	14	62	43	-	119
Mareko Fana (75D)	0.12	0.71	-	15	61	43	-	119
Serrano (0.45 m)[a]	0.13	0.88	-	12	66	40	-	118
Serrano (0.7 m)[b]	0.12	0.76	-	19	60	39	-	118
FAO 56 (sweet pepper)[c]	0.15	1.00	0.80	25 to 30[d]	35[d]	40[d]	20[d]	120 to 125[d]

Notes: a: 0.45 m row spacings; b: 0.7 m row spacings; c: Allen *et al*. (1998) data for sub-humid climates (RH_{min} = 45%, $U_2 \approx 2$ m s^{-1}); d: Allen *et al*. (1998) data for Europe and Mediterranean regions; 25D or 75D: Irrigated to field capacity when 20 to 25% or 70 to 75 % of plant available water was depleted, respectively.

The time between planting and effective full cover can vary with management practices, climate and cultivar (Allen *et al*., 1998). A marked difference in the time to reach effective full cover was observed between the cultivars. Long Slim under high planting density reached effective full cover on day 66 after planting, while Malaga reached effective full cover on day 83 after planting. It appears that although differences were small, high density planting and high irrigation regime tended to shorten the time between planting and effective full cover.

Mid-season Kcb values for all cultivars and treatments ranged between 0.70 and 1. Long Slim under high density planting gave a mid-season Kcb value of 1, and Malaga under both high and low planting density, and Mareko Fana under high irrigation regime gave mid-season Kcb values close to 1, which is the FAO's recommended Kcb value for sweet pepper. However, cultivars Jalapeno, Mareko Fana, Serrano and Long Slim under low irrigation regime and/or low density planting gave mid-season Kcb values lower than 0.9.

All the cultivars and treatments produced mid-season Kcb values that are markedly higher than mid-season Kcb values reported by Jovanovic & Annandale (1999) for chilli and green peppers. This is because all the cultivars included in the present study have a long growing season with prolific canopy growth compared to those cultivars used by Jovanovic & Annandale (1999). High density planting and early November planting, in the present study, also may have contributed to higher Kcb values.

In all cultivars and treatments, the duration of the development stage was longer than that of the mid-season stage, which is in agreement with results reported by Jovanovic & Annandale (1999). However, Allen *et al*. (1998) reported that the duration of the mid-season stage is longer than the development stage for sweet pepper. The variation can be attributed to the differences in criteria used to mark the end of the developmental stage. Allen *et al*. (1998) assumed the beginning of the mid-season when the crop has attained 70 to 80% ground cover (FI = 0.7 to 0.8). In the present study and that of Jovanovic & Annandale (1999), the end of the development stage was marked when the crop attained an FI value of 90% of maximum FI, since peppers did not reach FI values of 0.7 to 0.8.

No cultivar, except Malaga, reached the end of mid-season, according to the set criterion, due to the fact that fruits were harvested while green and thus the experiments were terminated before plant senescence. The late-season Kcb value Malaga was greater than 0.8, and similar to the late-season Kcb value recommended for sweet pepper by Allen *et al*. (1998). The purpose for which the produce is harvested (green pepper versus red pepper) dictates the time of harvest. This directly dictates the length of the late-season stage and hence the late season Kcb value, as Kcb values decrease linearly from the end of mid-season to the end of the late season growth stages. The present late season Kcb value is the average value for 6 days during the late season, as opposed to the Kcb value reported by Allen *et al*. (1998) which is the average value of 20 days during the late season.

New cultivars are released regularly due to market demand and the broad genetic basis of the species. This makes it important to predict FAO-type crop factors that would likely fit new cultivars. Table 6.5 and Figure 6.3 present some morphological characteristics of the five cultivars considered in the experiments. Understanding features of these cultivars and their corresponding FAO-type crop factors can aid in estimating Kcb values for newly released cultivars. Generally, cultivars with high FI, LAI and/or Hc_{max} values gave relatively greater Kcb values as compared to cultivars with relatively low FI, LAI and/or Hc_{max} values. Furthermore, high density planting and high irrigation regime appeared to increase Kcb values. Accordingly, a newly released cultivar of short to medium height and small to medium canopy size, similar to cultivars Jalapeno, Long Slim and Serrano, can have mid-season Kcb values of 0.7 to 0.9 under optimum soil water regime and/or high planting density. Similarly, cultivars with medium to tall plant height and medium to large canopy size, similar to cultivars Malaga and Mareko Fana, can be assigned a mid-season Kcb value of 0.9 to 1 under optimum soil water regime and/or high planting density. If either deficit irrigation and/or low density planting are intended, the mid-season Kcb values need to be reduced by at least 0.1. Generally, initial season Kcb values of 0.12 to 0.14 appear to be acceptable for hot pepper cultivars (depending on the initial canopy size).

Table 6.5 Some features of the hot pepper cultivars used in the experiment

Cultivar	Features		
	Stems	Leaves	Canopy structure
Jalapeno	Short, thick	Thick, medium sized, broad	Small, compact
Serrano	Thin, long with many branches	Thin, medium sized, broad	Medium, less compact
Long Slim	Thin, long with many branches	Big, pointed	Medium, less compact
Malaga	Many arising from the base	Thick, very big, broad	Large, compact
Mareko Fana	Long, thick	Thick, big, broad	Large, less compact

A

D

B

E

C

Figure 6.3 Photos of hot pepper cultivars used in the experiments. A: Jalapeno, B: Long Slim, C: Malaga, D: Mareko Fana, E: Serrano.

6.3.3 Water-use and crop coefficients

Figure 6.4 presents Kc values (sum of Kcb and soil evaporation coefficient, Ke) for cultivar Long Slim. An initial Kc value of 0.6, as recommended by Allen *et al*. (1998) for sweet pepper, was used to construct the graph, as an initial Kc value could not be calculated due to rainfall events in the first three weeks of the experiment. Drainage and runoff were assumed zero in the calculation of ETc, as the trial was conducted under a rainshelter for which irrigation amount did not exceed the measured deficit when refilling the soil profile to FC.

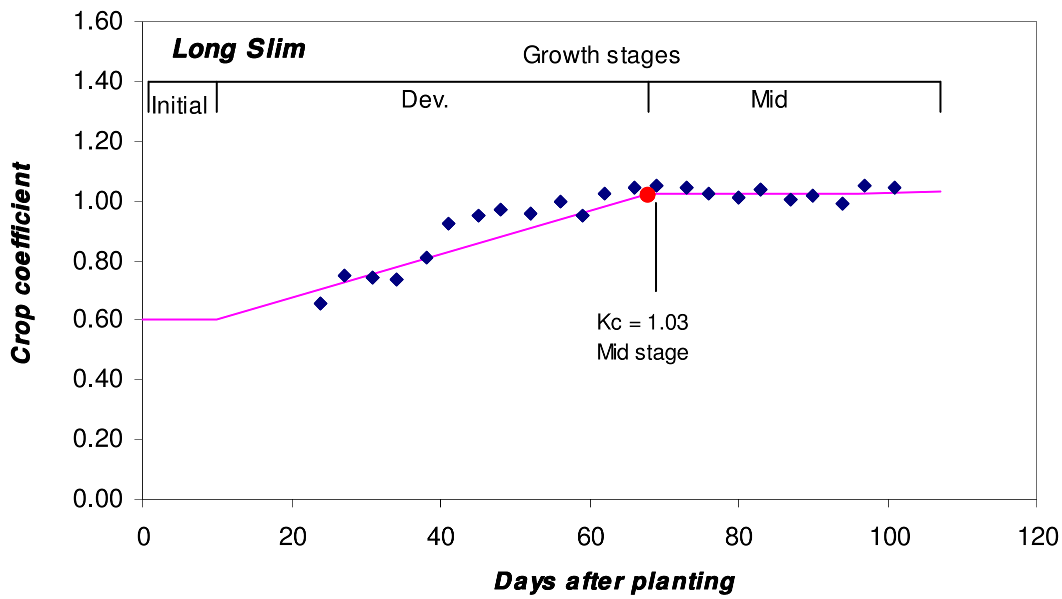


Figure 6.4 Crop coefficient (Kc) calculated for hot pepper cultivar Long Slim. Points are calculated Kc values.

Development stage Kc values increased from 0.65 to 1.05 for Long Slim. The calculated mid-stage Kc value (1.03) is slightly lower than those reported by Allen *et al*. (1998) for sweet pepper (1.05) and by Miranda *et al*. (2006) for tabasco pepper (1.08-1.22). Under standard growing conditions, Kc is a reflection of the evapotranspiration potential of a crop (Allen *et al*., 1998). Thus, the observed variation in mid-stage Kc values between this study and those reported by the above-mentioned authors can be attributed to the evapotranspiration potential difference between cultivars considered in the respective studies. Furthermore, climatic conditions under which the experiments were conducted dictate the reference evapotranspiration and evapotranspiration potential, which are the two variables determining Kc.

Table 6.6 presents the soil water storage, simulated seasonal soil evaporation (E_{sim}), crop transpiration (T_{sim}) and evapotranspiration (ET_{sim}) for various cultivars. The measured evapotranspiration (ET_{meas}) for Long Slim is also shown. These values were determined under optimum growing conditions (high irrigation, high plant density, or a combination of the two). The negative ΔS values indicate a loss in soil water storage. Evapotranspiration (ET_{meas}) was measured only for Long Slim, as this experiment was conducted in a rainshelter. Evapotranspiration for the remaining four cultivars could not be measured accurately due to high rainfall interference during the growing season. Hence, it was not possible to apply the soil water balance equation (Jovanovic & Annandale, 1999), as runoff and drainage could not be measured.

The cumulative potential evapotranspiration calculated (PET) in a given environment is a function of plant height and length of growing season (Allen *et al*., 1998). In the present study, ET_{sim} for all cultivars ranged between 390 and 546 mm. The total ET_{sim} deviated by 30 mm from the ET_{meas} for cultivar Long Slim. All evapotranspiration values reported here fall outside the range reported by Doorenbos & Kassam (1979) for pepper, which varies from 600 to 1250 mm, depending on the region, climate and cultivar. Growing conditions, climate and cultivar differences may have contributed to the observed differences between the present results and those of Doorenbos & Kassam (1979). Furthermore, water lost through drainage and canopy interception was not accounted in this study, which might have contributed to the relatively low ET values reported here. On the contrary, seasonal evapotranspiration reported by Jovanovic & Annandale (1999) were lower than those obtained in this study, as cultivars considered in the two studies differed in the total length of the growing season and canopy size.

Table 6.6 Soil water storage (ΔS), and the simulated seasonal value of evaporation from the soil surface (E_{sim}), transpiration (T_{sim}), evapotranspiration (ET_{sim}) and measured seasonal evapotranspiration (ET_{meas}) for five hot pepper cultivars

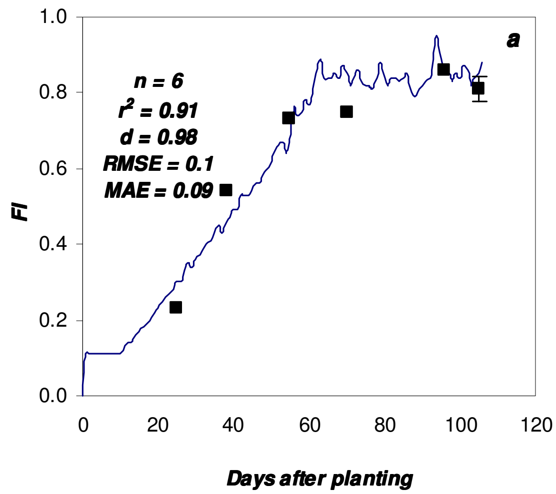
Cultivar	ΔS (mm)	E_{sim}	T_{sim}	ET_{sim}	ET_{meas}
Jalapeno	11	136	254	390	
Long Slim	-6	115	392	507	477
Malaga	4	138	408	546	
Mareko Fana	-3	139	386	525	
Serrano	-5	147	365	512	

6.3.4 Model simulation results

Figure 6.5 shows measured and simulated values of fractional interception (FI), and Figure 6.6, soil water deficit to field capacity (deficit) for cultivar Long Slim under high irrigation regime (a, calibration) and deficit irrigation (b, validation) conditions, using the new Kcb values determined for cultivar Long Slim under 25D. The SWB model calculates the following statistical parameters for testing model prediction accuracy: Willmott's (1982) index of agreement (d), the root mean square error (RMSE), mean absolute error (MAE) and coefficient of determination (r^2). According to De Jager (1994), d and r^2 values > 0.8 and MAE values < 0.2 indicate reliable model predictions. The RMSE is a generalized standard deviation, measuring the magnitude of the difference between predicted and measured values for subgroups or other effects or relationships between variables

The model predicted FI well for both high (calibration data) and deficit (validation data) irrigation treatments. However, the soil water deficit to field capacity (deficit) was predicted with less accuracy, but sufficiently well for irrigation scheduling purposes, as statistical parameters were only marginally outside the acceptable reliability criteria. The size of the canopy directly influences the rate of transpiration (Villalobos & Fereres, 1990; Steyn, 1997). In the present study, a slight overestimation of FI almost throughout the growing season was observed in both high and low irrigation conditions, which might have resulted in an overestimation of daily water usage. Maximum transpiration (T_{max})

value of 9 mm day^{-1} and leaf water potential at T_{max} (ψ_{lm}) value of -1500 J kg^{-1} were used as input parameters to run the model (Jovanovic & Annandale, 1999). The satisfactory model test results obtained for both FI and deficit simulations indicated that the chosen T_{max} and ψ_{lm} values are reasonably acceptable.



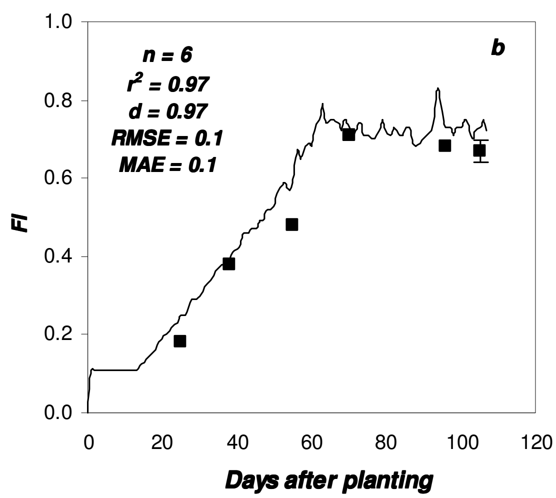


Figure 6.5 Measured (points) and simulated (lines) fractional interception (FI) during the growing season for cultivar Long Slim under high irrigation (calibration, a) and water stress conditions (validation, b). Vertical bars are ± one standard error of the measurement.

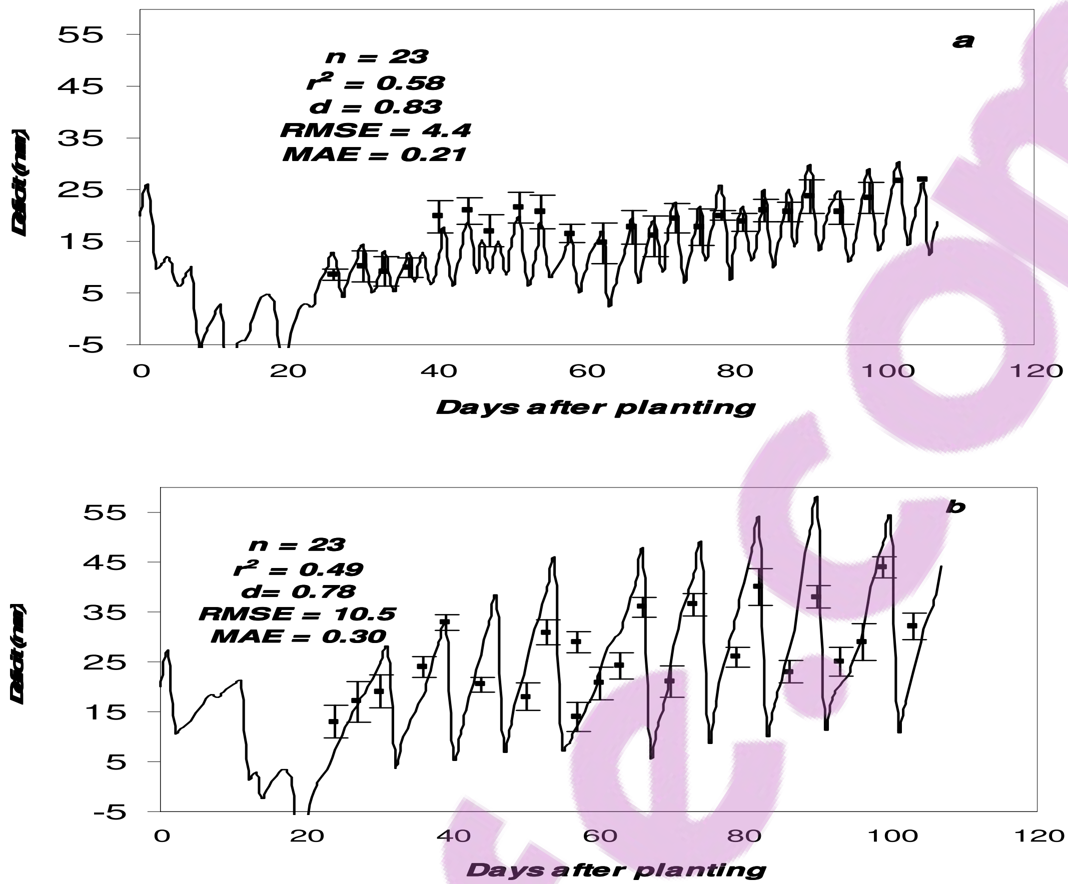


Figure 6.6 Measured (points) and simulated (lines) soil water deficit to field capacity (Deficit) during the growing season for cultivar Long Slim under high irrigation regime (calibration, a) and low irrigation regime (validation, b). Vertical bars are ± one standard error of the measurement.

6.4 CONCLUSIONS

A database of basal crop coefficients and growth periods were determined for five hot pepper cultivars, using weather data and plant parameters such as plant height and canopy cover. A simple procedure that utilizes canopy cover was followed to mark the beginning and end of the different growth stages and determine their Kcb values.

The duration of different growth stages and their corresponding Kcb values were cultivar and growing condition dependent. These results can be useful for estimating Kcb values of newly released hot pepper cultivars, based on their growth patterns. A new cultivar of short to medium height and small to medium canopy size can have a mid-season Kcb value of 0.7 to 0.8 under an optimum soil water regime and/or high planting density conditions. Similarly, cultivars of medium to tall height and medium to large canopy size can be assigned a mid-season Kcb value of 0.9 to 1 under good soil water supply conditions and/or high planting density. If either deficit irrigation and/or low density planting are intended, the mid-season Kcb values need to be reduced by at least 0.1. Generally, initial season Kcb values ranging from 0.12 to 0.14 appears to be acceptable for most hot pepper cultivars (depending on the initial canopy size).

A crop coefficient value of 1.03 for the mid-season stage and seasonal evapotranspiration of 577 mm were estimated for cultivar Long Slim. Evapotranspiration simulated across cultivars ranged from 390 to 546 mm. Simulation results showed that the simple FAO crop factor based model, which is embedded in the SWB model, could reasonably well simulate FI and the soil water deficits to field capacity.

CHAPTER 7

SWB PARAMETER DETERMINATION AND STABILITY ANALYSIS UNDER DIFFERENT IRRIGATION REGIMES AND ROW SPACINGS IN HOT PEPPER (*Capsicum annuum* L.) CULTIVARS

Abstract

Hot pepper (*Capsicum anunum* L.) is an irrigated and high value cash crop. Irrigation can be scheduled with crop models, such as SWB. Since SWB is a generic crop model, determination of crop-specific model parameters for each crop is required to schedule irrigation. Ascertaining stability of crop-specific model parameters across cultivars and different growing conditions helps to ensure transferability of parameters. The objective of this study was to determine crop-specific model parameters for five hot pepper cultivars and to analyse the stability of these parameters across the five cultivars, three irrigation regimes and two row spacings. Detailed weather, soil and crop data were collected from three field trials conducted in the 2004/05 growing season at the Hatfield Experimental Farm, University of Pretoria and used to generate a database of model parameters. These include canopy radiation extinction coefficient, radiation use efficiency, specific leaf area, leaf-stem partitioning parameter, vapour pressure-corrected dry matter/water ratio and thermal time requirements for developmental stages.

Almost all crop-specific model parameters studied appeared to remain stable under different irrigation regimes and row spacings. However, marked differences in almost all crop-specific model parameters were observed due to cultivar differences in canopy structure, size and dry matter production. Therefore, the investigated crop-specific model parameters should be transferable to simulate growth and irrigation scheduling over different irrigation regimes and row spacings within a specific cultivar. Crop-specific model parameters for new hot pepper cultivars may be estimated from this database, using canopy characteristics, day degrees to maturity and dry matter production potential.

Keywords: crop growth modelling, crop parameter, hot pepper, irrigation scheduling, SWB model

7.1 INTRODUCTION

Hot pepper (*Capsicum annuum* L.) is a warm season, high value cash crop. Irrigation is standard practice in hot pepper production (Wein, 1998). Both under- and over-irrigation can be detrimental to the profitability of crops. Under-irrigation will result in yield and quality reduction, while over-irrigation can lead to a rise in the water table, leaching of agro-chemicals to groundwater and accumulation of salt on the soil surface, which have damaging environmental impacts and waste water, energy and nutrients.

One avenue of increasing water-use efficiency and protecting the environmental against degradation is the adoption of irrigation scheduling. Various techniques and instruments are available for irrigation scheduling. Quantifying soil water or plant water status using different instruments can give an idea of how much and when to irrigate (Jones, 2004). Nevertheless, an approach that takes into account the soil-plant-atmosphere continuum in determining the water requirement of a crop is more realistic in predicting its water requirements (Annandale *et al*., 1999). Nowadays models are often utilized for this purpose.

Various models, from simple empirical equations to complex dynamic mechanistic simulators, are available to estimate plant water requirements, using soil, plant, climatic and management data (Smith, 1992; Sinclair & Seligman, 1996). Mechanistic models usually grow the canopy to simulate water requirements; however, such models require crop-specific model parameters, which are not readily available for all crops and conditions (Hodges & Ritchie, 1991; Annandale *et al*., 1999). One such model is the Soil Water Balance (SWB) model (Annandale *et al*., 1999). The SWB is a mechanistic, user-friendly, daily time step, generic crop irrigation scheduling model. It is capable of simulating yield, different growth processes, and field water balance components.

As SWB is a generic crop model, determination of crop-specific model parameters for each crop is crucial to simulate growth and schedule irrigations. Crop-specific model parameters are the reflection of a cultivar's canopy characteristics, day degrees to different phenological stages and potential dry matter production, which in turn are affected by a cultivar's genotype and growing conditions. For instance, crop-specific model parameters were shown to differ across cultivars (Kiniry *et al*., 1989; Annandale *et al*., 1999), vapour pressure deficit differences (Tanner & Sinclair, 1983; Stockle & Kiniry, 1990), irrigation frequencies (Tesfaye *et al*., 2006), row spacings (Flénet *et al*., 1996; Jovanovic *et al*., 2002) and other growing conditions (Monteith, 1994; Sinclair & Muchow, 1999).

Hot pepper cultivars exhibit considerable biodiversity: cultivars differ vastly in attributes such as growth habit, length of growing season, cultural requirements, fruit size, pigmentation and pungency (Bosland, 1992). Therefore, there is a need to determine crop-specific model parameters for a particular cultivar and to ascertain stability of these parameters under different growing conditions. The objective of this study was to determine SWB crop-specific model parameters of five hot pepper cultivars differing in growth habit and length of growing season. A further objective was to analyze stability of the parameters across five cultivars, three irrigation regimes and two row spacings.

7.2 MATERIALS AND METHODS

7.2.1 Experimental site and treatments

Details of the site and treatments are provided in paragraph 6.2.1 of Chapter 6.

7.2.2 Crop management and measurements

Seven-week-old hot pepper seedlings of the respective cultivars were transplanted into dripping laid fields. Plants were irrigated for 1 hour (12.5-15.5 mm) every other day for three weeks until plants were well established. Thereafter, plants were irrigated to field capacity, each time the predetermined soil water deficit was reached, according to the treatment. In the open field 2 experiment, the plots were irrigated to field capacity when 50-55 % of plant available water was depleted. Irrigation was scheduled using soil water deficit measurements made using a model 503DR CPN Hydroprobe neutron water meter (Campbell Pacific Nuclear, California, USA). Readings were taken twice a week, at 0.2 m increments to a depth of 1.0 m, from access tubes installed in the middle of each plot and positioned between rows.

Based on soil analysis results and target yields, 150 kg ha^{-1} N and 50 kg ha^{-1} K were applied to all experiments. The open field experiments, however, also received 75 kg ha^{-1} P. The N application was split, with 50 kg ha^{-1} applied at planting, followed by a 100 kg ha^{-1} top dressing eight weeks after transplanting. Weeds were controlled manually. Preventative spraying for fungal diseases was done using Benomyl ® (1H – benzoimidazole) and Bravo ® (chlorothalonil), while red spider mites were controlled with Metasystox ® (oxydemeton–methyl).

The fraction of photosynthetically active radiation (PAR) intercepted by the canopy (FI_{PAR}) was measured using a sunfleck ceptometer (Decagon Devices, Pullman, Washington, USA). The PAR measurements for a plot consisted of three series of measurements conducted in rapid succession on cloudless days. A series of measurements consisted of one reference reading above and ten readings beneath the canopy, which were averaged. FI_{PAR} was then calculated as follows:

$$FI_{PAR} = 1 - \left(\frac{PAR\, below\ canopy}{PAR\ above\ canopy} \right) \quad (7.1)$$

Growth analyses were carried out at 15 to 25 day intervals by harvesting four plants from each plot. The sampled plants were separated into leaves, stems and fruits. Leaf area was measured with an LI 3100 belt driven leaf area meter (Li-Cor, Lincoln, Nebraska, USA). Samples were then oven dried to a constant mass and weighed.

Daily weather data were collected from an automatic weather station located about 100 m from the experimental site. The automatic weather station consisted of an LI 200X pyranometer (Li-Cor, Lincoln, Nebraska, USA) to measure solar radiation, an electronic cup anemometer (MET One, Inc., USA) to measure average wind speed, an electronic tipping bucket rain gauge (RIMCO, R/TBR, Rauchfuss Instruments Division, Australia), an ES500 electronic relative humidity and temperature sensor and a CR10X data-logger (Campbell Scientific, Inc., Logan, Utah, USA).

7.2.3 Crop-specific model parameters determination and data analysis

Weather and growth analysis data were used to determine crop-specific model parameters. These included canopy radiation extinction coefficient, radiation use efficiency, specific leaf area, leaf-stem partitioning parameter, vapour pressure-corrected dry matter/water ratio and thermal time requirements for developmental stages (Jovanovic *et al*., 1999).

The canopy radiation extinction coefficient for PAR (K_{PAR}) was determined using a basic equation describing transmission of solar radiation through the plant canopy, which is similar to Bouguer's law (Campbell & Van Evert, 1994):

$$FI_{PAR} = 1 - \exp(-K_{PAR}\ LAI) \quad (7.2)$$

where FI_{PAR} is fractional interception of PAR, and LAI is leaf area index ($m^2\ m^{-2}$).
The light extinction coefficient for solar radiation (K_s) is used by SWB to predict radiation-limited dry matter production (Monteith, 1977) and for partitioning evapotranspiration into evaporation from the soil surface and crop transpiration (Ritchie,

1972). The K_{PAR} was converted to K_s following procedures recommended by Campbell and Van Evert (1994).

$$K_s = K_{bd}\sqrt{a_s} \quad (7.3)$$

$$K_{bd} = K_{PAR}\sqrt{a_p} \quad (7.4)$$

$$a_s = \sqrt{a_p a_n} \quad (7.5)$$

where K_{bd} is canopy radiation extinction coefficient for 'black' leaves which diffuse radiation, a_s is leaf absorptance of solar radiation, a_p is leaf absorptance of PAR, and a_n is leaf absorptance of near infrared radiation (NIR, 0.7-3 µm). The value of a_p was assumed to be 0.8, while a_n was assumed to be 0.2 (Goudriaan, 1977).

Radiation use efficiency (E_c, g MJ^{-1}) is determined based on a linear relationship established by Monteith (1977) between accumulated crop dry matter and intercepted solar radiation, which is:

$$\varepsilon DM = E_c\ \varepsilon FI_s\ R_s \quad (7.6)$$

where DM is dry matter production (g m^{-2}), FI_s is fractional interception for total solar radiation, and R_s is daily total incident solar radiation (MJ m^{-2}). FI_s was determined by using Eq. (7.2), by substituting K_s in place of K_{PAR}. The E_c was determined by fitting a linear regression equation between cumulative biomass production and cumulative R_s interception. The slope of the regression line forced through the origin represents E_c.

The leaf-stem partitioning parameter was determined as a function of SLA, LAI and CDM, by combining Eqs. (7.7) through (7.9) (Jovanovic *et al.*, 1999). The slope of the regression line represents the leaf-stem partitioning parameter in $m^2\ kg^{-1}$.

$$LDM = CDM/(1 + p\ CDM) \quad (7.7)$$

$$CDM = LDM + SDM \quad (7.8)$$

LDM is used to calculate LAI as follows:

$$LAI = SLA\ LDM \quad (7.9)$$

where LDM is leaf dry matter (kg m^{-2}), CDM is canopy dry matter (kg m^{-2}), SDM is stem dry matter (kg m^{-2}), LAI is leaf area index (m^2 m^{-2}) and SLA is the specific leaf area in m^2 kg^{-1}.

Vapour pressure deficit-corrected dry matter/water ratio (DWR) of five hot pepper cultivars was calculated following Tanner & Sinclair (1983):

$$DWR = (DM\ VPD)/PT \tag{7.10}$$

where DM (kg m^{-2}) is above-ground biomass, and was measured at harvest, whilst VPD represents the seasonal average vapour pressure deficit. Both VPD and DWR are in Pascal (Pa). PT (mm) is potential transpiration and was calculated from potential evapotranspiration and canopy cover following Allen *et al*. (1998). Daily VPD calculated from measurements of maximum air temperature (Ta_{max}), minimum air temperature (Ta_{min}), maximum relative humidity (RH_{max}) and minimum relative humidity (RH_{min}) adopting the following procedure recommended by the FAO 56 report (Allen *et al*., 1998):

$$VPD = \left(\frac{e_{sTa\max} + e_{sTa\min}}{2} \right) - e_a \tag{7.11}$$

where E_{sTamax} is saturated vapour pressure at maximum air temperature (kPa), E_{sTamin} is saturated vapour pressure at minimum air temperature (kPa) and e_a is actual vapour pressure (kPa).

Saturated vapour pressure (e_s) at maximum (Ta_{max}) and minimum air temperature (Ta_{min}) was calculated by replacing T with Ta_{max} and Ta_{min} (°C) in the following equation (Allen *et al*., 1998):

$$e_s = 0.6108 \exp\left[\frac{17.27\,T}{T + 237.3} \right] \tag{7.12}$$

e_a was calculated from measured daily Ta_{max}, Ta_{min}, RH_{max} and RH_{min} using the following equation (Allen *et al*., 1998):

$$e_a = \frac{e_s(T_{\min})\dfrac{RH_{\max}}{100} + e_s(T_{\max})\dfrac{RH_{\min}}{100}}{2} \tag{7.13}$$

Growing day degree (GDD) (d °C) was determined from daily average air temperature (T_{avg}) following Monteith (1977):

$$GDD = \left(T_{avg} - T_b\right)\Delta t \qquad (7.14)$$

where T_b is the temperature (°C) below which development is assumed to cease and Δt is the time step (one day). The T_b value recommended by Knott (1988) (11 °C) was used in this study.

The calculated crop-specific model parameters were analyzed using SAS statistically software version 9.1 (SAS, 2003) to see if there was significant statistical differences due to treatment effects. When a significant difference was observed due to a treatment, the F-test was conducted using SAS statistical software to separate means at $P = 0.05$.

7.3 RESULTS AND DISCUSSION

7.3.1 Canopy radiation extinction coefficient for PAR (K_{PAR})

The K_{PAR} is a crop-specific model parameter describing the canopy structure, and used to determine FI from LAI, using Eq. (7.2). The FI is used by the SWB model to partition potential evapotranspiration into soil evaporation and crop transpiration. The K_{PAR} can be used to calculate photosynthesis as a function of intercepted PAR. Figure 7.1 shows the fitted regression lines between the natural logarithm of transmitted PAR and LAI for five hot pepper cultivars for the intermediate irrigation treatment (irrigated when 50-55 % plant available soil water was depleted) and low plant density (row spacing of 0.7 m), to investigate K_{PAR} variability due to cultivar difference. The absolute value of the slope of the regression represents K_{PAR}.

A significant ($p \leq 0.05$) difference in K_{PAR} values was observed among some cultivars (Figure 7.1). Cultivar Serrano (0.72) and Long Slim (0.66) had a significantly ($p \leq 0.05$) greater K_{PAR} value than Malaga (0.49), which had the lowest K_{PAR} value, but no significant differences were observed among the remaining four cultivars. Calculated K_{PAR} for all five cultivars under different irrigation regimes and/or row spacings are shown in Table 7.1. The slopes of regressions were tested for similarity using the F-test. Neither row spacing nor irrigation regime had a significant ($p>0.05$) effect on K_{PAR} of the cultivars. The highest K_{PAR} value (0.86) was calculated for cultivar Long Slim under high irrigation and high plant density, while the lowest (0.49) K_{PAR} value was calculated for Malaga under intermediate irrigation and low density planting. In general, an increasing trend in K_{PAR} values was observed as irrigation regime was increased, while a decreasing trend was observed in K_{PAR} as plant density was decreased. Thus, although not significant, it appeared that high plant density and high irrigation regime tended to increase light interception efficiency.

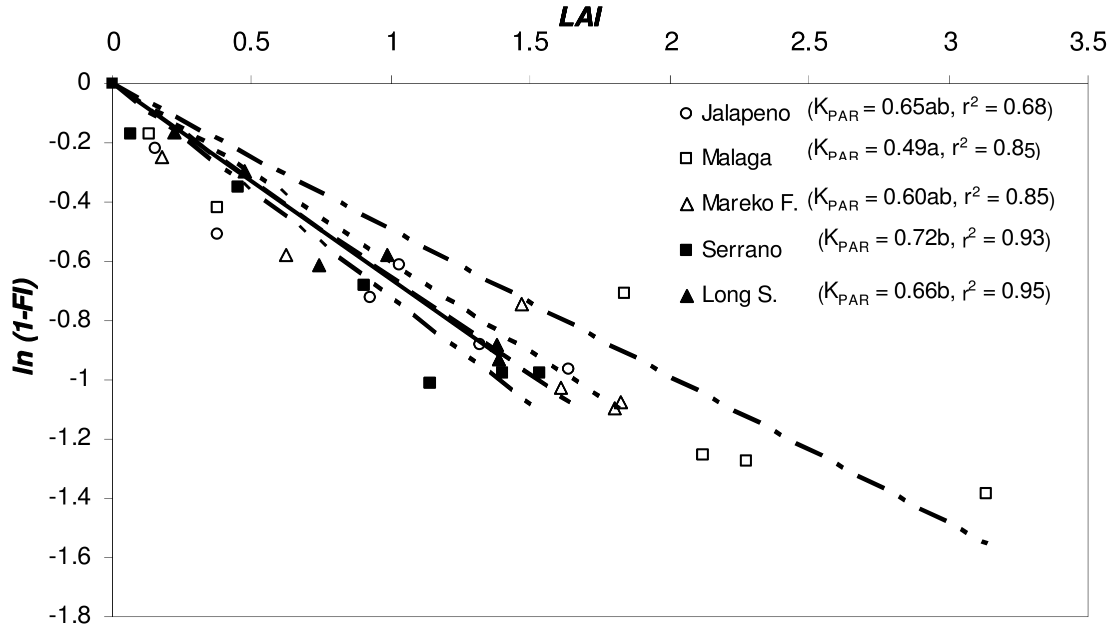


Figure 7.1 Regression between leaf area index (LAI) and natural logarithm of transmitted PAR for five hot pepper cultivars under the medium irrigation regime (55D) and 0.70 m row spacing. The slope of the regression line (K_{PAR}) and the coefficient of determination (r^2) are shown in brackets. K_{PAR} values followed by the same letter are not significantly different ($p > 0.05$).

The canopy extinction coefficient for solar radiation (K_s) is shown in Table 7.1. The K_s is used by SWB to predict radiation-limited dry matter production (Monteith, 1977) and for partitioning evapotranspiration into evaporation from the soil surface and crop transpiration (Ritchie, 1972). Eqs (7.3) to (7.5) were used to convert K_{PAR} into K_s (Campbell & Van Evert, 1994).

The high coefficient of determination (r^2) values observed for K_{PAR}, as well as the stability of this parameter over different growing conditions, indicate that this parameter is stable under various growing conditions. Hence it can be used to simulate growth of crops under various growing conditions.

Table 7.1 Test of homogeneity of regression coefficient for canopy extinction coefficients for PAR (K_{PAR}) and radiation use efficiency (E_c) for five hot pepper cultivars under different row spacing and/or irrigation frequencies

Experiment	Cultivar	Treatment	K_{PAR} (r^2)	K_s	E_c (g MJ^{-1})(r^2)
Open field 1	Jalapeno	0.70 & 25D	0.62a (0.81)	0.44	0.95a (0.89)
		0.70 & 55D	0.65a (0.68)	0.46	0.87a (0.86)
		0.70 &75D	0.57a (0.50)	0.40	0.79a (0.89)
	Malaga	0.70 & 25D	0.59a (0.90)	0.42	0.77a (0.84)
		0.70 & 55D	0.49a (0.85)	0.35	0.70a (0.90)
		0.70 & 75D	0.52a (0.70)	0.37	0.62a (0.93)
	Mareko Fana	0.70 & 25D	0.75a (0.88)	0.53	0.88a (0.94)
		0.70 & 55D	0.60a (0.85)	0.42	0.81a (0.93)
		0.70 & 75D	0.59a (0.84)	0.42	0.79a (0.90)
Open field 2	Jalapeno	0.45 & 55D	0.66a (0.84)	0.46	1.01a (0.93)
		0.70 & 55D	0.64a (0.68)	0.45	0.91a (0.79)
	Malaga	0.45 & 55D	0.57a (0.78)	0.41	0.80a (0.87)
		0.70 & 55D	0.55a (0.89)	0.39	0.69a (0.93)
	Serrano	0.45 & 55D	0.76a (0.85)	0.54	1.00a (0.90)
		0.70 & 55D	0.72a (0.93)	0.51	0.80a (0.93)
Rainshelter	Long Slim	0.45 & 25D	0.86a (0.89)	0.61	1.00a (0.96)
		0.45 & 55D	0.85a (0.71)	0.60	0.89a (0.87)
		0.45 & 75D	0.83a (0.66)	0.59	0.80a (0.89)
	Long Slim	0.70 & 25D	0.67a (0.90)	0.47	0.81a (0.96)
		0.70 & 55D	0.66a (0.95)	0.46	0.75a (0.95)
		0.70 & 75D	0.59a (0.92)	0.42	0.68a (0.96)

K_s: canopy extinction coefficients for total solar radiation; 25D, 55D & 75D: irrigated at 20-25, 50-55, and 70-75 % depletion of plant available water, respectively; 0.45: 0.45 m row spacing; 0.70: 0.70 m row spacing; column figures within the same cultivar followed by the same letter are not significantly different ($p>0.05$). Figure in brackets is coefficients of determination.

The K_{PAR} is a function of leaf size and orientation (Saeki, 1960, as cited by Tesfaye *et al.*, 2006) and can range from 0.3 to 1.3. A K_{PAR} value less than one implies non-horizontal or clumped leaf distributions, while a K_{PAR} value greater than one refers to horizontal or regular distributions (Jones, 1992). High K_{PAR} values were calculated for Serrano and Long Slim due to the fact that they tend to have full canopy cover at low LAI. For all cultivars and treatments, the K_{PAR} values calculated were < 1, indicating that the canopy structure of hot pepper tends to be non-horizontal. Crops with non-horizontal canopy structure absorb a lower fraction of the incident radiation than crops with horizontal canopy structure at low LAI (Jovanovic *et al*., 1999), suggesting that hot pepper is inefficient in radiation interception.

Canopy radiation extinction coefficient for PAR (K_{PAR}) was reported to be affected by difference in soil water (Tesfaye *et al*., 2006), row spacings (Flénet *et al*., 1996; Jovanovic *et al*., 2002) and cultivar (Kiniry *et al*., 1989). Flénet *et al*. (1996) reported a significant increment in K_{PAR} of sunflower, soybean, sorghum and maize as row spacing decreased from 1.00 to 0.35 m, indicating greater radiation interception efficiency in narrow rows. According to Flénet *et al*. (1996), this improvement in radiation interception ability of the crops was attributed to the result of a more even distribution of the plants and hence of the foliage. The lack of significant differences in K_{PAR} values in the present study was probably due to the selection of two row spacings which were not sufficiently different from each other. Furthermore, detecting the presence of significant changes in K_{PAR} due to a treatment effect may be confounded, as K_{PAR} is a coefficient of an empirical equation that models a complex phenomenon like canopy height, canopy width and leaf orientation over the course of time (Flénet *et al*., 1996).

7.3.2 Radiation use efficiency (E_c)

The E_c is a crop-specific model parameter used to calculate dry matter production under conditions of radiation-limited growth, using Eq. (7.6) (Monteith, 1977). Figure 7.2 presents DM of five hot pepper cultivars, under intermediate irrigation and low density planting, as a function of the daily cumulative product of FI and PAR. The slope of the regression line forced through the origin represents the efficiency of conversion of intercepted radiation to dry matter.

Calculated E_c for all five cultivars under different irrigation regimes and/or row spacings are shown in Table 7.1. The slopes of regressions were tested for similarity using the F-test. Both high irrigation regime (25D) and high density plantings (0.45 m) tended to increase E_c values, although their effects on E_c were not significant (P>0.05). The highest E_c value was calculated for cultivar Jalapeno (1.01 g MJ^{-1}) under medium irrigation regime and narrow row spacing, while the lowest E_c value was calculated for cultivar Malaga (0.62 g MJ^{-1}) under low irrigation regime and wide row spacing (Table 7.2).

When the cultivars that received the same treatment (medium irrigation regime, 55D and wide row spacing, 0.70 m) are compared, Jalapeno had the highest E_c value (0.87 g MJ^{-1}), followed by Mareko Fana (0.83 g MJ^{-1}) and Serrano (0.80 g MJ^{-1}) (Figure 7.2). The E_c values for Malaga (0.70 g MJ^{-1}) and Long Slim (0.75 g MJ^{-1}) were the lowest and were also significantly lower than those of Jalapeno.

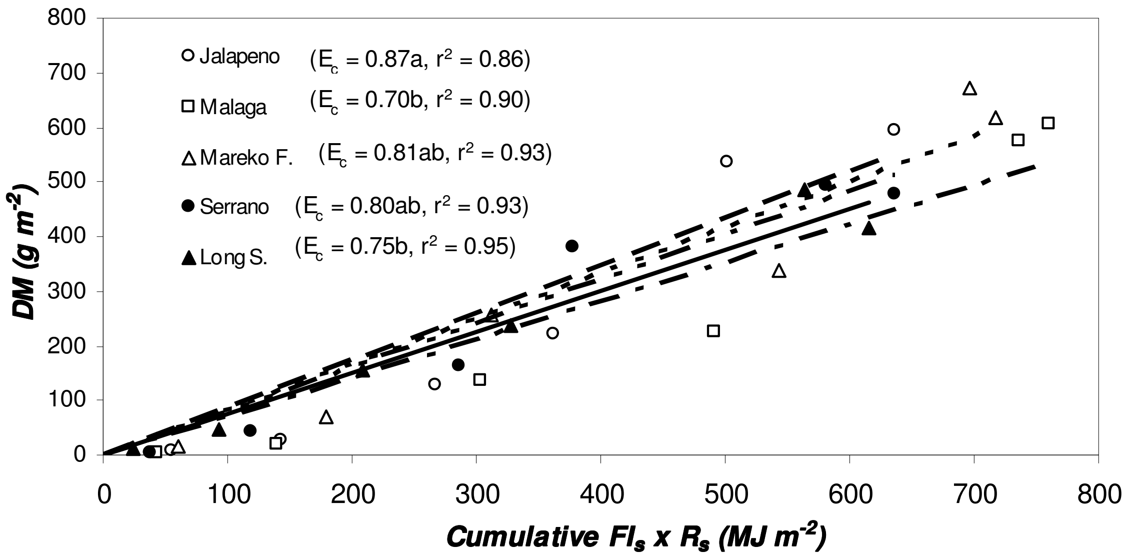


Figure 7.2 Top dry matter (DM) production of five hot pepper cultivars, under medium irrigation regime (55D) and 0.7 m row spacing, as a function of the cumulative product of fractional interception (FI) and total solar radiation (R_s). Radiation conversion efficiency (E_c) and the coefficient of determination (r^2) are shown in brackets. E_c values followed by the same letter are not significantly different (P>0.05).

The E_c value is reported to be influenced by water deficit, nutrition, pests and disease (Monteith, 1994; Sinclair & Muchow, 1999; Tesfaye *et al*. 2006). The E_c values calculated in the present study were lower than those reported by Jovanovic & Annandale (1999) for chilli pepper (1.6 g MJ^{-1}) and green pepper (1.5 g MJ^{-1}).

Table 7.2 Leaf-stem partitioning parameter (p), specific leaf area (SLA), vapour pressure deficit-corrected dry matter: water ratio (DWR) of five hot pepper cultivars

Experiment	Cultivar	Treatment	p (r^2) (m^2 kg^{-1})	SLA (m^2 kg^{-1})	DWR (Pa)
Open field 1	Jalapeno	0.70 & 25D	5.38a (0.48)	17.26a	2.77
		0.70 & 55D	4.04a (0.67)	17.07a	2.63
		0.70 &75D	7.59a (0.81)	16.92a	2.58
	Malaga	0.70 & 25D	5.44a (0.95)	21.03a	1.88
		0.70 & 55D	5.16a (0.89)	20.78a	1.76
		0.70 & 75D	5.73a (0.85)	18.98a	1.43
	Mareko Fana	0.70 & 25D	4.53a (0.97)	17.86a	2.10
		0.70 & 55D	3.60a (0.80)	17.48a	2.21
		0.70 & 75D	4.13a (0.79)	17.47a	2.04
Open field 2	Jalapeno	0.45 & 55D	3.30a (0.86)	17.42a	2.87
		0.70 & 55D	4.08a (0.87)	17.03a	2.82
	Malaga	0.45 & 55D	3.67a (0.72)	18.46a	1.95
		0.70 & 55D	5.23a (0.81)	17.93a	1.73
	Serrano	0.45 & 55D	7.82a (0.81)	19.16a	2.12
		0.70 & 55D	9.70a (0.96)	18.51a	1.75
Rainshelter	Long Slim	0.45 & 25D	2.34a (0.58)	17.78a	2.17
		0.45 & 55D	3.94a (0.81)	18.47a	2.17
		0.45 & 75D	2.97a (0.50)	17.40a	1.89
	Long Slim	0.70 & 25D	2.92a (0.62)	17.00a	2.05
		0.70 & 55D	3.71a (0.66)	16.36a	2.22
		0.70 & 75D	3.48a (0.74)	16.78a	1.84

Notes: 25D, 55D, & 75D: irrigated at 20-25, 50-55, and 70-75 % depletion of plant available water, respectively; 0.45: 0.45 m row spacing; 0.70: 0.70 m row spacing. Column figures within the same cultivar followed by the same letter are not significantly different (P>0.05). Figure in parenthesis is coefficient of determination.

In agreement with the present study, Tesfaye *et al*. (2006) reported no significant effect of water stress on the E_c values of cowpea. However, significant differences in E_c values were reported for wheat due to phenology (Garcia *et al*., 1988) and for beans and chickpea due to water stress (Tesfaye *et al*., 2006). Furthermore, Monteith (1994) and Sinclair & Muchow (1999) indicated that growing conditions such as water supply and nutrient status have an influence on E_c values.

The high coefficient of determination (r^2) of these functions and the absence of significant differences in E_c values due to irrigation regime and/or row spacings treatment suggest that E_c is a relatively stable and predictable parameter in hot peppers. However, E_c values need to be determined for individual cultivars, as a marked difference was observed across cultivars, not only in this study but also between this study and that of Jovanovic & Annandale (1999).

7.3.3 Specific leaf area and leaf-stem partitioning parameter

Table 7.2 presents the leaf-stem partitioning parameters for the five hot pepper cultivars under different irrigation regimes and/or row spacings. Figure 7.3 shows the leaf-stem partitioning parameters for the five hot pepper cultivars for the medium irrigation regime (55D) and low plant density (0.70 m) treatments.

The SLA is used by SWB to calculate LAI using Eq. (7.9).The SLA was calculated as the seasonal average of the ratio of LAI to LDM. Analysis of variance was conducted to test whether treatments significantly affected SLA values of the hot pepper cultivars. SLA values for the five cultivars under different irrigation regimes and/or row spacings are shown in Table 7.2. Table 7.3 shows the SLA values for the five hot pepper cultivars when exposed to the same treatments (medium irrigation regime and narrow row spacing).

Significant differences in the leaf-stem partitioning parameter were observed among cultivars (Figure 7.3). Cultivar Serrano had significantly higher leaf-stem partitioning parameter (9. 70 m^2 kg^{-1}) than the other four cultivars. Neither irrigation regime nor row spacing significantly affected leaf-stem partitioning parameters (Table 7.2). However, although the effect was small and not significant, wide row sapcing appeared to increase the leaf-stem partitioning parameter.

The leaf-stem partitioning parameter values calculated here were higher than those reported by Jovanovic & Annandale (1999) for chilli pepper (1.04 m^2 kg^{-1}) and green pepper (1.07 m^2 kg^{-1}). This is probably due to the low SLA and canopy dry matter values recorded by Jovanovic & Annandale (1999). Due to the fact that leaf-stem partitioning parameter is a coefficient of an empirical equation that models a complex phenomenon like leaf mass, leaf area and stem mass over the course of time, it may be difficult to detect marked differences emanating from changes in irrigation regime and/or row spacing. This is because the effect of a particular treatment may not necessarily affect all these traits in a unidirectional way and at comparable rates. The robustness of this parameter under different growing conditions confirmed the merits of using one parameter per cultivar in crop simulations.

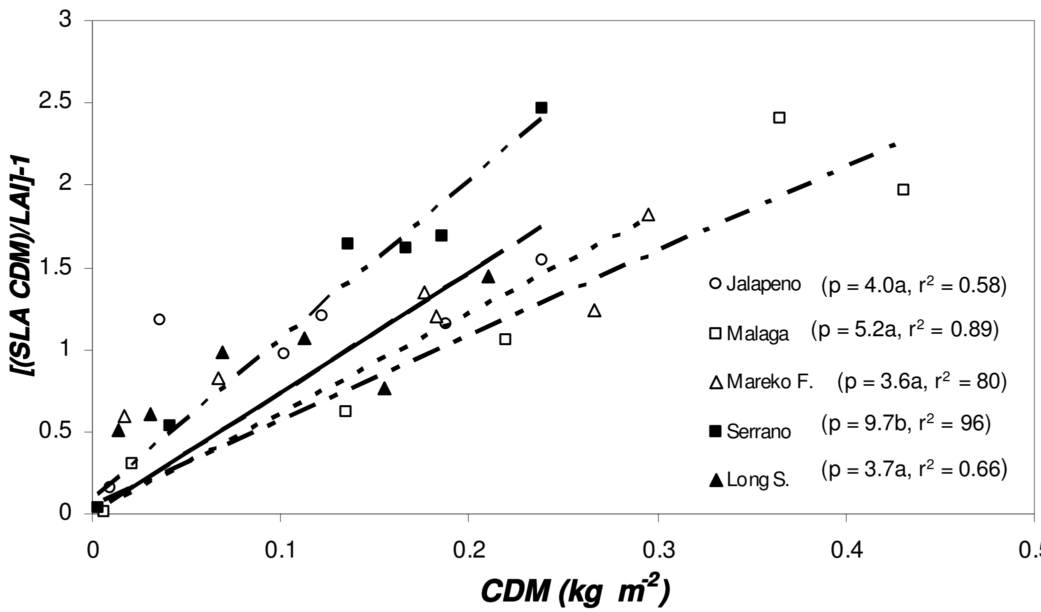


Figure 7.3 Determination of the leaf-stem dry matter partitioning parameter (p) as a function of canopy dry matter (CDM), specific leaf area (SLA) and leaf area index (LAI) for five hot pepper cultivars under medium irrigation and 0.7 m row spacing. The slope of the regression line (p, m^2 kg^{-1}) and the coefficient of determination (CD) are shown in brackets. p values followed by the same are not significantly different (P>0.05).

Significant differences in leaf-stem partitioning parameters were observed between cultivars (Figure 7.3). Cultivar Serrano had a significantly higher leaf-stem partitioning parameter (9.57 m^2 kg^{-1}) than the other four cultivars. Neither irrigation regime nor row spacing significantly affected leaf-stem partitioning parameters (Table 7.2). Furthermore, no consistent trend in leaf-stem partitioning parameter was observed as a result of changing the irrigation regime. However, although the effect was small and not significant, low density planting appeared to increase the leaf-stem partitioning parameter.

Neither irrigation regime nor row spacings significantly affected specific leaf area (SLA) (Table 7.2). Variable SLA values were observed among the cultivars (Table 7.3). Cultivar Malaga (20.78 m^2 kg^{-1}) had the higher SLA followed by Serrano (18.51 m^2 kg^{-1}), Mareko Fana (17.48 m^2 kg^{-1}), Jalapeno (17.07 m^2 kg^{-1}), and Long Slim (16.36 m^2 kg^{-1}).

SLA is shown to be a stable crop-specific parameter under different irrigation regimes and/or row spacings. Hence, the robustness of these parameters under different growing conditions confirmed the merits of using one parameter per cultivar in crop simulations. Cultivar difference in these parameters deserves important consideration as significant differences was observed due to cultivar.

Table 7.3 Specific leaf area (SLA), vapour pressure-corrected dry matter: water ratio (DWR), day degrees to 50% flowering (DDF) and maturity (DDM) for five hot pepper cultivars under 0.7 m row spacing and medium irrigation regime (55D)

Cultivar	SLA (m^2 kg^{-1})	VPD (Pa)	DWR (Pa)	DDF (d °C)	DDM (d °C)
Jalapeno	17.07	1045	2.77	450	1290
Malaga	20.78	1035	1.76	690	1530
Mareko Fana	17.48	1024	2.21	470	1330
Serrano	18.51	1045	1.75	470	1425
Long Slim	16.36	1046	2.22	570	1295

7.3.4 Vapour pressure deficit-corrected dry matter/water ratio (DWR)

Transpiration efficiency is influenced by climate, notably vapour pressure deficit (VPD) (Tanner & Sinclair, 1983). DWR is a crop-specific parameter measuring water use (transpiration) efficiency by accounting for variation in atmospheric conditions, especially for VPD. Table 7.2 shows DWR as affected by different irrigation regimes and/or row spacings. DWR values for the five hot pepper cultivars exposed to the same treatments (intermediate irrigation and low plant density) are shown in Table 7.3. Statistical analysis for DWR was not done as data are obtained for single observations. Of the cultivars, Jalapeno had the highest DWR value, followed by Mareko Fana, Long Slim, Serrano and Malaga. Generally, high irrigation regime and decreased row spacing increased the DWR.

DWR values reported for hot pepper in the present study (1.73 – 2.87 Pa) are lower than those reported by Jovanovic *et al*. (1999) for chilli (4.5 Pa) and green peppers (4.5 Pa). The probable reason for the marked difference in DWR values between the two studies is the high potential transpiration and the low E_c calculated in the present study, as compared to that of Jovanovic *et al*. (1999). This, in turn, is due to high FI and growing day degrees to maturity recorded in the present study, compared to Jovanovic *et al*. (1999). The results of the present study indicated the presence of a positive association between radiation conversion efficiency (E_c) and DWR, while DWR seemed to relate negatively with growing day degrees to maturity.

7.3.5 Thermal time requirements

Growing day degrees (GDD) for the five hot pepper cultivars to 50% flowering and maturity were determined and are presented in Table 7.3. Marked differences in GDD for both 50% flowering and maturity were observed. Cultivar Jalapeno attained both 50% flowering (450 d °C) and maturity (1290 d °C) earlier than the other cultivars, while Malaga reached 50% flowering (690 d °C) and maturity (1530 d °C) later than the other cultivars.

7.3.6 Crop-specific model parameters for newly released cultivars

The ability to predict crop-specific model parameters that would likely fit new hot pepper cultivars is imperative, as new cultivars are released regularly due to market demand and the broad genetic basis of the species. Furthermore, the time and resources required for determining crop-specific model parameters for new cultivars is usually prohibitive. Important features of the five cultivars considered in this study are shown in Table 7.4. Figure 6.3 shows photos of hot pepper cultivars used in the experiments. Accordingly, a new cultivar with near horizontal canopy structure, similar to Long Slim and Serrano will probably have K_{PAR} values between 0.60 and 0.80. On the other hand, for a cultivar with vertically oriented leaves, like Jalapeno, it seems appropriate to assign a K_{PAR} value around 0.45. In between these categories, cultivars whose canopy structure ranges between vertically oriented leaves and near horizontal leaf arrangements, similar to Malaga and Mareko Fana, may have K_{PAR} values in the range of 0.45 to 0.65.

Similarly, a new early maturing cultivar with a small canopy and medium dry matter production capacity (like Jalapeno), or with medium maturity, large canopy and with high dry matter production (like Mareko Fana) can have an E_c value >0.9 g MJ^{-1}. For new cultivars with early maturity, medium canopy size and low dry matter production (like Long Slim), or with late maturity, large canopy and medium to high dry matter production (like Malaga) it appears appropriate to assign an Ec value of around 0.70 to 0.80 g MJ^{-1}. A cultivar with medium maturity, medium canopy and with low dry matter production (like Serrano) will probably have an Ec value around 0.8 g MJ^{-1}. For Serrano and Long Slim cultivars there is a need to increase the E_c value at least by 0.2 g MJ^{-1} as row width is decreased from 0.7 m to 0.45 m.

The leaf-stem partitioning parameter for all cultivars, except Serrano ranged between 2.34 and 7.59 m^2 kg^{-1}, and therefore new cultivars that do not share Serrano's features, will probably have their leaf-stem partitioning parameters in the range of 2.34 and 7.59 m^2 kg^{-1}. A cultivar with high stem mass in relation to leaf and with medium canopy size (similar to Serrano) should be assigned a leaf-stem partitioning parameter value of around 8.5 m^2 kg^{-1}.

A cultivar with early maturity, small canopy and medium dry matter production (like Jalapeno) can have a DWR value around 2.5 Pa and above. A cultivar with medium maturity, large canopy and with high dry matter production (like Mareko Fana), or with short maturity, medium canopy and with low dry matter production (like Long Slim) can have a DWR value between 1.9 and 2.2 Pa. A cultivar with long maturity, large canopy and with high dry matter production capacity (like Malaga), or with medium maturity, medium canopy and with low dry matter production (like Serrano) should have a DWR value of around 1.8 Pa. Increasing the DWR from the reported values is necessary, as the DWR reported here represents the lower limit since underground dry matter is not included in the determination of DWR and furthermore, potential transpiration instead of actual transpiration was utilized in calculation.

Generally, understanding features of hot pepper cultivars for which crop-specific model parameters were determined can aid to estimate parameters that likely best fit new cultivars. Cultivar features such as time to maturity, canopy structure and size, and level of dry matter production are important when trying to adapt crop-specific parameters of a cultivar to new cultivars whose cultivar-specific model parameters are not yet experimentally determined.

Table 7.4 Some features of the hot pepper cultivars considered for the estimation of the SWB model parameters

Features				Range of parameter values calculated***				Example
Stems	Leaves	Canopy structure	DM* (kg ha^{-1})	K_{PAR}	E_c (g MJ^{-1})	p**(m^2 kg^{-1})	DWR (Pa)	
Short & thick	Thick, medium sized & broad	Small & compact	5944	0.38-0.47	0.88-1.02	4.04-7.59	2.5-2.9	Jalapeno
Many arising from the base	Thick, very big & broad	Large & compact	6070	0.41-0.51	0.56-0.74	5.16-5.94	1.4-2.1	Malaga
Long & thick	Thick, big & broad	Large & less compact	6721	0.45-0.65	0.94-0.97	3.60-4.13	2.0-2.2	Mareko F.
Thin & long with many branches	Thin, medium sized & broad	Medium & less compact	4782	0.67	1.05	9.70	1.75	Serrano
Thin, long with many braches	Big & pointed	Medium & less compact	4863	0.61-0.70	0.61-0.79	2.92-3.71	1.8-2.2	Long Slim

Notes: *: top dry matter determined for medium frequent irrigation and low plant density; **: leaf-stem partitioning parameter; ***: figures indicated excludes for high plant density.

7.4 CONCLUSIONS

Results of the study showed that almost all crop-specific model parameters studied appeared to remain stable under different irrigation regimes and row spacings. This is attributed to the fact that most of these crop-specific model parameters integrate more than two variables over the course of time, and therefore treatments might not affect them in similar ways and rates across all variables. However, a significant difference in almost all of the crop-specific model parameters was observed due to cultivar differences. This reflects inherent cultivar variability in their ability to capture resources (solar radiation, water) and convert these resources into dry matter. Therefore, it was concluded that the investigated crop-specific model parameters should be transferable to simulate growth and irrigation scheduling over different irrigation regimes and row spacing. However, caution must be exercised against adopting crop-specific model parameters developed for a particular cultivar for other cultivars whose crop-specific model parameters have not yet been determined.

Understanding cultivar features like time to maturity, canopy structure and size, and level of dry matter production are important when trying to adapt crop-specific model parameters of a cultivar to new cultivars whose cultivar-specific model parameters have not yet been experimentally determined.

CHAPTER 8

THERMAL TIME REQUIREMENTS FOR THE DEVELOPMENT OF HOT PEPPER (C*apsicum annuum* L.)

Abstract

Pant development is sensitive to temperature and understanding temperature response function helps to model growth using cardinal temperatures. The objective of this investigation was to quantify temperature response functions of various developmental stages of two hot pepper cultivars (Jalapeno and Mareko Fana). Cardinal temperatures, namely the base (T_b), optimum (T_m) and cut-off temperature (T_x) for various developmental stages were also determined. Jalapeno and Mareko Fana were investigated in four growth cabinets; each at constant temperature, ranging from 10 to 32.5 °C, in steps of 7.5 °C. Results from the growth cabinet study were evaluated using independent field data collected from field experiments. A T_b of 8.5 °C, T_m of 24 °C and T_x of 36 °C describe germination of the cultivar Jalapeno. A T_b of 13.5 °C, T_m of 22 °C and T_x of 40 °C describe post-germination developmental stages of Jalapeno. A T_b of 12.5 °C, T_m of 21.5 °C and T_x of 35 °C describe post-germination developmental stages of Mareko Fana. Thermal time requirements from transplanting to flowering ranged from 198 °C d to 280 °C d and from transplanting to maturity ranged from 799 °C d to 913 °C d for the two cultivars in the growth cabinet and open field studies.

Keywords: cardinal temperatures, germination, hot pepper, germination, thermal time

8.1 INTRODUCTION

Temperature, solar radiation, water and nutrients are the most important abiotic variables that affect plant growth and development and the quantification of their effects on plants form the basis of simulation models of crop production (Atkinson & Porter, 1996). However, distinction needs to be made between the effects of these variables on growth and development as these two processes involve different aspects of plant processes. According to Atkinson & Porter (1996), growth is defined as an irreversible increase in dry matter, resulting from the maintenance of disequilibrium between the accumulation and the loss of environmental resources. On the other hand, developmental processes are recognized either via changes in number of plant organs, or via the time taken for particular morphological events, such as flowering to occur.

Growth is more affected by total radiation received, rather than temperature (Monteith, 1977), whereas plant development is sensitive to temperature (Monteith, 1981; Hodges, 1991). Temperature increment or decrement even for a few degrees usually leads to a remarkable change in developmental changes in plants. The effect of temperature on plant development rate is often described by using the thermal time, or 'heat unit' concept. Particularly in the area of crop phenology and development, the concept of heat units, measured in growing-degree-days (GDD, °C-day), has vastly improved description and prediction of phenological events compared to other approaches such as time of the year or number of days (Russelle, *et al*. 1984; McMaster & Smika, 1988; McMaster & Wilhelm. 1997). Consequently, the thermal time concept is getting wider application in crop modelling. One widely used thermal time quantification approach is the one which relates developmental rate (DR) linearly to temperature above a crop or cultivar specific base temperature, at or below which the developmental rate remains zero (Tollenaar *et al*., 1979), plus in some applications with addition of maximum temperature above which DR remains constant (Hodges, 1991). Gilmore & Rogers (1958) as cited by Yin *et al*. (1995) presented a bilinear model that included a reversal linear function to account for the declining DR at temperatures higher than optimum temperature when describing the elongation of maize seedlings in relation to temperature. Yin *et al*. (1995) used a beta function to describe the relationship between temperatures and DR. In spite of the variation in the mathematical models used to describe the relationship between DR and temperature, most models recognize three sets of temperatures which are: base temperature, maximum temperature and optimum temperature in describing the DR-temperature models. At base and maximum temperatures growth is assumed to stop, whereas at optimum temperature developmental rate proceeds at its maximum rate. These temperatures are known as cardinal temperatures and are important in the calculation of thermal time (GDD) (Campbell & Norman, 1998).

The fact that from germination to fruit setting and maturity, plants require different temperature regimes necessitates quantification of the response of the hot pepper developmental stages to different temperatures. Furthermore, the wide genotypic variations within the hot pepper species (Bosland, 1992) make it important to determine the cardinal temperatures for a particular cultivar. Knowledge about hot pepper response to different regimes of temperature for different growth stages and identification of the cardinal temperatures would help to improve modelling this crop's development. Thus, growth cabinet and field experiments were conducted with the following objectives:

1. to determine cardinal temperatures for various developmental stages germination, emergence, vegetative, flowering, and fruit maturity) of hot pepper,
2. to quantify the thermal time requirements for these developmental stages, and
3. to validate the growth chamber results with an independent data set from field experiments.

8.2 MATERIALS AND METHODS

Growth cabinets and field trials were carried out in this study. In the growth cabinet studies, the cardinal temperatures for germination and subsequent developmental stages were estimated, which were then used to calculate thermal time requirements. A comparison was then made between thermal time requirements determined in the growth cabinets at constant temperature and those observed in the field trials under fluctuating temperatures.

8.2.1 Germination study

The study was conducted at the Hatfield Experimental Farm of the University of Pretoria, Pretoria, under controlled conditions from April 7 to May 15, 2006. Hot pepper cultivar Jalapeno was used in the study. Seeds were germinated in Petri dishes lined with filter paper at four different constant temperatures, ranging from 10 to 32.5 °C in a growth cabinet; in steps of 7.5 °C. The filter paper was first soaked in distilled water and then 100 seeds were spread on the filter paper. Treatments were replicated three times. Daily inspection was made to note germination progress. Water was applied daily. Germination was defined as the protrusion of the radicle through the testa by more than 5 mm. The average results of the cultivar from the three replicates were plotted against time to obtain a germination progression curve. From these curves, the time taken to reach certain cumulative germination percentages could be determined through interpolation.

8.2.2 Developmental stage experiments

The study was conducted at the Hatfield Experimental Farm the University of Pretoria, Pretoria, under controlled conditions from 5 October 2005 to 10 May 2006. Four growth cabinets and two cultivars (Mareko Fana and Jalapeno) were used to quantify response in rates of development to temperature changes. The former cultivar is a cultivar that grows widely in Ethiopia and the latter one is from South Africa. Both cultivars were grown in four cabinets, each at constant temperature, ranging from 10 to 32.5 °C, in steps of 7.5 °C. Later, Mareko Fana was grown at 29 °C in a separate growth cabinet due to the failure of the crop to flower at 32.5 °C. Photoperiod was maintained at 13 hrs (quantitative short day plant) for all treatments (Demers & Gosselin, 2002).

Six-week-old hot pepper seedlings of the respective cultivars were transplanted into a growth medium consisting of a fine river sand and vermiculite mixture (1:1 v/v), in 3 litre pots. Twenty pots per cultivar were placed in each growth cabinet. Two seedlings were planted per pot and later thinned to one plant after the seedlings survived the transplanting shock. Pots were watered daily with a complete nutrient solution and excess nutrient solution was allowed to drain freely through openings at the bottom of the pots. Shuffling of the pots in a cabinet was done weekly to limit the effect of uneven air and light distribution within the cabinets.

For the emergence study, 50 seeds of each cultivar were sown in seedling trays at the temperatures specified above. Daily inspection was made to note emergence progress. Water was applied daily. Emergence was defined as the protrusion of the plumule (cotyledon) through the soil surface by more than 5 mm. The average results of the cultivar from the two replicates were plotted against time to obtain an emergence progression curve. A specific growth stage was reached when 50% of the seeds in seedling trays or plants in growth cabinets achieved the developmental stage being considered (emergence, leaf number, flowering or maturity).

8.2.3 Field experiment

An independent data set from a field study conducted at the University of Pretoria, Hatfield Experimental Farm during the 2004/05 growing season was used to validate results of the growth chamber studies.

8.2.4 Data collection and analysis

8.2.4.1 Cardinal temperature determination

Cardinal temperatures for germination, emergence, vegetative stage, flowering, and maturity were determined by fitting linear functions to temperature and developmental rate data. Base temperature and maximum temperatures were taken as the lower and higher temperature values when the development rate becomes zero. The temperature where development rate reached a maximum was assumed to be the optimal. The rate of development was calculated as the reciprocal of the time needed for the completion of a particular developmental stage concerned.

8.2.4.2 Thermal time determination

Using cardinal temperatures as input, the thermal time (τ) for different temperatures was determined both for plants grown under growth cabinet and field conditions, using the following equations (Monteith, 1977; Campbell & Norman, 1998, Olivier & Annandale, 1998):

$$\tau = 0 \quad T_b > \bar{T} > T_x \qquad (8.1)$$

$$\tau = \left(\bar{T} - T_b\right)\Delta t \quad T_b < \bar{T} < T_m \qquad (8.2)$$

$$\tau = \left[\frac{\left(T_x - \bar{T}\right)\left(T_m - T_b\right)}{\left(T_x - T_m\right)}\right]\Delta t \quad T_m < \bar{T} < T_x \qquad (8.3)$$

Where $\bar{T}$ is the average of the daily maximum and minimum temperatures when the increment Δt is taken as 1 day, T_b is base temperature, T_m is the optimum temperature and T_x the maximum temperature. Below T_b and above T_x, no thermal time will be accumulated and it is assumed that no development takes place (Eq. (8.1)). According to Eq. (8.2), thermal time increases linearly between T_b and T_m. Between T_m and T_x thermal time decreases linearly (Eq. (8.3)).

8.3 RESULTS AND DISCUSSION

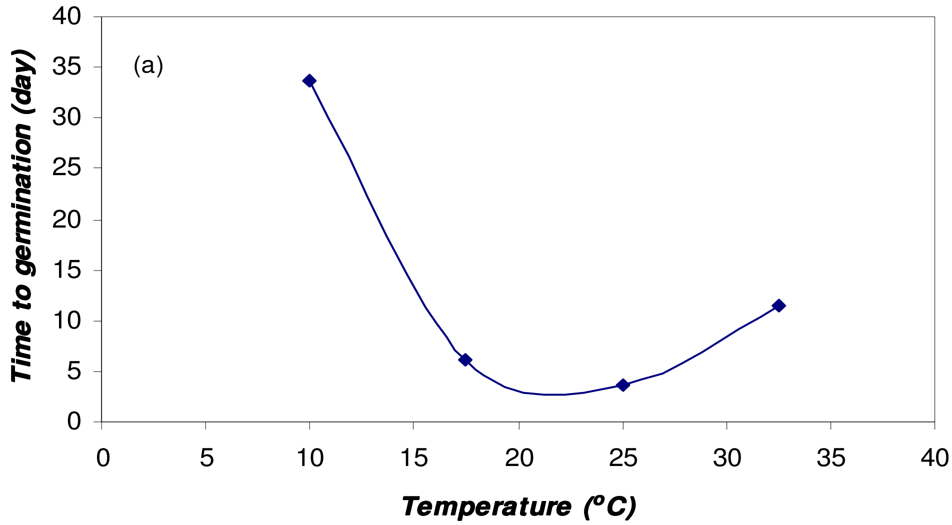
8.3.1 Germination

Figure 8.1a illustrates the time taken to reach 50% germination of the cultivar Jalapeno at four constant temperatures. Developmental rate was shortest at air temperature between 17.5 °C and 25 °C. The 'U' shape of this curve is typical of the temperature reaction of many developmental processes (Wagner *et al*., 1987).

The reciprocal of the time needed for the completion of a developmental process corresponds to the rate of development (Figure 8.1b). A mathematical equation describing the rate and temperature relationships needs to be selected to determine the cardinal temperatures from the few data points generated under controlled conditions (constant air temperatures). Olivier and Annandale (1998) and Ali-Ahmadi & Kafi (2007) working on pea and kochia, respectively, demonstrated the applicability of linear regressed equations in describing temperature effect on germination rate. Thus, for the present study linear regression lines were fitted to determine the cardinal temperature for germination.

Visual observation of Figure 8.1b indicates that the optimum temperature lies somewhere between 17.5 °C and 25 °C. A straight line was fitted through the points below the optimum temperature and extrapolated to the x-axis where developmental rate is zero, to determine base temperature. Similarly, a line through points above the optimum temperature was extrapolated to determine maximum temperature.

In both cases, T_b (< 10 °C) and maximum temperature (>32.5 °C) were varied by 0.5 °C until the standard error estimate of y (50% germination rate) was minimized. The intersection of the two regression lines, which is determined by simultaneous equation solving procedure, provides estimates of the maximum developmental rate and optimum temperature (Summerfield *et al*., 1991; Olivier & Annandale, 1998).



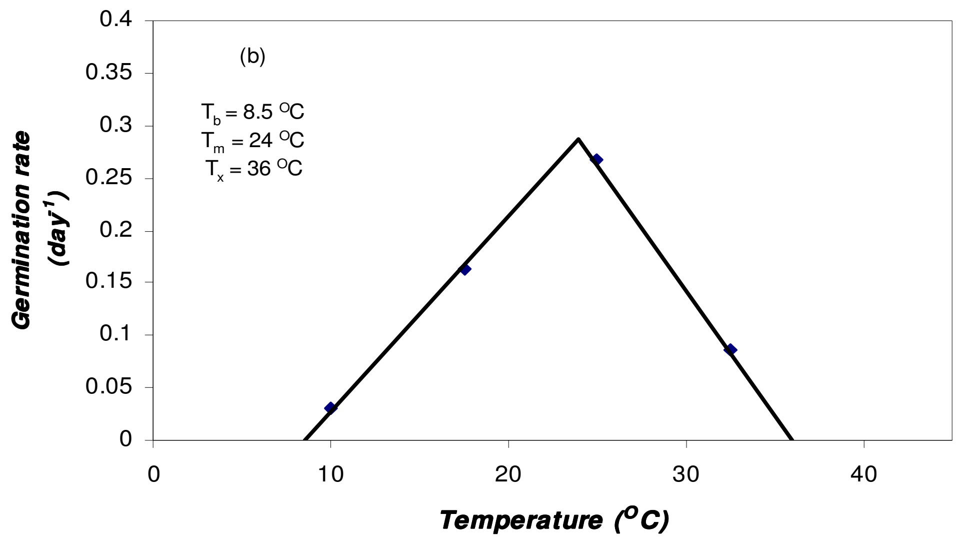


Figure 8.1 Temperature response of time for 50% germination for the cultivar Jalapeno (a), determination of the cardinal temperatures for 50% germination for the cultivar Jalapeno (b).

Accordingly, a base temperature of 8.5 °C, an optimum temperature of 24 °C and a maximum temperature of 36 °C were found to describe the relationship between temperature and germination rate in hot pepper cultivar Jalapeno. The same values may be utilized for other cultivars that are early to medium maturing, with fruit size ranging from small to medium and with relatively intermediate leaf growth habit, provided that no other guidelines are available.

Thermal time requirements for 50% germination of Jalapeno seed, at constant temperatures, were calculated using the estimated cardinal temperatures and Eqs. (8.1)-(8.3). Results for the cultivar Jalapeno are presented in Figure 8.2. The thermal time requirements for 50% germination for Jalapeno varied between 51 and 62 day degrees when calculated for four different constant air temperatures using cardinal temperatures determined in the study.

The small variation in thermal time expressed by the low coefficient of variation (CV =2.4%) and standard error estimate (SE = 1.9 °C d) revealed that a linear thermal time expression can be used to model seed germination of hot pepper cultivar Jalapeno. An average day degree value of 56 appeared reasonably acceptable to use as thermal time requirements for 50% germination for the cultivar Jalapeno and other cultivars that are early to medium maturing, with fruit size ranging from small to medium and with relatively intermediate leaf growth habit in the absence of other research results.

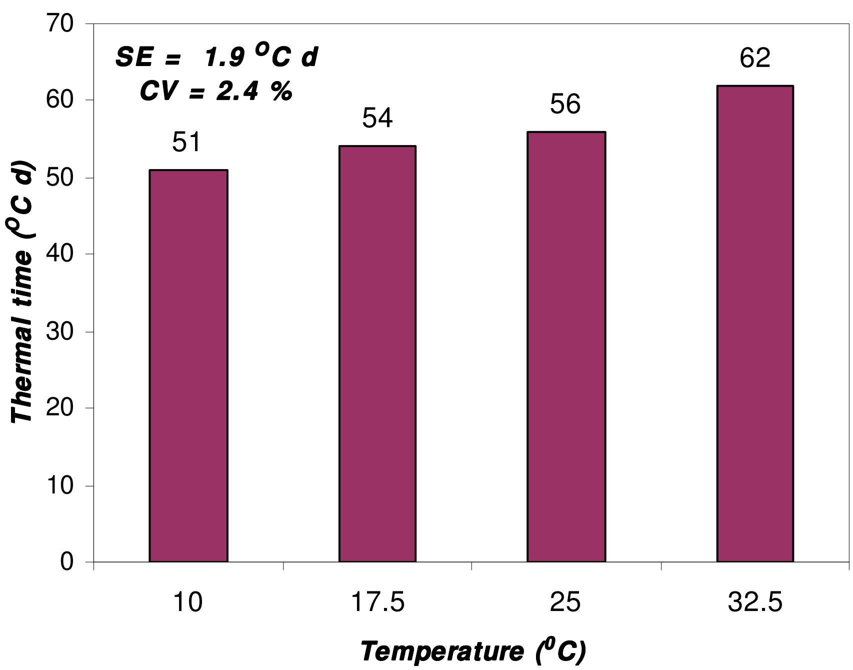


Figure 8.2 Thermal time requirement for 50% germination, calculated at four constant temperatures for the cultivar Jalapeno.

8.3.2 Developmental stages

Figures 8.3a and 8.3b show the time required from sowing to reach various developmental stages for the cultivars Jalapeno and Mareko Fana, respectively. Different authors used different mathematical expressions to quantify temperature effect on rates of different developmental stages. Various mathematical expressions are used depending on the variability of species, temperature regimes or process being simulated. Omanga *et al*. (1995) and Olivier & Annandale (1998) used bilinear equations to describe the response of pigeon pea and pea crop developmental rate to temperature, respectively, while Yin *et al*. (1995) using cassava, maize and rice, suggested asymmetric functions (the Beta function) to describe developmental rate and temperature relationship. Wagner *et al*. (1987) employed exponential functions to describe relationships between developmental rate of insects and temperature. In the present study, owing to the limited data points (3 pairs of data points in most cases) two linear regression lines were fitted to determine the cardinal temperatures for developmental stages (Figures 8.4a and 8.4b).

In order to simplify the description and prediction of phenological events and modelling of hot pepper, an effort was made to determine a single set of cardinal temperatures describing the different developmental stages. Visual observation does not give much clue as to the optimum temperature range due to the limited data points (Figures 8.3a and 8.3b). However, from the relationship between temperature and rates of germination (Figure 8.1a) and emergence (8.3a), it could be assumed, with a reasonable degree of accuracy, that the optimum temperature falls between 17.5 and 25 °C. Furthermore, the extremely low rate of flowering observed at the extreme high temperatures suggests that optimum temperature for the same process falls between 17.5 and 25 °C and not between 25 and 29°C (in Mareko Fana) or 25 and 32.5 °C (in Jalapeno). Thus, two temperatures, i.e., 25 and 32.5 °C in Jalapeno and 25 and 29 °C in Mareko Fana were used to estimate maximum temperature.

Developmental rate is zero at a maximum temperature, so by arbitrarily selecting a maximum temperature above 32.5 °C for Jalapeno and 29 °C for Mareko Fana, three points were available for the linear regression lines between 25 °C and maximum temperature. The standard error of the y estimates of the regression lines for the respective developmental stages were summed to get an indication of total error. This was done for several maximum temperatures in 0.5 °C increments until the error was minimized (Olivier & Annandale, 1998). This occurred at a maximum temperature of 40 °C for Jalapeno and 35 °C for Mareko Fana (Figures 8.4a and 8.4b). These values are markedly higher than the 26.6 °C, which is the maximum temperature reported in literature for hot pepper (Knot, 1988).

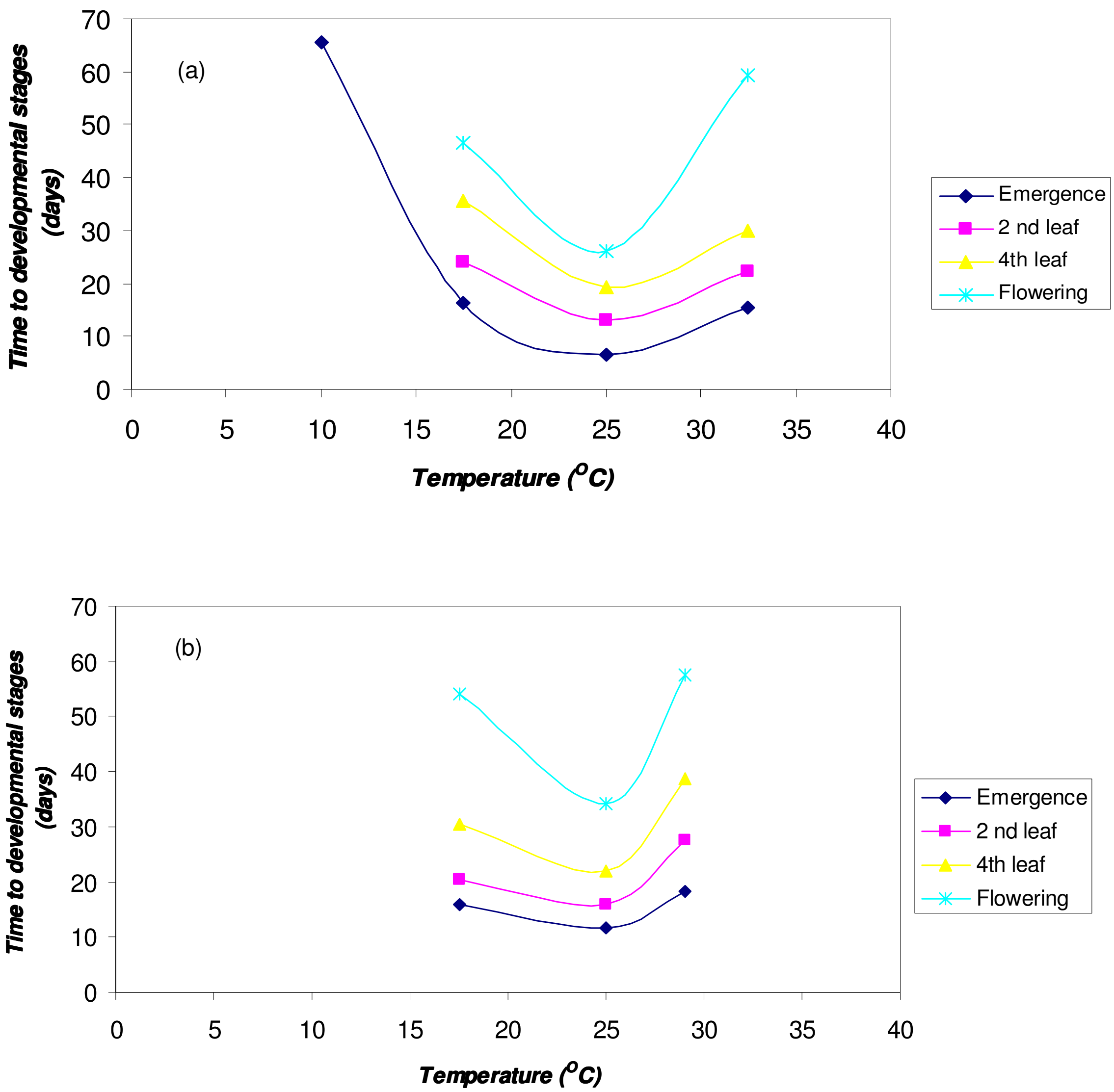


Figure 8.3 Temperature response of time from sowing/transplanting to developmental stages for the cultivar Jalapeno (a) and Mareko Fana (b).

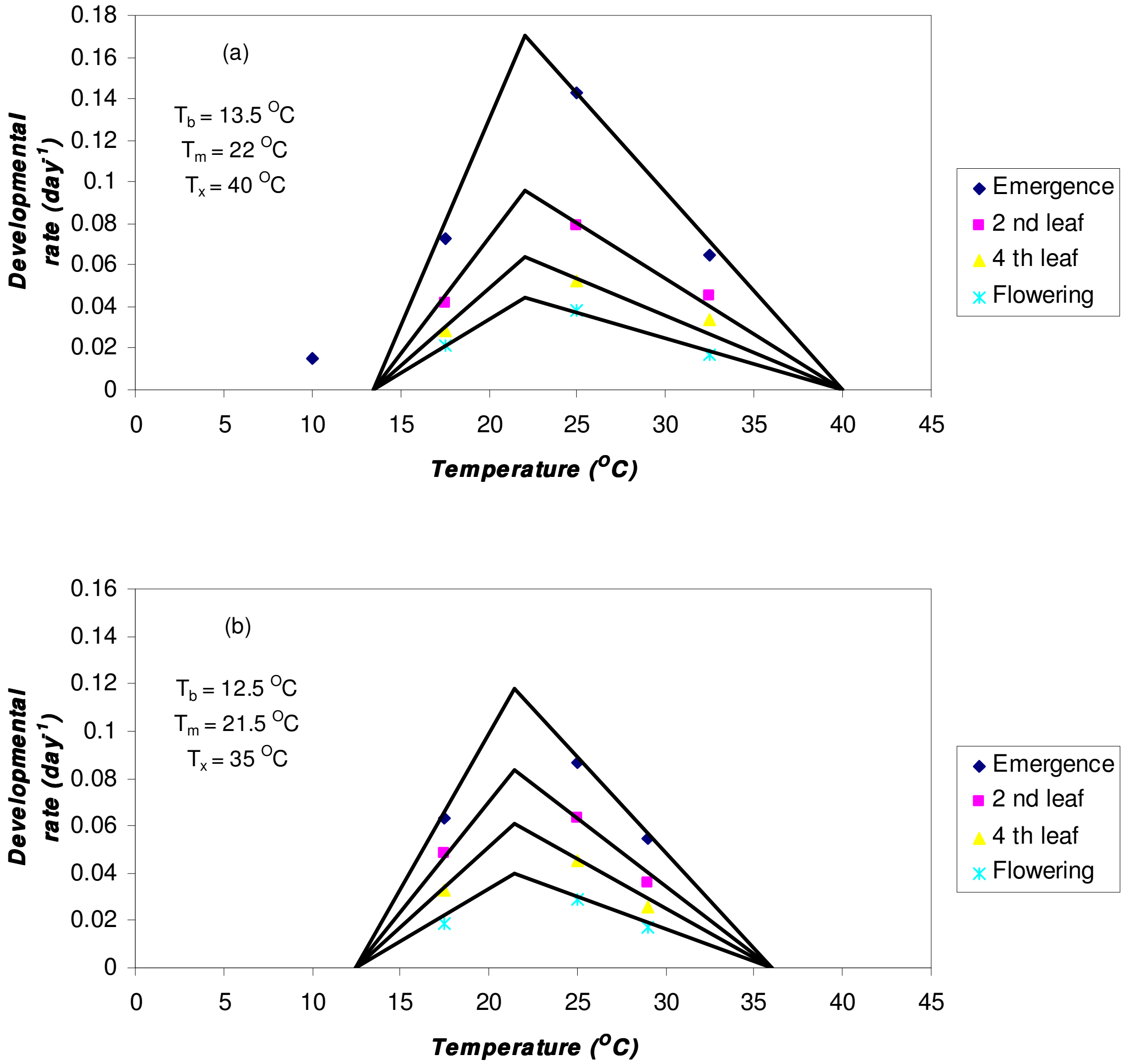


Figure 8.4 Determination of the cardinal temperatures for various developmental stages for the cultivar Jalapeno (a) and Mareko Fana (b).

Maximum temperature estimation requires considerable extrapolation, resulting in exceedingly high maximum temperature estimation (Craufurd *et al*., 1998). According to Craufurd *et al*. (1998) the maximum temperature estimates for leaf appearance rate in sorghum ranged between 36.8 to 58.9 °C, which appeared to be an overestimation. Likewise, Yan & Hunt (1999) employing beta distribution and using data from Cao & Moss (1989) found the maximum temperature estimates for leaf emergence to fall between 43.3 and 50 °C for wheat genotypes, and between 42.5 and 46.4 °C for barley genotypes.

Temperatures between 17.5 and 25 °C were randomly selected in 0.5 °C increments to estimate optimum temperatures of the respective cultivars with the assumption that the optimum temperature falls between 17.5 and 25 °C. Four points are therefore available, including the maximum temperature for estimating the optimum temperature. Linear regression lines were fitted using four points for all developmental stages considered. The standard error of the y estimates of the regression lines for the respective developmental stages were summed to get an indication of total error. Optimum temperature was assumed at the temperature (x value) where the total standard error of the y estimate of the regressions of all developmental stages was at a minimum. Error was minimized at T_m of 22 °C for Jalapeno and 21.5 °C for Mareko Fana (Figures 8.4a and 8.4b). Knot (1988) reported an optimum temperature of 22.5 °C for hot pepper, which appears to agree with the present results for the cultivar Jalapeno, whereas optimum temperature for Mareko Fana seems markedly lower than the value reported in literature.

The same procedure described above was utilized to determine base temperature. Here three data points (including the optimum temperature) are available. The total standard error of the y estimates for developmental stages was at the minimum at a base temperature of 13 °C for Jalapeno and 12.5 °C for Mareko Fana (Figures 8.4a and 8.4b). Knot (1988) reported a base temperature of 11 °C, which appears to be sufficiently lower than the present results, suggesting the need to consider genotypic differences.

Hot peppers require day temperatures of 24-30 °C and night temperatures of 10-15 °C for optimum growth (Smith *et al*., 1998). The present study confirmed the fact that too high a night temperature is more detrimental to reproductive development than the vegetative growth as either flowering failed to materialize at 32.5 °C in Mareko Fana or it occurred after roughly 3 months at 29 °C in Mareko Fana and at 32.5 °C in Jalapeno. Thus, if emphasis is given to modelling of flowering and fruit maturity it is reasonable to use maximum temperature values lower that the values reported here as these traits were hardly expressed at high constant day and night temperatures. On the contrary, if emphasis is given to emergence and vegetative growth, it appears that considering high values for maximum temperature are reasonable.

8.3.3 Validating results with field data

The cardinal temperatures determined in the growth cabinets for each cultivar were used to calculate thermal time requirements for flowering and maturity stages in the field (Figure 8.5). The thermal time requirement in both cultivars was determined from the growth cabinet average constant temperature of 25 °C for flowering and maturity (harvest) using separate cardinal temperatures for individual cultivars. The reason for using the above constant temperature is that this is the only constant temperature where both cultivars achieved flowering and maturity.

In the field, Mareko Fana required 280 °C d for flowering and 913 °C d for maturity, while Jalapeno required 242 °C d for flowering and 799 °C d for maturity. In the growth cabinet, Mareko Fana required 227 °C d for flowering and 860 °C d for maturity, while Jalapeno required 198 °C d for flowering and 816 °C d for maturity. Mareko Fana seedlings in the growth cabinets flowered four days earlier than those in the open fields, while Jalapeno seedlings in the growth cabinets flowered five days earlier than those in the open fields. The prediction error for maturity was five days for Mareko Fana and nine days for Jalapeno. This is probably due to the fact that seedlings in the open field experienced severe transplanting shock and, therefore, took longer to acclimatize in the new environment, which is much harsher in the open field environment. Olivier & Annandale (1998) cited the spatial and temporal temperature variations between growth cabinet and field conditions for the observed difference in thermal time requirements for various developmental stages of peas grown in growth cabinets and open field.

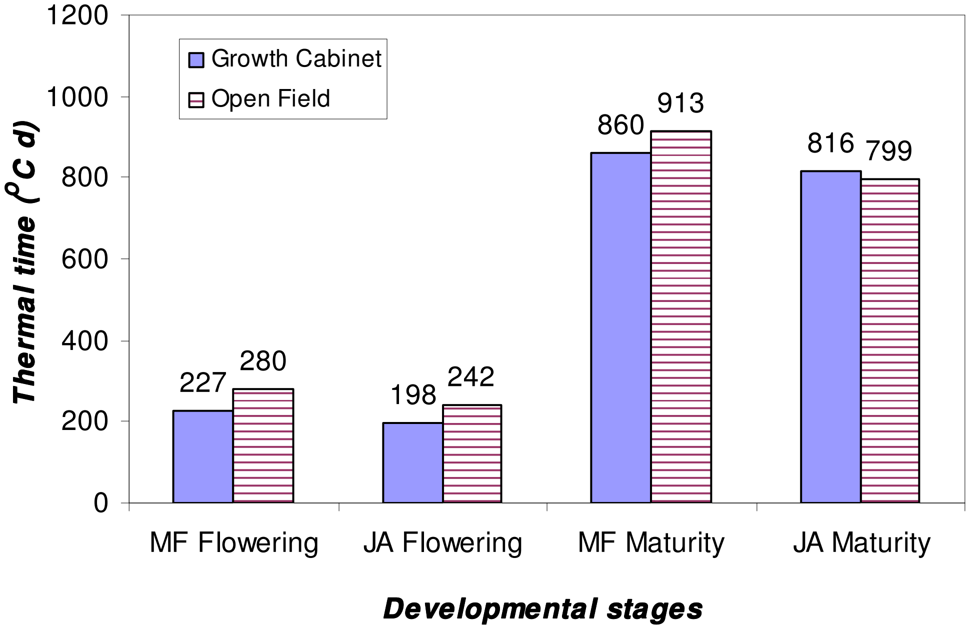


Figure 8.5 Comparison of growth cabinet and field thermal time requirements of flowering and maturity for the cultivars Mareko Fana (MF) and Jalapeno (JA) using growth cabinet determined cardinal temperatures.

8.4 CONCLUSIONS

It appears that a marked difference exists between hot pepper cultivars with respect to their cardinal temperatures, especially maximum temperatures and thus thermal time requirements to complete different developmental stages. Distinction needs to be made between vegetative and flowering stages, as these developmental stages behave differently to low and high temperatures, in that high temperatures significantly limit the development rate of reproductive growth while the effect on vegetative rate is minimal. For sake of simplicity, a base temperature of 12.5 °C and optimum temperature of 22 °C seems to be reasonably acceptable for the hot pepper cultivars studied here. However, retaining the maximum temperature values of individual cultivars is recommended, as the results for the two cultivars appeared to differ markedly.

Knowledge of the cardinal temperatures and the thermal time requirements for the developmental stages of hot pepper can enhance nursery management and planning of operations like transplanting and harvesting. It also improves scheduling of staggered planting and prediction of harvest time from the use of long-term average temperature for continuous supply of fresh produce to the market. Furthermore, understanding the cardinal temperatures and thermal time requirements of individual cultivars would improve the modelling of respective hot pepper cultivars for simulating growth and irrigation scheduling.

CHAPTER 9

CALIBRATION AND VALIDATION OF THE SWB IRRIGATION SCHEDULING MODEL FOR HOT PEPPER (*Capsicum annuum* L.) CULTIVARS FOR CONTRASTING PLANT POPULATIONS AND IRRIGATION REGIMES

Abstract

Irrigation is standard practice in hot pepper production and sound irrigation scheduling increases productivity. Irrigation can be scheduled using various tools, including computer modelling. The Soil Water Balance (SWB) model is a mechanistic, generic crop irrigation scheduling model. Calibration and validation of the model using reliable data is required to ensure accurate simulations. Detailed weather, soil and crop data were collected from three field trials conducted in the 2004/05 growing season at the Hatfield Experimental Farm, University of Pretoria. Model calibration was done using crop-specific model parameters determined under optimum growing conditions, while model validation was done using data generated under water stress and/or low planting density conditions. The SWB model was successfully calibrated for the cultivars Jalapeno, Long Slim and Serrano for most growth parameters and the soil water deficit was predicted with reasonable accuracy. Validation simulations were inside or marginally outside the reliability criteria imposed for deficit irrigation treatments. However, caution must be exercised when using crop-specific model parameters developed under optimum plant population to simulate growth under low plant population conditions, as most of the validation simulations were outside the reliability criteria for Long Slim under low density planting and deficit irrigation treatments. This is due to the fact that the SWB model does not account for plant population.

Keywords: hot pepper, irrigation regime, irrigation scheduling, plant population, SWB model

9.1 INTRODUCTION

Hot pepper (*Capsicum annuum* L.) is a warm season, high value cash crop. Generally, its production is confined to areas where available water is limited and, therefore, irrigation is standard practice in hot pepper production (Wein, 1998). The crop is sensitive to water stress (Delfine *et al*., 2000). Both under- and over-irrigation is detrimental to the profitability of crops. Under-irrigation may result in yield and quality reduction, while over-irrigation could lead to excessive percolation, which has environmental consequences and wastes water, nutrients and energy (to pump water).

Cultural practices such as variety (Ismail & Davies, 1997; Jaimez *et al*., 1999) and planting density (Cantliffe & Phatak, 1975; O'Sullivan, 1980; Taylor *et al*., 1982; Tan *et al*., 1983) were reported to influence plant response to irrigation water application. Vigorously growing crops (cultivars) tend to exhaust soil water more rapidly than those cultivars with a slower growth habit. Consequently, vigorous cultivars are usually planted in wider rows to avoid competition among neighbouring plants and also to prevent mutual shading of plant canopies (Jolliffe, 1988). Tan *et al*. (1983) reported similar cucumber yield for high and low plant populations when grown without irrigation, but they observed significant plant population effects under irrigated conditions. Taylor (1980), working on soybean, observed no difference in yield among 0.25, 0.5, 0.75 and 1 m wide row spacings in 1976, a drier than normal growing season. In the 1975 growing season with relatively normal rainfall, yield tended to increase as row spacing decreased, but the differences were not significant. During 1977 with greater than normal and preplant irrigation, soybeans in 0.25 m rows out-yielded those in 1.0 m rows by 17%.

Models that incorporate such varied growing conditions would enhance our understanding of how to manage agricultural inputs such as water and planting density for profitable crop production and environmental protection. A large number of crop physiological models have been developed for different applications (Sinclair & Seligman, 1996). The Soil Water Balance (SWB) model is a mechanistic, user-friendly, daily time step, generic crop growth and irrigation scheduling model (Annandale *et al*., 1999). It is capable of simulating yield, different growth processes, and field water balance components. This type of information can assist producers and researchers to make decisions to alter inputs, maximize profit, and reduce soil erosion (Kiniry *et al*., 1997).

Crop-specific model parameters can vary for different cultivars (Kiniry *et al*., 1989; Annandale *et al*., 1999), vapour pressure deficit differences (Stockle & Kiniry, 1990), irrigation frequencies (Tesfaye, 2006), row spacings (Flénet *et al*., 1996; Jovanovic *et al*., 2002) and other growing conditions (Monteith, 1994; Sinclair & Muchow, 1999). Furthermore, since crop models are often tested against long-term mean yields, models for aiding decision making must be able to accurately simulate growth and yield in extreme conditions (Xie *et al*., 2001).

Although crop-specific model parameters vary for different plant populations and irrigation regimes, the SWB model has not been validated for various plant populations and irrigation regimes in hot pepper. Therefore, this study was conducted to calibrate and validate the SWB model for different hot pepper cultivars under contrasting plant populations and/or irrigation regimes.

9.2 MATERIALS AND METHODS

9.2.1 Experimental site and treatments

Details of the site and treatments are provided in paragraph 6.2.1 of Chapter 6.

9.2.2 Crop management and measurements

Seven-week-old hot pepper seedlings of the respective cultivars were transplanted into the field. Drip irrigation was used in all three trials. Plants were irrigated for 1 hour (12.5-15.5 mm) every other day for three weeks (until plants were well established). Thereafter, plants were irrigated to field capacity, each time the treatments soil water deficit was reached (Table 6.2). In the open field experiment 2 (where row spacings and cultivars are the treatment), plants were irrigated to field capacity when 50-55% of plant available soil water was depleted. Based on soil analysis results and target yield, 150 kg ha^{-1} N and 50 kg ha^{-1} K were applied to the rainshelter and to the open field experiments, the open field experiment also received 75 kg ha^{-1} P. N application was split, with 50 kg ha^{-1} at planting, followed by a 100 kg ha^{-1} top dressing eight weeks after transplant. Weeds were controlled manually. Fungal diseases were controlled using Benomyl® (1H – benzimidazole) and Bravo® (chlorothalonil) sprays, while red spider mites were controlled with Metasystox® (oxydemeton–methyl) applied at the recommended doses.

Plots were regularly monitored and the number of plants attaining the flowering and maturity stages was recorded. Dates of flowering and maturity were recorded when 50% of the plants in a plot reached these stages.

Soil water deficit measurements were made using a model 503DR CPN Hydroprobe neutron water meter (Campbell Pacific Nuclear, California, USA). Readings were taken twice a week, at 0.2 m increments to a depth of 1.0 m, from access tubes installed in the middle of each plot and positioned between rows.

Growth analyses were carried out at 15 to 25 day intervals by harvesting four plants from a plot. Eight plants from the central two rows were reserved for yield measurements. Fruits were harvested three times during the season. The sampled plants were separated into leaves, stems and fruits, and oven dried to a constant mass. Leaf area was measured with an LI 3100 belt driven leaf area meter (Li-Cor, Lincoln, Nebraska, USA).

The fraction of photosynthetically active radiation (PAR) intercepted by the canopy (FI_{PAR}) was measured using a sunfleck ceptometer (Decagon Devices, Pullman, Washington, USA). The PAR measurements for a plot consisted of three series of measurements conducted in rapid succession on cloudless days. A series of measurements consisted of one reference reading above and ten readings beneath the canopy, which were averaged. FI_{PAR} was then calculated as follows:

$$FI_{PAR} = 1 - \left(\frac{PAR\, below\ canopy}{PAR\ above\ canopy} \right) \qquad 9.1$$

Daily weather data were collected from an automatic weather station located about 100 m from the experimental site. The automatic weather station consisted of an LI 200X pyranometer (Li-Cor, Lincoln, Nebraska, USA) to measure solar radiation, an electronic cup anemometer (MET One, Inc., USA) to measure average wind speed, an electronic tipping bucket rain gauge (RIMCO, R/TBR, Rauchfuss Instruments Division, Australia), an ES500 electronic relative humidity and temperature sensor and a CR10X data-logger (Campbell Scientific, Inc., Logan, Utah, USA).

9.2.3 The Soil Water Balance model

The Soil Water Balance (SWB) model is a mechanistic, real-time, user-friendly, generic crop irrigation scheduling model (Annandale *et al*., 1999). It is based on the improved version of the SWB model described by Campbell & Diaz (1988). The SWB model contains three units, namely, weather, soil and crop unit. The weather unit of the SWB model calculates the Penman-Monteith grass reference daily evapotranspiration (ETo) according to the recommendations of the Food and Agriculture Organization of the United Nations (Allen *et al*., 1998). The soil unit simulates the dynamics of soil water movement (runoff, interception, infiltration, percolation, transpiration, soil water storage and evaporation) in order to predict the soil water content. In the crop unit, the SWB model calculates crop dry matter accumulation in direct proportion to transpiration corrected for vapour pressure deficit (Tanner & Sinclair, 1983). The crop unit also calculates radiation-limited growth (Monteith, 1977) and takes the lower value of the two. This dry matter is partitioned into roots, stems, leaves and grains or fruits. Partitioning depends on phenology, calculated with thermal time and modified by water stress. The model also accounts for the effect of water stress on growth, reducing canopy size by stress index parameter, the ratio between actual and potential transpiration. The SWB model, however, does not have a routine to account for variations in plant population.

The main strength of the SWB model compared to models that are more detailed is that it requires fewer crop input parameters, while still predicting the crop growth and soil water balance reasonably well. The generic nature of the SWB model further allows simulating growth and soil water balance of several crops with the same user-friendly software package, unlike species specific models (Jovanovic *et al*., 2000).

9.2.4 Determination of crop-specific model parameters

Field data collected from well-watered and/or high planting density treatments of three field experiments during the 2004/05 growing season were used to estimate the following crop-specific model parameters: radiation extinction coefficient, vapour pressure deficit-corrected dry matter water ratio, radiation use efficiency, maximum crop height, day degrees at the end of vegetative growth, day degrees for maturity, specific leaf area, and leaf-stem partitioning parameters, following the procedures described by Jovanovic *et al*. (1999). Furthermore, the crop-specific model parameters that were not generated from field experiments were obtained from literature or estimated by calibrating the model against measured field data.

9.2.5 Cultivars used in calibration and validation studies

Calibration and validation of the model was done for cultivars Jalapeno, Serrano and Long Slim. Jalapeno is an early maturing cultivar with relatively large sized fruits and is characterized by intermediate canopy growth. Serrano is an intermediate maturing cultivar and bears small fruits and is characterized by relatively intermediate to prolific canopy growth. Long Slim is an early maturing cultivar with medium sized fruits and with an intermediate to prolific canopy growth.

9.2.6 Model reliability test

The SWB model calculates the following statistical parameters for testing model prediction accuracy: Willmott's (1982) index of agreement (d), the root mean square error (RMSE), mean absolute error (MAE) and coefficient of determination (r^2). According to De Jager (1994), d and r^2 values > 0.8 and MAE values < 0.2 indicate reliable model predictions. RMSE reflects the magnitude of the mean difference between predicted and measured values.

9.3 RESULTS AND DISCUSSION

The complete list of crop-specific model parameters determined under optimum growing conditions and then used to calibrate the model is shown in Table 9.1. As an example only three cultivars are included in the model calibration and validation.

Table 9.1 Crop-specific model parameters calculated from growth analysis on high irrigation regime (25D) and/or high density planting (HD) and used to calibrate the SWB model for different hot pepper cultivars

Crop-specific parameter	Variety & treatment		
	Jalapeno (25D)	Serrano (NR)	Long Slim (25D-NR)
Canopy extinction coefficient for total solar radiation (K_s)*	0.33	0.42	0.51
Canopy extinction coefficient for PAR** (K_{PAR})*	0.47	0.59	0.72
vapour pressure deficit-corrected dry matter/water ratio DWR* (Pa)	2.77	2.12	2.17
Radiation use efficiency E_c* (kg MJ^{-1})	0.00102	0.00105	0.00103
Base temperature (°C)	11	11	11
Optimum temperature (°C)	22.5	22.5	22.5
Cut-off temperature (°C)	26.6	26.6	26.6
Emergence day degrees*(°C d)	0	0	0
Day degrees at the end of vegetative growth* (°C)	410	470	570
Day degrees for maturity* (°C d)	1290	1425	1295
Transition period day degrees**** (°C d)	800	900	500
Day degrees for leaf senescence**** (°C d)	1000	1000	1000
Canopy storage **(mm)	1	1	1
Leaf water potential at maximum transpiration ***(kPa)	-1500	-1500	-1500
Maximum transpiration ***(mm d^{-1})	9	9	9
Maximum crop height H_{max}***** (m)	0.6	0.7	0.8
Maximum root depth RD_{max} *** (m)	0.6	0.6	0.6
Specific leaf area SLA* (m^2 kg^{-1})	17.26	19.16	17.78
Leaf stem partition parameter p* (m^2 kg^{-1})	5.38	7.82	2.34
Total dry matter at emergence ***(kg m^{-2})	0.0019	0.0019	0.0019
Fraction of total dry matter partitioned to roots***	0.2	0.2	0.2
Root growth rate*** (m^2 $kg^{-0.05}$)	6	6	6
Stress index***	0.95	0.95	0.95

Notes: *Calculated according to Jovanovic *et al.* (1999); ***PAR: photosynthetically active radiation *** Adopted from Annandale *et al.* (1999); **** Estimated by calibration against measurement of growth, phenology, yield and water-use; ***** Measured.

Figures 9.1, 9.2 and 9.3 display model calibration results. The model predicted fractional interception of photosynthetically active radiation (FI green leaf), leaf area index (LAI), top dry matter (TDM) and harvestable dry matter (HDM) very well for Jalapeno (Figure 9.1), Serrano (Figure 9.2) and Long Slim (Figure 9.3). However, the soil water deficit to field capacity (Deficit) was predicted with less accuracy, but sufficient for irrigation scheduling purposes, as the calibration simulations were only marginally outside the reliability criteria. Error that might have been introduced during calibration of the neutron probe due to small sampling size, as a single soil profile was dug to sample soil for determination of volumetric soil water content, may have contributed to the difference observed between measured and simulated soil water deficits to field capacity.

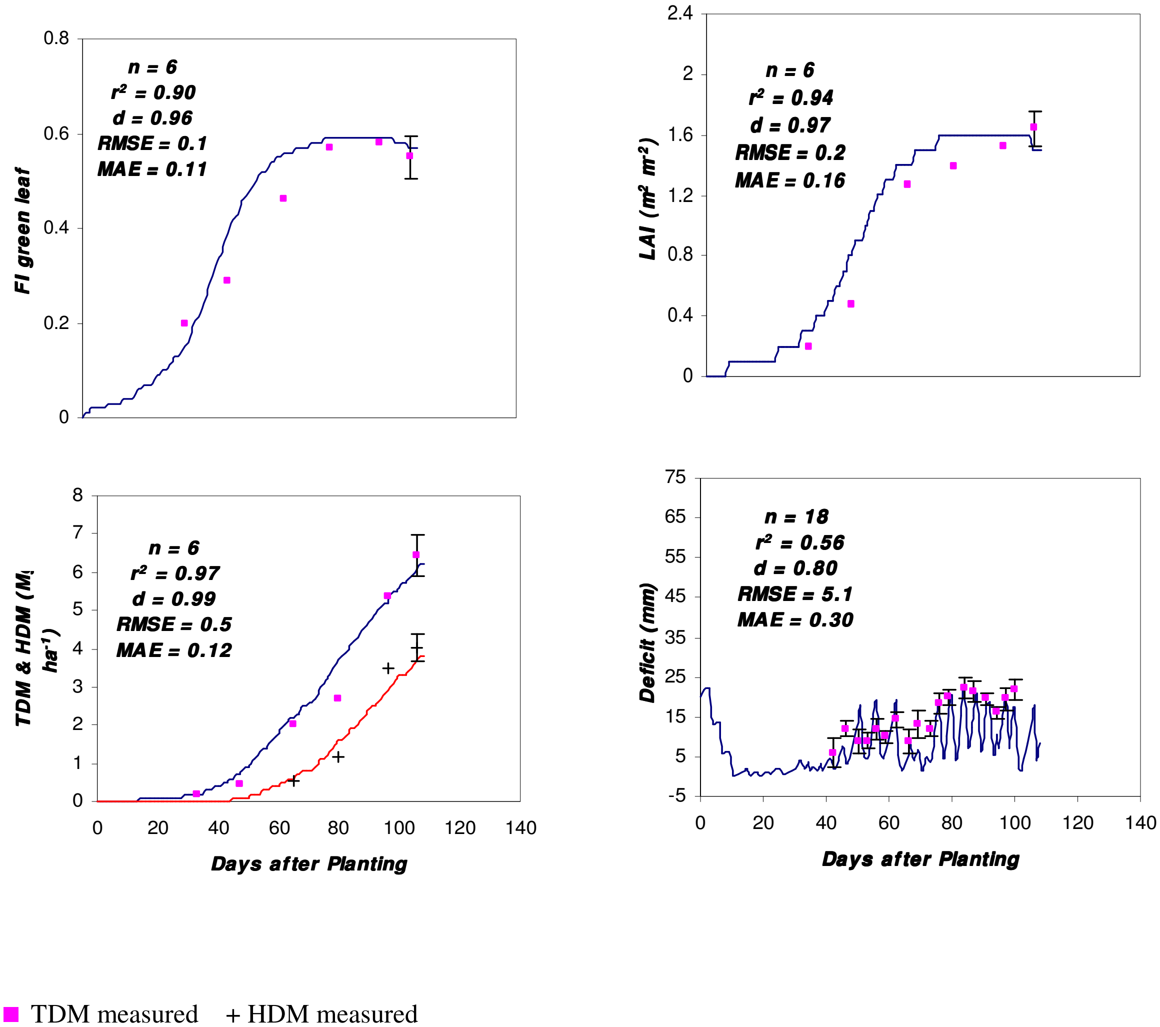


Figure 9.1 Simulated (solid lines) and measured values (points) of fractional interception (FI), leaf area index (LAI), soil water deficit (Deficit), top dry matter (TDM) and harvestable dry matter (HDM) [Jalapeno calibration, well irrigated]. Vertical bars are ± 1 standard error of the measurement.

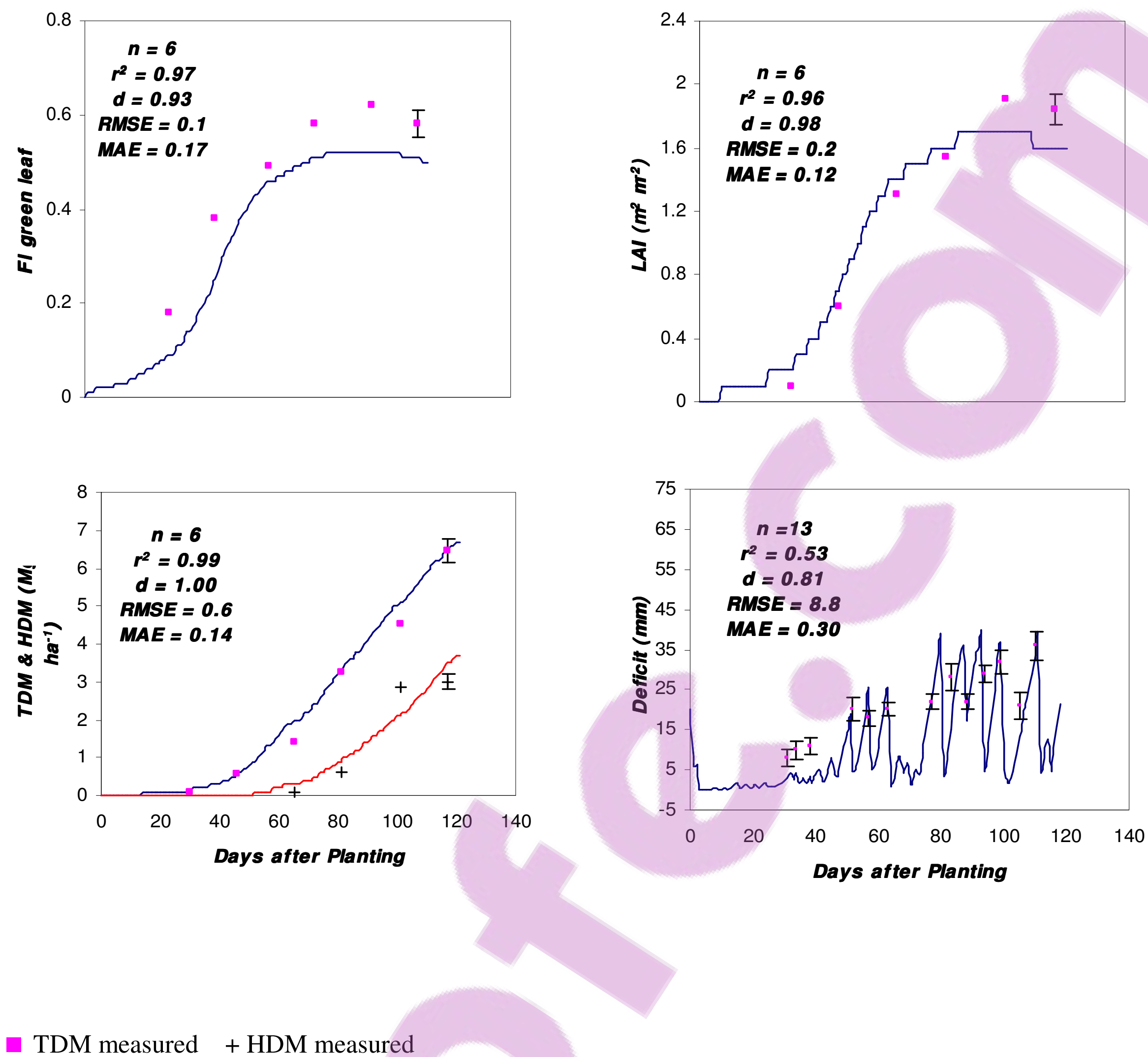


Figure 9.2 Simulated (solid lines) and measured values (points) of fractional interception (FI), leaf area index (LAI), soil water deficit (Deficit), top dry matter (TDM) and harvestable dry matter (HDM) [Serrano calibration, high density planting]. Vertical bars are ± 1 standard error of the measurement.

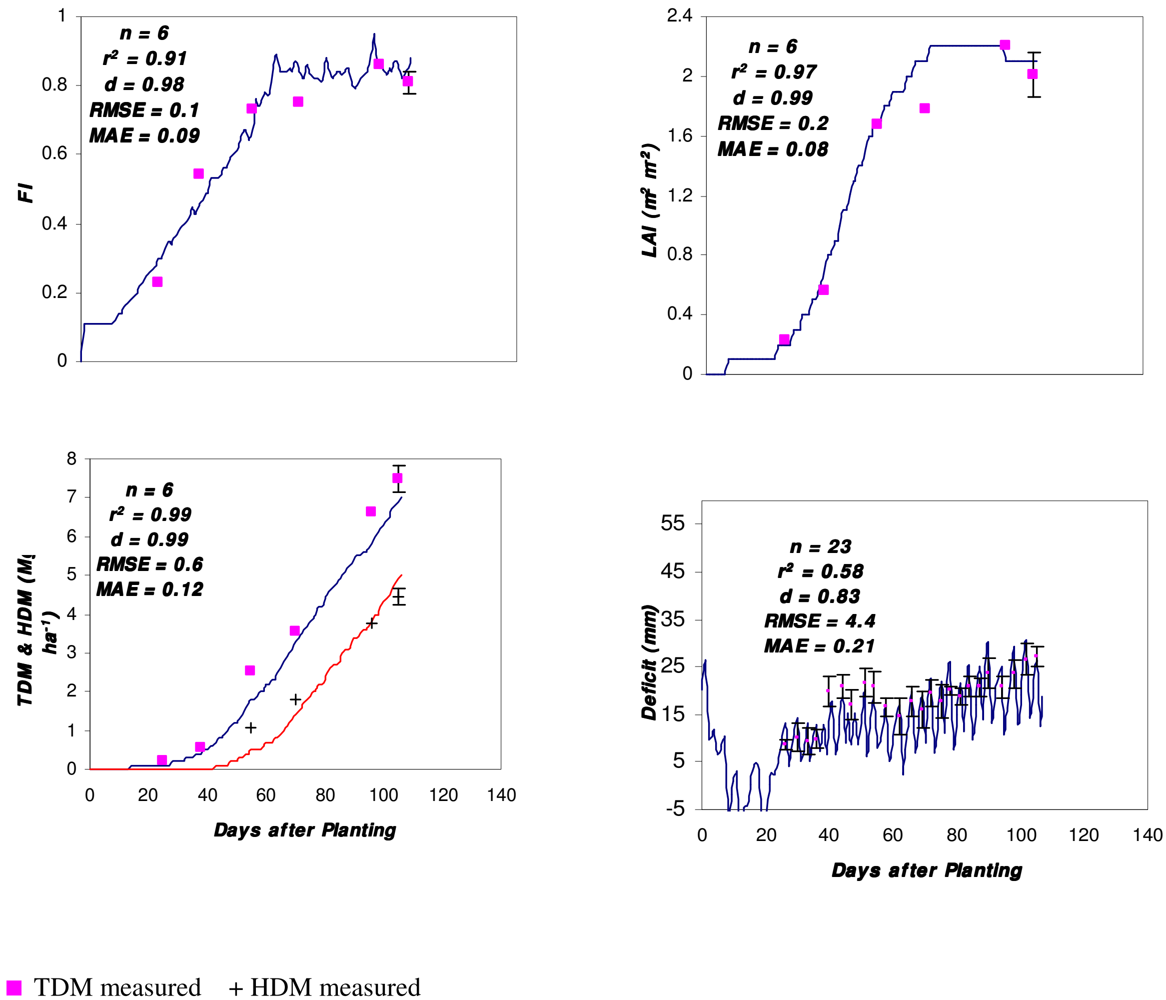
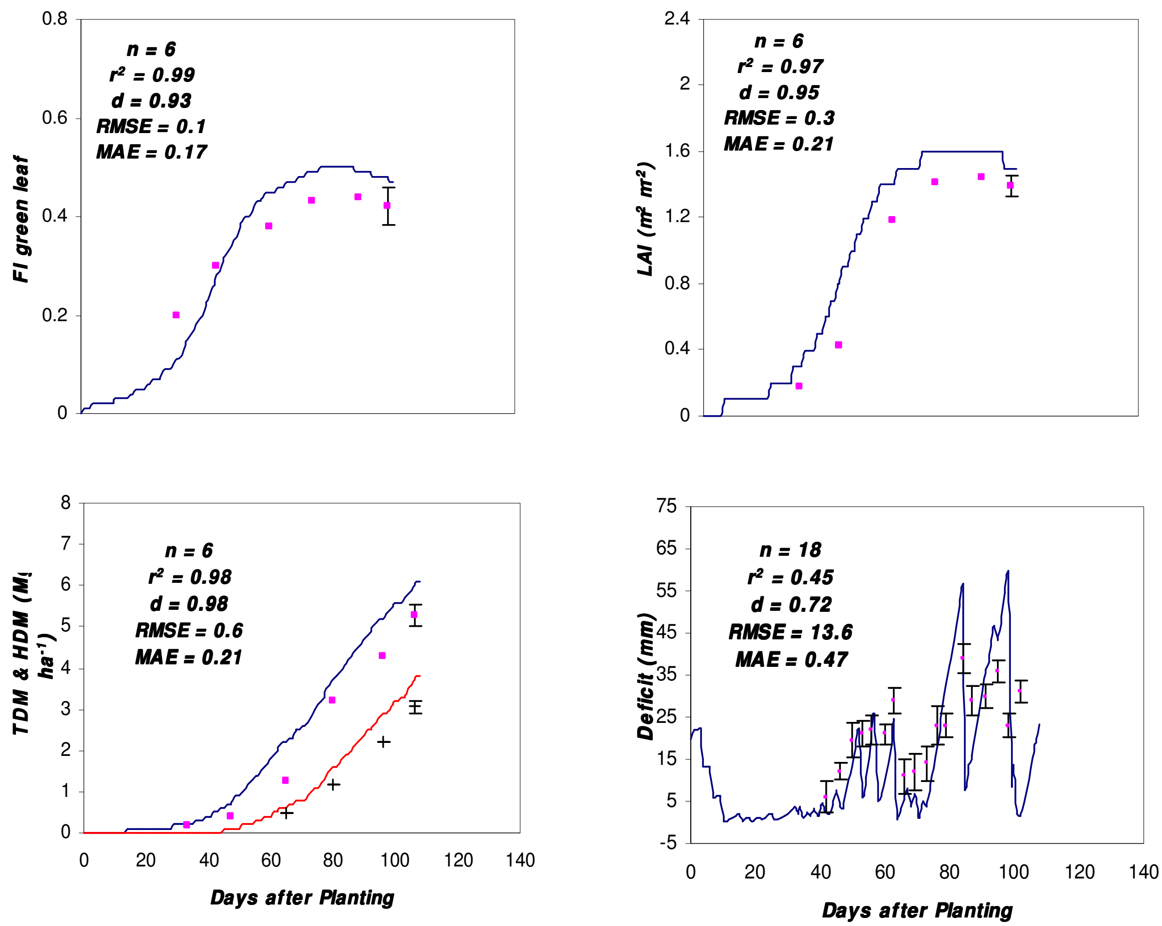


Figure 9.3 Simulated (solid lines) and measured values (points) of fractional interception (FI), leaf area index (LAI), soil water deficit (Deficit), top dry matter (TDM) and harvestable dry matter (HDM) [Long Slim calibration, well irrigated and high density planting]. Vertical bars are ± 1 standard error of the measurement.

Model validation was carried out using data collected from water stressed and/or row planting density treatments. Model validation results for Jalapeno under deficit irrigation and for Serrano under low planting density are shown in Figures 9.4 and 9.5, respectively. FI was underestimated at an early stage, while it was overestimated at later stages of development for Jalapeno, which appeared to have resulted in an underestimation of soil water deficit at the early stage and overestimation in later stages. Similar trends in simulated FI and soil water deficit were observed in the validation results for Serrano (Figure 9.5) and Long Slim (Figure 9.6). FI is used by the model to partition precipitation and irrigation into the evaporation and transpiration (Annandale *et al*., 1999). The size of the canopy directly influences the rate of transpiration (Villalobos & Fereres, 1990; Steyn, 1997). Therefore, in the present study, a reduction in the value of the simulated FI has resulted in an underestimation, while an increase in the value of the simulated FI has resulted in an overestimation of daily water usage.

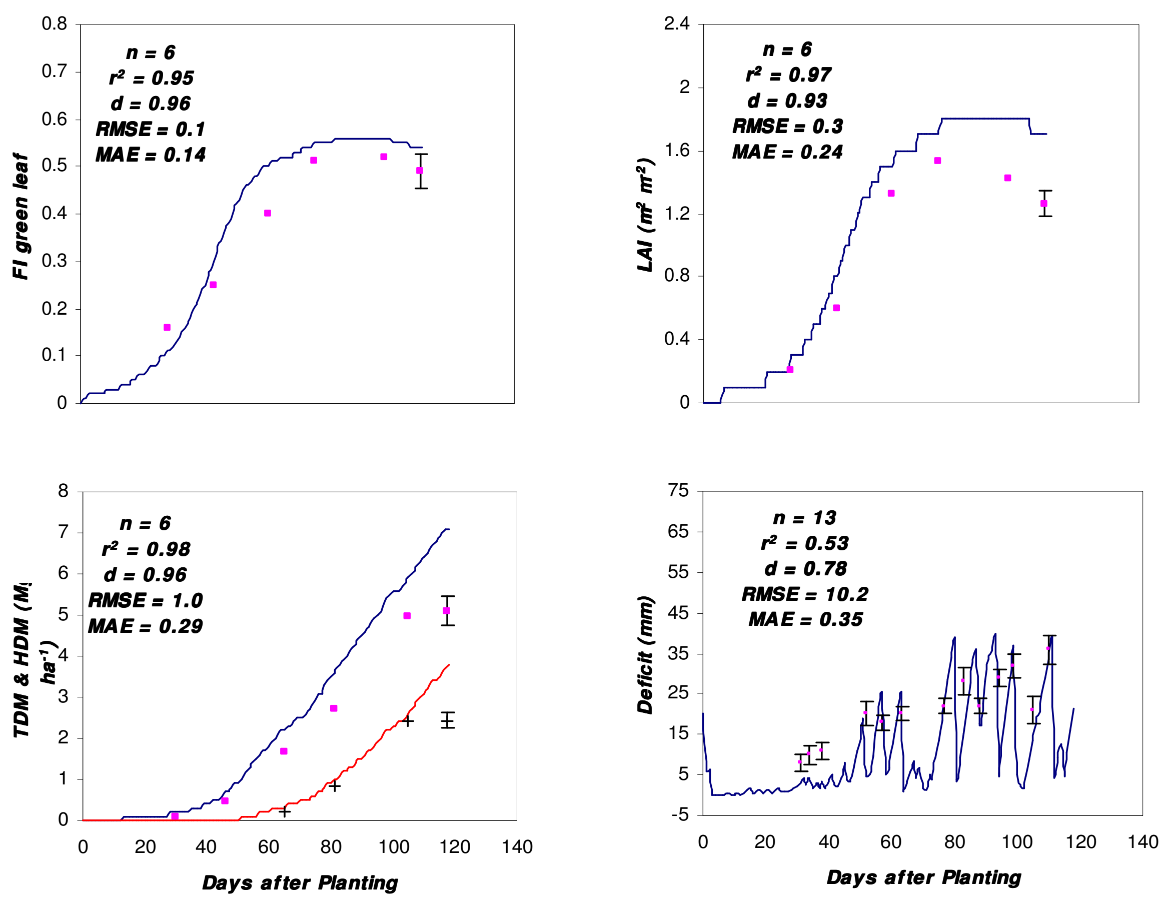
In Jalapeno under low irrigation regime (75D), LAI and TDM and HDM production were underestimated early in the season, while mid and late in the season they were overestimated (Figure 9.4), although the mean difference between measured and simulated values were small (RMSE value of 0.2 m^2m^{-2} for LAI and RMSE value of 0.6 Mg ha^{-1} for dry matter production). The fact that the SWB model accounts for water stress allow the model to simulate growth under water stressed growing conditions with a reasonable degree of accuracy (Annandale *et al*., 1999). Hence, in the present study, the model validation statistical parameters were inside or marginally outside the reliability criteria set for most growth parameters under deficit irrigation, confirming that the SWB model can simulate growth and soil water balance components under varied irrigation regimes reasonably well.

For Serrano at low planting density, at an early stage FI, LAI, TDM and HDM were simulated well, but mid and late in the season, they were all overestimated (Figure 9.5). This appears to have resulted in overestimation of soil water deficit for the major part of the season. For Long Slim, which was grown under water stress and low planting density, the FI, LAI, TDM and HDM were markedly overestimated as confirmed by high RMSE and MAE values (Figure 9.6). Consequently, high soil water deficits were simulated, which were markedly different from the measured deficits. The SWB model does not take plant population into account but rather considers the given plant population as optimal, which apparently resulted in the overestimation of canopy size in Serrano and Long Slim, eventually leading to the overestimation of crop water-use and soil water deficits. Therefore, caution must be taken when using crop-specific model parameters developed under optimum plant population to simulate growth under low plant population conditions using SWB model.



■ TDM measured + HDM measured

Figure 9.4 Simulated (solid lines) and measured values (points) of fractional interception (FI), leaf area index (LAI), soil water deficit (Deficit), top dry matter (TDM) and harvestable dry matter (HDM) [Jalapeno validation, deficit irrigation]. Vertical bars are ± 1 standard error of the measurement.



■ TDM measured + HDM measured

Figure 9.5 Simulated (solid lines) and measured values (points) of fractional interception (FI), leaf area index (LAI), soil water deficit (Deficit), top dry matter (TDM) and harvestable dry matter (HDM) [Serrano validation, low density planting]. Vertical bars are ± 1 standard error of the measurement.

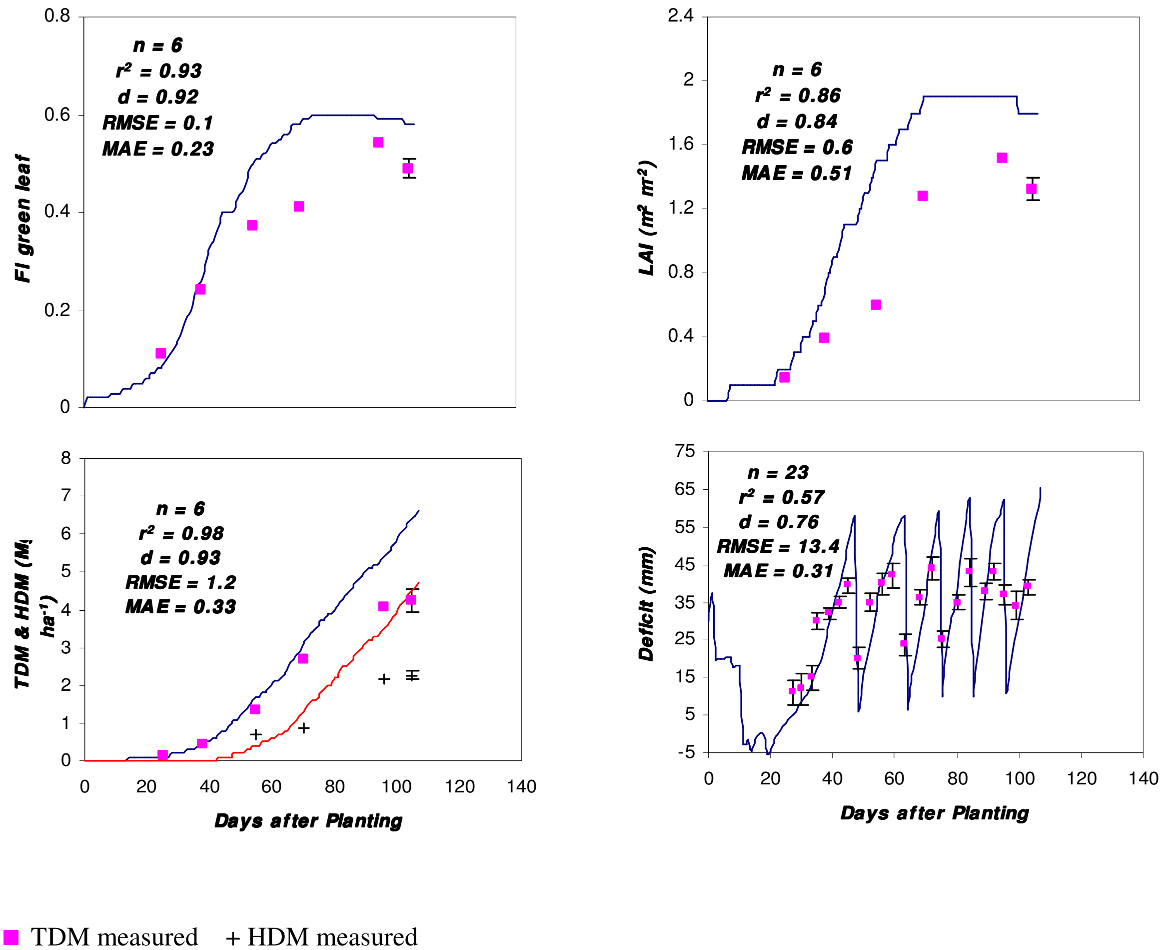


Figure 9.6 Simulated (solid lines) and measured values (points) of fractional interception (FI), leaf area index (LAI), soil water deficit, top dry matter (TDM) and harvestable dry matter (HDM) [Long Slim validation, deficit irrigation and low density planting]. Vertical bars are ± 1 standard error of the measurement.

9.4 CONCLUSIONS

A database of crop-specific model parameters was generated for three South African cultivars (Jalapeno, Serrano and Long Slim). The cultivars represent a wide range of growth habits and fruiting characteristics. The SWB model was successfully calibrated and validated for these cultivars for several growth parameters, and the soil water deficit to field capacity was predicted with an accuracy that is sufficient for irrigation scheduling. Validation simulations were inside or marginally outside the reliability criteria for deficit irrigation treatments, confirming that the SWB model can simulate growth and soil water balance components under varied irrigation regimes reasonably well. However, caution must be exercised when using crop-specific model parameters that are developed for optimum plant population conditions to simulate growth under low planting populations, as most of the validation simulations were outside the reliability criteria imposed for Long Slim under these conditions.

The model could be improved to account for the effects of plant population on important crop-specific model parameters such as the canopy radiation extinction coefficient, by setting up experiments that investigate the effect of different plant populations on crop-specific model parameters.

CHAPTER 10

PREDICTING CROP WATER REQUIREMENTS FOR HOT PEPPER CULTIVAR MAREKO FANA AT DIFFERENT LOCATIONS IN ETHIOPIA USING THE SOIL WATER BALANCE MODEL

Abstract

Hot pepper is an important cash crop in Ethiopia. Irrigation is a standard practice in hot pepper production. In the absence of real-time climate and crop data, know-how and computing facilities, there is a need to generate semi-flexible irrigation schedules to assist irrigators. Irrigation schedules and water requirements for growing Mareko Fana in five hot pepper growing regions of Ethiopia were determined using crop-specific model parameters determined for cultivar Mareko Fana, long term climate, soil and management data.

Simulated irrigation requirements for hot pepper cultivar Mareko Fana production ranged between 517 mm at Melkassa and 775 mm at Alemaya. The longest simulated average irrigation interval was observed for Alemaya (9 days), while the lowest was observed for Bako (6 days). The depth of irrigation ranged from 35 mm in Zeway to 28 mm in Bako. The difference in climatic variables and soil types among the sites for which this study was done to influences the timing and depth of irrigation events.

Keywords: Ethiopia, hot pepper, irrigation calendars, SWB model, irrigation requirements

10.1 INTRODUCTION

Irrigation agriculture in Ethiopia is in its infancy stage, and those irrigation regimes currently existing in different schemes across the country were not monitored for the past several years (Geremew, 2008). The same author indicated that the irrigation regimes in Godino (Ethiopia) in potato and onion performed poorer than the scientific methods, SWB and re-filling soil water deficit to field capacity as monitored by neutron water meter. This, in part, can be attributed for the low water-use efficiency of crops under traditional irrigation schemes.

Water-use efficiency can be improved through practicing irrigation scheduling. Irrigation scheduling is the practice of applying the right amount of water at the right time for plant production. Irrigation scheduling is traditionally based on soil water measurement, where the soil water status is measured directly to determine the need for irrigation. Examples are monitoring soil water by means of tensiometers (Cassel & Klute, 1986), electrical resistance and heat dissipation soil water sensors (Jovanovic & Annandale, 1997), or neutron water meters (Gardner, 1986). A potential problem with soil water based approaches is that many features of the plant's physiology respond directly to changes in water status in the plant tissues, rather than to changes in the bulk soil water content. Apart from this, soil heterogeneity requires many sensors, selecting a position that is representative of the root zone is difficult, and sensors usually measure water status at root zone (Jones, 2004). The availability and lack of know-how discourage adoption of this approach by poor farmers.

The second approach is to base irrigation scheduling decisions on plant response, rather than on direct measurements of soil water status (Bordovsky *et al*., 1974; O'Toole *et al*., 1984). However, the majority of systems require instruments beyond the reach of ordinary farmers. High technical know-how and the time required to use these instruments usually discourage their ready application. Furthermore, most physiological indices of plant water stress (leaf water potential, leaf water content, diffusion resistance, canopy temperature) not only involve measurements that are complex, time consuming and difficult to integrate, but are also subject to errors (Jones, 2004). On top of this, if our measurement target is only one aspect (plant) of the soil-plant-atmosphere continuum, it may be difficult to estimate plant water requirements realistically, as the system is very interrelated.

The third option is soil water balance calculations, where the soil water status is estimated by calculation using a water balance approach in which the change in soil water over a period is given by the difference between the inputs (irrigation plus precipitation) and losses (runoff plus drainage plus evapotranspiration) (Allen *et al*., 1998). The input parameters are easy to measure using conventional instruments like rain gauge for rainfall and irrigation, and water meters for irrigation. The runoff and drainage could be either estimated from soil parameters or directly measured *in situ* or would be assumed negligible based on soil condition and water supply. Evapotranspiration can be estimated from climatic variables (Doorenbos & Pruitt, 1992; Allen *et al*., 1998) or from pan evaporation (Elliades, 1988; Sezen *et al*., 2006).

Currently, application of the soil water balance method for irrigation scheduling is growing because of better understanding of the soil-plant-atmosphere continuum and the ready availability of computer facilities to compute complex equations. Various computer software aids are available that utilize soil, plant, atmosphere and management data to estimate plant water requirements. Annandale *et al*. (1999) demonstrated, on many fruit, vegetable and field crops, SWB model to predict the plant water requirements realistically. Elsewhere, different authors (Smith, 1992; Allen *et al*., 1998) employing similar principles working on different crops under different conditions came up with similar conclusions. Furthermore, collecting and analyzing the long-term climatic data help to understand the evaporative demand of the atmosphere and the potential water supply of a region in a growing season for better water management (Smith, 2000). This information coupled with crop, soil and management data enables us to generate irrigation calendars using computer software.

An irrigation calendar is a simple chart or guideline that indicate when and how much to irrigate. It is generated by software using data of long term climatic, soil, irrigation type and crop species, and management. It can be made flexible by including real-time soil water and rainfall measurement in the calculation of water requirements of a crop. Work by Hill & Allen (1996) in Pakistan and USA, and by Raes *et al.* (2000) in Tunisia have shown a semi-flexible irrigation calendar facilitated the adoption of irrigation scheduling due to less technical knowledge required in understanding and employing the irrigation scheduling. In this regard, the SWB model is equipped with the necessary facilities to enable the development of irrigation calendars and water requirements of specific crops from climatic, soil, crop and management data. The objectives of the present study were:

1. to estimate the water requirements of hot pepper (cultivar Mareko Fana) and evaluate its productivity across five ecological regions of Ethiopia using the SWB model, and
2. to establish irrigation schedules of hot pepper for five ecological regions of Ethiopia using the SWB model and long term weather data.

10.2 MATERIALS AND METHODS

10.2.1 Site and procedures description

Five ecological regions of Ethiopia were selected for the study. The choice of locations was based on data availability and distribution of hot pepper production in the country. Daily climatic data (maximum and minimum average temperatures, rainfall, sunshine hours, wind speed, relative humidity) were obtained from the National Meteorology Service Agency (NMSA), Ethiopia. Furthermore, the FAO international climatic data base (monthly average) was consulted for those climatic variable records that were not available locally. The different stations used in the study, and their geographic descriptions are presented in Table 10.1 and Figure 10.1.

Table 10.1 Geographical description of the stations used for the study

Station	Latitude (°N)	Longitude (°E)	Altitude (m)
Alemaya	9.26	41.01	1980
Awassa	7.05	38.29	1750
Bako	9.07	37.05	1650
Melkassa	8.24	39.19	1540
Zeway	7.55	38.42	1640

The long term daily and/or monthly climatic data were averaged to get daily averages. Then these values were entered into the SWB model for simulation. Hot pepper is prone to water stress due to its shallow root system (Dimitrov & Dvtcharrom, 1995), high stomata density, large transpiring leaf surface and elevated stomata opening (Wein, 1998). Consequently, a 40% depletion of plant available soil water level was used as irrigation scheduling criterion. Soil physical properties were obtained from analysis of samples collected from the sites (Table 10.3). Initial soil water content at planting time was assumed to be equivalent to field capacity for all stations. The local hot pepper cultivar (Mareko Fana) was used as virtual crop. The crop-specific model parameters used for the simulation are listed in Table 10.4. These parameters were determined from an experiment conducted at the Hatfield Experimental Farm, Pretoria during the 2004/05 growing season. Parameters not calculated from the field experiment were estimated either by calibrating against the measured growth data or by consulting literature.

Table 10.2 Monthly climatic variables of the five ecological regions of Ethiopia during the growing season

Sites	Climatic Variables	Growing season						
		Dec	Jan	Feb	Mar	Apr	May	Jun
Alemaya	Ta_{max}	22.2	21.8	22.5	23.6	24.6	25.2	24.4
	Ta_{min}	9.5	9.8	9.6	10.8	12.2	12.4	12.3
	U_2	1.5	1.4	1.5	1.5	1.6	1.6	1.2
	Solar	20.9	21.6	21.2	21.6	21.7	21.2	18.7
	RF	10.9	13.6	23.2	59.8	116.9	99.0	45.2
Awassa	Ta_{max}	27.9	28.6	29.1	29.3	28.3	27.1	25.7
	Ta_{min}	7.7	9.0	11.3	12.2	13.0	13.0	13.1
	U_2	1.3	1.5	1.8	1.7	1.5	1.5	1.8
	Solar	20.9	21.0	21.5	21.3	19.2	19.9	18.3
	RF	15.4	30.5	41.0	62.6	120.0	120.8	98.8
Bako	Ta_{max}	29.0	29.7	30.0	29.8	25.5	24.7	25.7
	Ta_{min}	13.3	14.2	15.3	16.6	16.2	15.3	15.3
	U_2	1.7	1.5	1.7	1.7	1.6	1.5	1.1
	Solar	20.2	19.9	20.7	21.2	20.7	19.7	18.2
	RF	11.8	11	17.3	52.5	64.3	157.4	207.7
Melkassa	Ta_{max}	25.8	26.6	28.1	19.2	30.3	30.2	28.1
	Ta_{min}	10.5	12.0	13.2	14.5	15.0	14.5	16.3
	U_2	0.60	0.80	0.69	0.58	0.60	0.60	0.80
	Solar	19.7	20.5	22.2	22.9	23.1	22.2	21.3
	RF	4.5	10.9	27.4	47.9	51.9	59.0	67.6
Zeway	Ta_{max}	25.4	25.4	27.1	27.7	28.2	27.2	27.3
	Ta_{min}	9.8	11.9	12.5	12.6	12.2	11.6	12.8
	U_2	1.7	1.7	1.9	1.7	1.7	1.9	2.5
	Solar	22.1	21.6	22.0	22.3	22.3	22.9	21.3
	RF	3.4	13.6	35.3	55.0	70.8	77.5	84.7

Notes: Ta_{mex}: average maximum air temperature (°C); Ta_{min}: average minimum air temperature (°C); U_2: average daily wind speed at 2 m height ($m\ s^{-1}$); Solar: Solar radiation ($MJ\ m^{-2}\ day^{-1}$); RF: rainfall (mm).

Figure 10.1 Geographic distribution of the five ecological regions of Ethiopia considered in the study.

Table 10.3 Soil physical properties for the five ecological regions of Ethiopia

Stations	Sand (%)	Silt (%)	Clay (%)	FC (mm m^{-1})	PWP (mm m^{-1})	PAW (mm m^{-1})	BD (Mg m^{-3})	ST
Alemaya	53.1	19.5	27.4	313	194	119	1.31	SCL
Awassa	58.3	18.3	23.4	283	172	111	1.35	SCL
Bako	36	26	38	338	241	97	1.16	CL
Melkassa	36	38	26	380	263	117	1.20	SL
Zeway	17.8	34.8	47.4	377	251	126	1.20	C

FC: field capacity, PWP: permanent wilting point, PAW: plant available water, BD: bulk density, ST: soil texture, SCL: sandy clay loam, CL: clay loam, C: clay; SL: sandy loam.

Table 10.4 Crop-specific model parameters of Mareko Fana used to run the SWB model

Parameter	Value	Parameter	Value
Canopy extinction coefficient for total solar radiation (K_s)*	0.46	Canopy storage **(mm)	1
vapour pressure deficit-corrected dry matter/water ratio DWR* (Pa)	2.1	Leaf water potential at maximum transpiration **(kPa)	-1500
Radiation use efficiency E_c* (kg MJ^{-1})	0.00094	Maximum transpiration **(mm d^{-1})	9
Base temperature (°C)	11	Maximum crop height H_{max}**** (m)	0.7
Optimum temperature (°C)	22.5	Maximum root depth RD_{max} ** (m)	0.6
Cut-off temperature (°C)	26.6	Specific leaf area SLA* (m^2 kg^{-1})	17.86
Emergence day degrees*(°C d)	0	Leaf stem partitioning parameter* (m^2 kg^{-1})	4.53
Day degrees at the end of vegetative growth* (°C d)	550	Total dry matter at emergence **(kg m^{-2})	0.0019
Day degrees for maturity* (°C d)	1330	Fraction of total dry matter partitioned to roots**	0.2
Transition period day degrees*** (°C d)	600	Root growth rate** (m^2 $kg^{-0.05}$)	6
Day degrees for leaf senescence*** (°C d)	1000	Stress index**	0.95

Notes: *: calculated according to Jovanovic *et al*., 1999; **: Adopted from Annandale *et al.* (1999); ***: estimated by calibration against measurement of growth, phenology, yield and water-use; ****: measured.

Irrigated hot pepper production scenarios were simulated for five ecological regions of Ethiopia. The same planting date (5 December) was considered for all stations. The assumption behind this particular planting time is that it coincides with the end of the main growing season and the start of a dry season during which negligible frost attack occurs making the season suitable for irrigated hot pepper production (Table 10.2).

10.2.2 The Soil Water Balance model

The Soil Water Balance (SWB) model is a mechanistic, real-time, user-friendly, generic crop irrigation scheduling model (Annandale *et al*., 1999). It is based on the improved version of the soil water balance model described by Campbell & Diaz (1988). The SWB model contains three units, namely, the weather, soil and crop units. The weather unit of the SWB model calculates the Penman-Monteith grass reference daily evapotranspiration (ETo) according to the recommendations of the Food and Agriculture Organization of the United Nations (Allen *et al*., 1998). The soil unit simulates the dynamics of soil water movement (runoff, interception, infiltration, transpiration, soil water storage and evaporation) in order to quantify soil water content. In the crop unit, the SWB model calculates crop dry matter accumulation in direct proportion to vapour pressure deficit-corrected dry matter/water ratio (Tanner & Sinclair, 1983). The crop unit also calculates radiation-limited growth (Monteith, 1977) and takes the lower of the two. This dry matter is partitioned to the roots, stems, leaves and grains or fruits. Partitioning depends on phenology, calculated with thermal time and modified by water stress.

Input data to run the model include site and crop characteristics. The site-specific data include weather (daily maximum and minimum temperatures, solar radiation, wind speed and vapour pressure), altitude, latitude, and hemisphere. In the absence of measured data on solar radiation, wind speed, and vapour pressure; the model is equipped with functions for estimating these parameters from available weather data according to FAO 56 recommendation (Allen *et al*., 1998).

Soil input data such as the runoff curve number, drainage fraction and maximum drainage rate, soil layer characteristics (thickness, volumetric soil water content at field capacity and permanent wilting points, initial volumetric water content, and bulk density) are also required to run the model.

The crop-specific model parameters required to run the growth model in the SWB model includes canopy radiation extinction coefficient, vapour pressure deficit-corrected dry matter/water ratio, radiation use efficiency, base temperature, optimum temperature for crop growth, cut-off temperature, maximum crop height, day degrees at the end of vegetative growth, day degrees for maturity, transition period day degrees, day degrees for leaf senescence, maximum root depth, fraction of total dry matter translocated to heads, canopy storage, leaf potential at maximum transpiration, maximum transpiration, specific model leaf area, leaf-stem partitioning parameter, total dry matter at emergence, fraction of total dry matter partitioned to roots, root growth rate and stress index.

10.3 RESULTS AND DISCUSSION

In absence of technical knowledge on how to measure and access real-time data on soil, crop and climate, and use these data to compute real-time soil water requirement of a crop, the SWB model is capable of generating a fixed irrigation calendar from site specific data and the crop being grown. Table 10.5 shows the format of the irrigation calendar generated by the SWB model. Room for rain is left so recommended irrigation amount could be calculated by subtracting rainfall amount since the previous irrigation from the irrigation requirement indicated by the SWB. The generated irrigation calendar can easily be adopted by farmers as the information contained in this calendar indicates when and how much to irrigate. Furthermore, following recorded rainfall, irrigation rate can be reduced making the irrigation calendar flexible.

Table 10.5 Irrigation calendar output format of the SWB model

Irrigation Calendar

Farmer:______________________ Crop:__________________________

Field: _______________________ Planting date: ___________________

Soil type: ____________________ Management option: ______________

Irrigation frequency option: ____

Date	Irrigation requirement (mm)	Rain since previous irrigation (mm)	Recommended irrigation (mm)

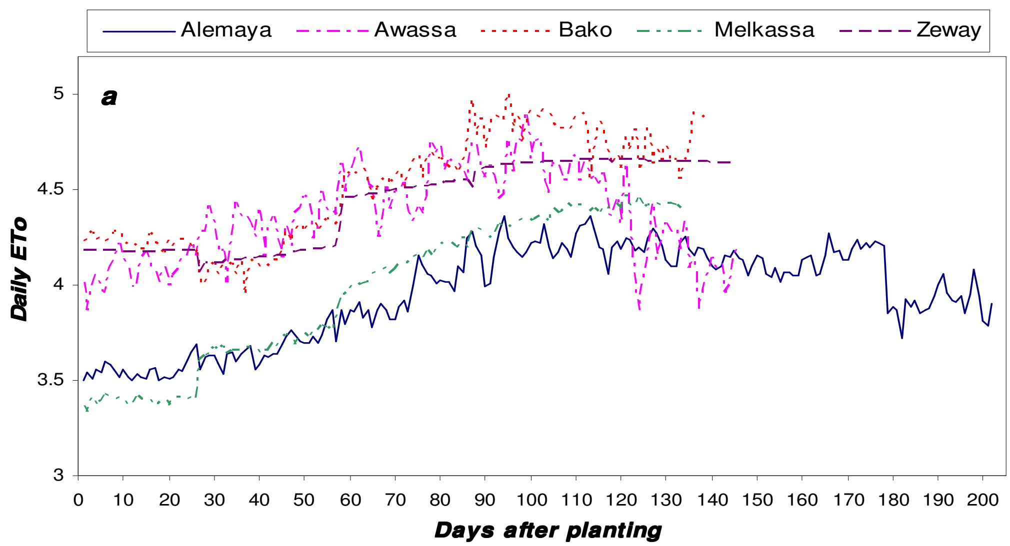
Table 10.6 presents simulated irrigation calendars for five ecological regions of Ethiopia for hot pepper production. Average irrigation interval was 9 days at Alemaya, 8 days at Awassa, Melkassa and Zeway and 6 days at Bako. The variation in simulated irrigation interval between the stations investigated is explained by climatic differences between the sites, especially in relative humidity, solar radiation, temperature and wind speed (Table 10.4). Allen *et al.* (1998) reported that water requirements of a crop varies across different locations because of variability on

Table 10.6 Simulated irrigation calendars for five ecological regions of Ethiopia for hot pepper production

Alemaya		Awassa		Bako		Melkassa		Zeway	
Date	I	Date	I (mm)	Date	I (mm)	Date	I (mm)	Date	I (mm)
Jan 21	37.6	Jan 7	31.6	Jan 7	31.3	Jan 8	38.2	Jan 4	41.5
Jan 27	26.1	Jan 12	24.5	Jan 11	19.8	Jan 14	25.6	Jan 11	28.9
Feb 2	26.5	Jan 18	27.3	Jan 16	22.5	Jan 22	31.6	Jan 18	32.9
Feb 10	32.2	Jan 25	31.2	Jan 22	26.1	Jan 29	30.6	Jan 25	34.1
Feb 17	31.4	Jan 31	31.0	Jan 27	25.2	Feb 5	32.3	Feb 1	35.1
Feb 24	33.4	Feb 6	33.1	Feb 1	26.1	Feb 12	33.4	Feb 8	37.2
Mar 3	34.5	Feb 12	32.3	Feb 6	26.5	Feb 19	33.8	Feb 15	37.5
Mar 10	34.8	Feb 18	32.2	Feb 11	27.6	Feb 26	34.4	Feb 22	37.7
Mar 17	35.1	Feb 24	33.3	Feb 16	27.8	Mar 5	34.9	Mar 1	37.9
Mar 24	35.1	Mar 2	33.6	Feb 21	28.3	Mar 12	35.2	Mar 8	38.2
Mar 31	35.7	Mar 8	33.7	Feb 26	28.4	Mar 18	30.6	Mar 14	33.1
Apr 7	34.8	Mar 14	33.7	Mar 3	28.8	Mar 24	31.0	Mar 20	33.3
Apr 14	35.1	Mar 20	34.2	Mar 8	29.5	Mar 30	31.2	Mar 26	33.5
Apr 21	34.6	Mar 26	33.7	Mar 13	30.0	Apr 5	31.3	May 1	33.6
Apr 28	34.5	Apr 1	33.5	Mar 18	29.9	Apr 11	31.5	May 7	33.6
May 5	34.5	Apr 7	32.3	Mar 23	30.0	Apr 17	31.5	May 13	33.7
May 12	34.0	Apr 13	29.9	Mar 28	30.1			May 19	33.7
May 19	34.3	Apr 19	31.2	Apr 2	29.2			May 25	33.6
May 26	35.2	Apr 25	29.4	Apr 7	28.8				
Jun 2	35.6			Apr 12	29.0				
Jun 9	32.8			Apr 17	28.9				
Jun 16	33.5			Apr 22	29.1				
Jun 23	33.6								
Ave Int (day)	9		8		6		8		8
AI (mm)	33.7		31.7		27.9		32.3		35
Total (mm)	775		602		613		517		629

Notes: I: irrigation; Ave Int: average irrigation interval; AI: irrigation amount per irrigation event.

climatic variables, that is, air temperature, amount of sunlight, humidity and wind speed. This is clearly observed from Figure 10.2, where daily evapotranspiration and thermal time to maturity markedly differed among the sites as a result of climate variability. For instance, Alemaya tends to experience cooler temperatures compared to the other sites, resulting in longer intervals between subsequent irrigations. High temperature effects on evapotranspiration appear to be confounded by low wind speed in the case of Melkassa, resulting in the same irrigation interval with that of Zeway, which is relatively cooler than Melkassa but windier. Similarly, despite the similar prevailing hot temperatures at Bako and Melkassa, at Bako more frequent irrigations were simulated, compared to Melkassa, because of more windy conditions at Bako.



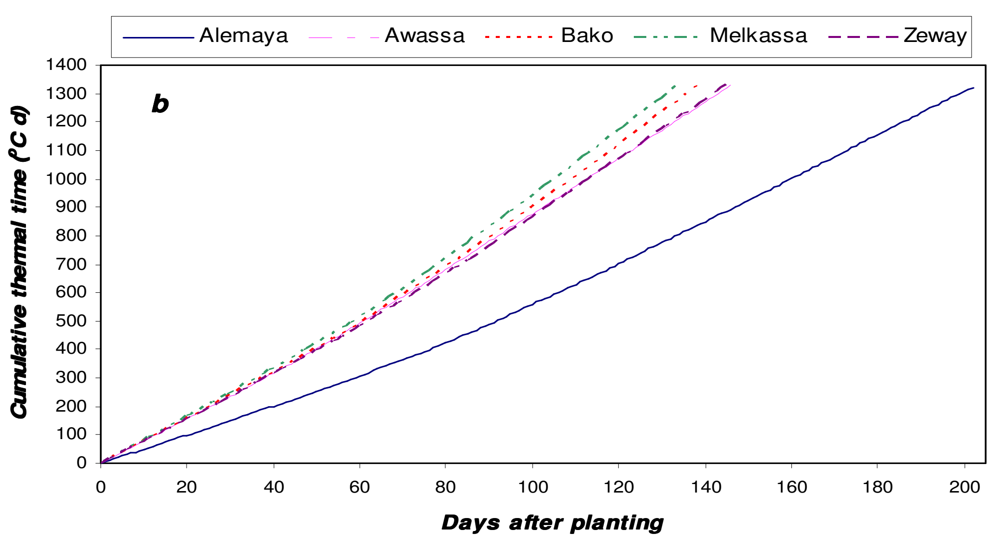


Figure 10.2 Penman-Monteith grass reference daily evapotranspiration (ETo) (a) and cumulative thermal time to maturity (b) for Mareko Fana under five ecological regions of Ethiopia.

Irrigation timing in the SWB scheduling is very flexible where irrigation criteria could be based on either soil water depletion level or fixed days of irrigation interval. A 40% depletion of plant available water was used in developing this irrigation calendar. The average water application per irrigation was 33.7 mm at Alemaya, 31.7 at Awassa, 27.9 mm at Bako, 32.3 mm at Melkassa and 35.0 mm at Zeway. Thus, irrigation amounts of 33.7, 31.7, 27.9, 32.3 and 35.0 mm at intervals of 9, 8, 6, 8 and 8 days at Alemaya, Awassa, Bako, Melkassa and Zeway, respectively, would keep the plant available depletion from falling below 40%.

Doorenbos and Kassam (1979) reported that the water requirements of peppers vary between 600 to 1250 mm, depending on climatic region and cultivar. In the present study, the total water applied (simulated irrigation) ranged between 517 mm at Melkassa to 775 mm at Alemaya. Simulated water requirements (evapotranspiration) for hot pepper cultivar Marko Fana production was 775 mm at Alemaya, 602 mm at Awassa, 613 mm at Bako, 517 mm at Melkassa and 629 mm at Zeway (Table 10.6). The simulated rate of transpiration (Table 10.7) also follows similar trend to that of total water requirements. At Pretoria, 494 - 586 mm of water was required for Mareko Fana production (Chapter 3, unpublished data). Climatic variables especially temperature which determines days to maturity (Monteith, 1977) appeared directly to influence simulated water requirements for hot pepper production between the sites. This was evident from comparing Alemaya and the other sites, where at Alemaya cooler temperature prolonged the time to maturity (Figure 10.2b) thereby requiring more water compared to the other sites.

Days to different physiological stages are simulated using heat unit principles that utilize temperature variables (Annandale *et al*., 1999). With a base temperature of 11, an optimum temperature of 22.5 and a maximum temperature of 26.6 (Table 10.3), the cultivar requires 1330 °C d to mature. Accordingly, hot pepper cultivar Mareko Fana required a total of 202 days at Alemaya, 146 days at Awassa, 138 days at Bako, 134 days at Melkassa and 145 days at Zeway to reach maturity (Table 10.8). The notable difference to days to maturity simulated is explained by the differences in mean daily temperature across the sites. In sites where the average temperature is high, the crop appeared to mature earlier (e.g. Melkassa) than sites where the average temperature is low (e.g. Alemaya). This is due to high thermal unit accumulation in sites where average temperature is relatively high.

Table 10.7 Simulated hot pepper soil water balance for five ecological regions of Ethiopia under full irrigation

Station	Irrigation (mm)	Transpiration (mm)	Evaporation (mm)	Drainage & interception (mm)
Alemaya	775	376	413	11
Awassa	602	292	338	9
Bako	613	287	337	10
Melkassa	517	231	297	7
Zeway	629	311	348	9

Simulated top dry matter production and harvestable dry matter production, respectively were 9.8 and 5.2 t ha^{-1} at Alemaya, 8.8 and 4.9 t ha^{-1} at Awassa, 7.7 and 4.1 t ha^{-1} at Bako, 7.3 and 4.0 t ha^{-1} at Melkassa and 10.6 and 5.8 t ha^{-1} at Zeway. The harvest index in the present study ranged between 0.53 and 0.56, which is very close to the harvest index recorded for the cultivar (0.53) with top dry matter production of 7.1 t ha^{-1} at Pretoria (Chapter 3, unpublished data). The large differences to days to maturity across different locations partially explain for big yield differences observed between locations with the exception at Zeway. At locations where the crop took longer days to mature it seems high solar radiation accumulated resulting in higher yields. Similarly, direct relationship between simulated transpiration and dry matter production across the sites was observed with the exception of Alemaya (Tables 10.7 and 10.8).

Table 10.8 Simulated hot pepper productivity at five ecological regions of Ethiopia under full irrigation

Station	Days to maturity (days)	TDM (t ha^{-1})	HDM (t ha^{-1})	Harvest index	WUE (TDM) [kg ha^{-1} mm^{-1}]	WUE (HDM) [kg ha^{-1} mm^{-1}]
Alemaya	202	9.8	5.2	0.53	12.6	6.9
Awassa	146	8.8	4.9	0.56	14.6	8.1
Bako	138	7.7	4.1	0.53	12.6	6.7
Melkassa	134	7.3	4.0	0.55	14.1	7.7
Zeway	145	10.6	5.8	0.55	16.9	9.2

Notes: TDM: top dry matter; HDM: harvestable dry matter; WUE: water-use efficiency.

High water-use efficiency (WUE) for both top dry matter and harvestable dry matter was simulated for Zeway while the lowest was simulated for Alemaya and Bako

(Table 10.8, Figure 10.3). The higher yield simulated at Alemaya did not result in higher WUE and the lowest yield simulated at Melkassa did not result in lowest WUE. This is because yield and biomass did not increase proportionally per unit of water utilized by crop at Alemaya as that of Zeway. And yield and biomass did not decrease proportionally per unit of water reduced at Melkassa as compared to Bako. Similar results have been reported for different cultivars at Pretoria (Chapter 3, unpublished data) whereby increased dry matter production with increased water application does not necessarily bring about improvement in WUE. Likewise, reduction in water application does not always guarantee improvement in WUE as yield reduction might outweigh water saved in terms of WUE.

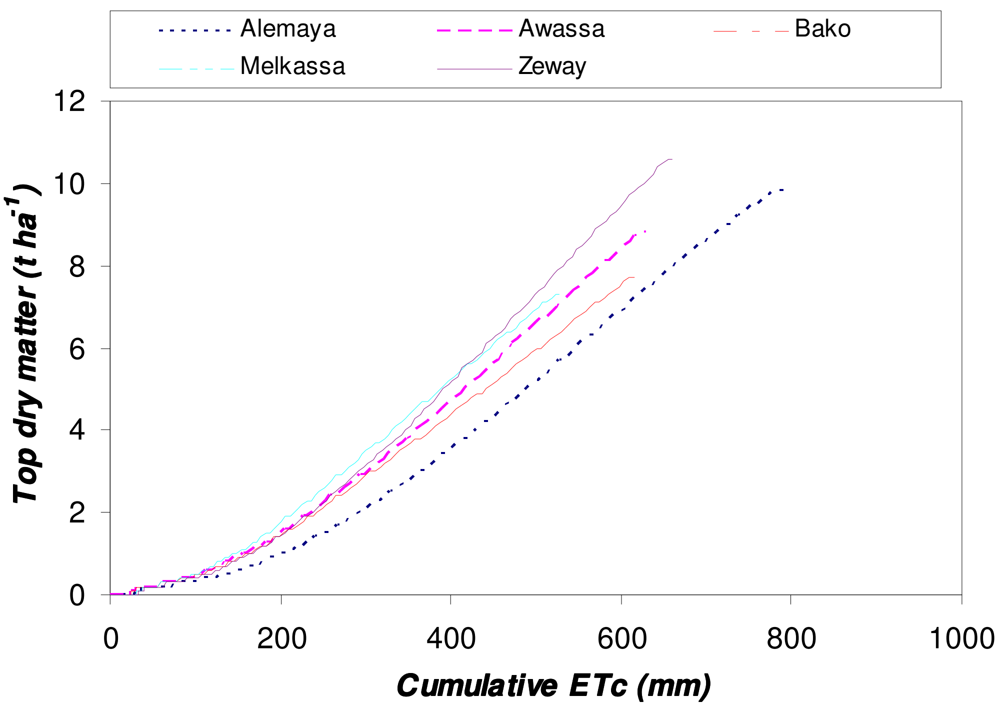


Figure 10.3 Relationship between cumulative crop evapotranspiration (ETc) and top dry matter production of Mareko Fana for five ecological regions of Ethiopia.

10.4 CONCLUSIONS

Irrigation calendars and water requirements for hot pepper production at five ecological regions of Ethiopia were established using the Soil Water Balance model. Water balance, days to maturity and dry matter production were simulated, and WUE and harvest index were calculated for the five ecological regions considered. The highest simulated average irrigation interval observed was at Alemaya, while the lowest was at Bako. There appeared marked variation in irrigation amount per irrigation and total water requirements among the five ecological regions studied. The variation in irrigation depth and interval across the different locations is due to difference in climatic variables, that is, relative humidity, solar radiation, temperature and wind speed. Temperature was used by the SWB model to simulate days to maturity, and hence it appeared that where the average temperature is low, the crop took a longer time to mature, which in turn contributed to high total water requirements in the cooler environment. Differences in soil water holding capacity also seems to contribute for variations in days between irrigation events

The generated irrigation calendars are simple to read and provide farmers with important information pertaining to scheduling irrigation. Furthermore, the generated irrigation calendar can be made flexible to account for rainfall, where recommendation on irrigation amounts could be calculated by subtracting rainfall amount since the previous irrigation from the irrigation requirement indicated by the SWB. This type of irrigation calendar can be easily generated by the district Ministry of Agriculture's irrigation specialist and the calendar can be disseminated to farmers using development agents working with the farmers. Owing to its simplicity, such irrigation calendars is expected to be highly adoptable by farmers for aiding irrigation scheduling.

CHAPTER 11

GENERAL CONCLUSIONS AND RECOMMENDATIONS

11.1 GENERAL CONCLUSIONS

Hot pepper is a warm season, high value cash crop, of which production is generally confined to areas where water is often limiting. Since the crop is sensitive to water stress irrigation is standard practice in hot pepper production. However, the amount of water available for irrigation is declining consistently as a result of pressure from other competing sectors (domestic, recreation, environmental and industrial uses). Furthermore, excess water application of irrigation is one of the main reasons for degradation of agricultural land through salinization. Hence there is a need to improve irrigation management and water-use efficiency in crop production. Furthermore, with hot pepper being a high value and labour-intensive cash crop, with high production costs, it is necessary to devise means of decreasing the cost of production. Irrigation as a tactical tool to increase productivity of hot pepper is recommended, because irrigation improves yield by its direct effect of mitigating water stress, and encourages farmers to invest in inputs such as fertilizers and improved cultivars.

Irrigation scheduling and deficit irrigation form part of proper irrigation management that are crucial for improving the water-use efficiency of hot pepper. Irrigation scheduling improves water-use efficiency by enabling an irrigator to use the right amount of water at the right time for plant production. Likewise, deficit irrigation, the deliberate and systematic under-irrigation of crops, increases the water-use efficiency of a crop by reducing evaporation, but maintaining yield that is comparable to a fully irrigated crop. It can also conserve water and minimize leaching of nutrients and pesticides to groundwater. Furthermore, understanding the variability of cultivar response to different irrigation regimes, and the influence of cultural practices such as row spacing on hot pepper response to irrigation are crucial in improving the water-use efficiency of hot pepper.

Accordingly, a series of field, rainshelter, growth cabinet and modelling studies were conducted: to investigate hot pepper response to different irrigation regimes and row spacings; to generate FAO-type crop factors and crop-specific model parameters; to calibrate and validate the Soil Water Balance (SWB) model, to develop irrigation calendars, and estimate water requirements of hot pepper under different growing conditions.

Canopy size and its configuration is an important crop characteristic that determines efficiency of radiation capture by a crop. This plant growth attribute is quantified using plant parameters such as LAI, SLA and FI, which are influenced by cultivar and growing conditions. In the present studies, the effects of row spacing, irrigation regime and cultivar differences on these parameters were investigated. Irrigation regime and row spacing significantly affected FI. Narrow row spacing significantly increased LAI, and although the effect was small, an increasing trend in LAI was observed for the high irrigation regime. The influence of irrigation regime and row spacing on SLA was inconclusive, while marked variation in SLA was observed among the cultivars. The higher solar radiation interception in the narrow row spacings is attributed to a more even leaf distribution than in the wider row. A reduction in FI due to water stress is attributed to the corresponding reduction in LAI as a result of water stress.

Water-use and water-use efficiency, in a crop are important variables employed to quantify the water usage and water-use efficiency of a crop. The water requirements of peppers vary between 600 to 1250 mm, depending on region, climate and cultivar (Doorenbos & Kassam, 1979). Seasonal water-use, in the open field experiment, across cultivars varied between 516 mm for Jalapeno and 675 mm for Malaga in the well-watered treatment (25D). Under severe water stress (75D), the seasonal water-use ranged from 430 mm for Jalapeno and 532 mm for Malaga. The variation in water-use among the cultivars is mainly attributed to the length of the growing season. The seasonal water-use in the rainshelter experiment varied between 539 mm for the well-watered and 369 mm for the water-stressed treatments. The corresponding average irrigation interval was three days for well-irrigated and 10 days for the water-stressed treatments.

Variable WUE results were reported for pepper with different irrigation regimes. In the present studies, WUE was improved for high density plantings, but remained unaffected by irrigation regime. WUE did not improve with a reduced irrigation regime, as the water saved was overshadowed by yield loss. High WUE were observed due to high plant density. This is attributed to the significant improvement in fresh and dry fruit mass as well as top dry matter produced due to high plant density. The WUE in terms of fresh and dry fruit yields were significantly influenced by cultivar, but WUE for top dry matter production was not cultivar dependent. The marked variation in WUE among cultivars is attributed to their differences in time to maturity and harvest index.

Fruit yield in hot pepper is a function of total dry matter production and harvest index. Fruit yield in hot pepper can also be related to fruit number per plant and average fruit mass. High irrigation regimes and high plant density significantly increased fresh and dry fruit yields. High irrigation regimes significantly improved the top, and stem dry matter, fruit number per plant and assimilate partitioned to fruit in both the rainshelter and open field experiments. Leaf dry matter and average fruit mass were not affected by irrigation regime in both the rainshelter and open field experiments. Variable results were obtained for assimilates partitioned to stems and leaves between the rainshelter and open field experiments as the irrigation regime changed.

The marked improvement in dry fruit yield by the higher irrigation regime was attributed to the corresponding significant increase in harvest index, fruit number and top dry mass observed under the high irrigation regime. The marked yield differences between the 25D and 55D treatments, in the rainshelter experiment, showed that mild water stress could cause substantial yield loss in hot pepper, confirming the sensitivity of hot pepper to water stress. Thus, it is recommended to maintain the depletion of plant available water between 20-25% for maximum yield. However, where the cost of fresh water is high, further research is recommended to establish optimal irrigation regimes between 25 and 55% depletion of plant available water. Furthermore, research that seeks to quantify the trade-off between the yield loss that would be incurred because of deficit irrigation, and the economic and ecological advantage that would be generated by practicing deficit irrigation, is recommended.

Top, leaf and stem dry matter yields were significantly improved due to increasing planting density. Assimilate partitioning, succulence and average fruit mass were unaffected by planting density. Planting density effects on fruit number was variable. The higher productivity observed due to narrow row spacing as compared to wide row spacing was attributed to higher top dry mass and fruit dry mass per unit area of land obtained under narrow row spacing than for wider rows. The cumulative compensatory growth (higher fruit number per plant, higher average fruit mass, and higher individual plant dry matter production) in wide row spaced plants was not adequate to offset the yield reduction incurred as a result of the reduction in the number of plants per unit area in wide row spacing.

Marked differences in leaf dry and stem dry matter yields, assimilate partitioning to fruits, leaves and stems were observed due to cultivar differences in both row spacing and irrigation regime studies, but the top dry matter production was not affected by cultivar differences. Fresh and dry fruit yields, average dry fruit mass, fruit number per plant, and succulence were significantly affected by cultivar differences in both irrigation regime and row spacing studies. Fruit number per plant and average fruit mass exhibited an inverse relationship for all cultivars.

Despite the fact that all the cultivars produced comparable top dry biomass yields, there were significant differences in dry and fresh fruit yields among the cultivars. Malaga, a cultivar with the highest fruit number, leaf area and leaf mass (per plant), gave the least fresh and dry fruit yields. Jalapeno, a cultivar with the highest harvest index and average fruit mass, produced the highest fresh and dry fruit yields. Thus, the yield differences among the cultivars were more attributed to differences in harvest index and average fruit mass than to differences in leaf area, top biomass or fruit number. The wide range in fresh fruit yield per unit land among the cultivars was attributed to the marked difference between cultivars in fruit succulence at harvest. No significant interaction effect was observed for most parameters studied, revealing that hot pepper response to row spacing did not depend on cultivar differences. Thus, it appears that appropriate row spacing that maximizes production of hot pepper can be devised across cultivars. Furthermore, the existence of a consistent inverse relationship between average dry fruit mass and fruit number per plant among the cultivars confirms the difficulty of simultaneously achieving improvement in these two parameters.

Overall, fruits remained the major sink, accounting for more than 51 % of the top dry mass, followed by stems (30%) and then leaves (19%). In the present studies, reduction in fruit number, probably due to flower abortion under water stress, may have enhanced accumulation of available dry matter in the remaining fruits, maintaining the final fruit mass of water stressed plants comparable to those fruits harvested from well-water plots.

In the absence of crop-specific model parameters for more complex irrigation scheduling models, an FAO-type crop factor can be utilized to schedule irrigation. Thus, a simple canopy-cover based procedure was used to determine FAO Kcb values and growth periods for different growth stages. A simple water balance equation was used to estimate the crop evapotranspiration and Kc values of cultivar Long Slim. In addition, initial and maximum rooting depths and maximum plant heights were determined. The test of this model revealed that this approach is very useful to predict soil water deficit.

A database of SWB model parameters was generated for four South African cultivars (Jalapeno, Malaga, Serrano, and Long Slim) and one Ethiopian hot pepper cultivar (Mareko Fana). Almost all crop-specific model parameters studied appeared to remain stable under different irrigation regimes and row spacings. This was because most of these crop-specific model parameters integrating several variables over the course of time. The conservative natures these parameters enable the use mechanistic models to simulate growth and water requirements as these models take environmental factors into accountl. However, significant differences for most crop-specific model parameters were observed due to cultivar differences. This is a reflection of the inherent cultivar variability in their ability to capture resources (solar radiation, water, nutrients) and convert them into dry matter.

Understanding cultivar features such as time to maturity, canopy structure and size, and level of dry matter production are important when trying to adapt crop-specific model parameters from a cultivar with an established set of crop-specific model parameters, to a newly released cultivar without having to perform a separate growth analysis and water balance study.

The SWB model was successfully calibrated and validated for the hot pepper cultivars for fractional interception, leaf area index, to dry matter production and harvestable dry matter production. The soil water deficit to field capacity was predicted with an accuracy that was sufficient for irrigation scheduling purposes. However, model validation statistical parameters under both low density and deficit irrigation conditions were outside the reliability criteria imposed.

It appears that marked differences exist between hot pepper cultivars with respect to their cardinal temperatures. This especially holds true for cut-off temperature to different developmental stages. Furthermore, distinction needs to be made between vegetative and flowering stages, as these developmental stages responded differently to low and high temperatures, in that high temperatures greatly limit the development rate of reproductive growth, while their effect on vegetative rate of development is minimal.

Irrigation calendars and water requirements for hot pepper production in five ecological regions of Ethiopia were estimated, using the calibrated SWB model. Simulated water requirements for hot pepper cultivar Mareko Fana production, ranged between 517 mm at Melkassa and 775 mm at Alemaya. The highest simulated average irrigation interval was observed for Alemaya (nine days), while the lowest was observed for Bako (six days). The depth of irrigation per event ranged from 35.0 mm in Zeway to 27.9 mm in Bako.

In final conclusion, this study demonstrated that water-use efficiency of hot pepper can be improved by exercising the following interventions: correct choice of cultivars, adoption of irrigation scheduling, and narrow row spacing (less than 0.7 m). Low regime irrigation (irrigating at 50-75% depletion of soil water available) seems disadvantageous for hot pepper production as it did not improve the WUE significantly. The study further showed that the SWB model is a useful tool for irrigation scheduling, generating irrigation calendars and estimating plant water requirements. It was also found to estimate yield and growth of hot pepper with a high degree of accuracy. Therefore, the model can be used to schedule irrigation and estimate yield. Where resources for computer and model application know-how are lacking, a flexible irrigation calendar can be generated using the SWB for an agro-ecological region by an irrigation expert to be utilized by resource-poor farmers.

This study further highlighted that most crop-specific model parameters were stable for different plant densities and irrigation regimes, thus confirming the conservative nature of these parameters under different growing conditions. However, significant cultivar differences were observed for most crop-specific model parameters. The study also indicated that vegetative and reproductive growth stages need to have separate sets of cardinal temperatures, as these developmental stages responded differently to the same set of cardinal temperatures.

11.2 GENERAL RECOMMENDATIONS

- It is recommended to maintain the percentage depletion of plant available water between 20-25% for maximum hot pepper production.
- Yield and water-use efficiency could be improved by decreasing the row spacing from 0.7 m to 0.45 m.
- Irrigation at high (55-75%) depletion of plant available water is not appropriate in hot pepper production until further research confirms the economic advantage of water saved and ecological benefit derived through low irrigation regime can outweigh the yield loss.
- The lack of interaction effects between cultivars and irrigation regimes, cultivars and row spacings, irrigation regimes and row spacings for yield, yield components and quality parameters indicate that improvements in these parameters can be achieved by setting up independent experiments of different irrigation regimes, row spacings, and cultivars and then by selecting the best performing combination.
- Most crop-specific model parameters studied appeared to remain stable under different irrigation regimes or row spacings. Thus, a single set of crop-specific model parameters can be used to simulate growth under different irrigation regimes or row spacings.
- It is recommended to consider hot pepper's cultivar differences in such attributes as canopy characteristics, thermal time to maturity and dry matter production before adopting crop-specific model parameters of a known cultivar for a new cultivar.
- Where know-how and computing facilities are available, the SWB model can be a powerful tool for real-time irrigation scheduling.
- Where a knowledge gap and lack of computing facilities prohibit the use of technologies, such as the SWB model, the FAO crop factor approach can be employed to schedule irrigation with an acceptable degree of accuracy. Furthermore, the SWB model can be used to generate a fixed irrigation depth and interval from long term climatic, crop, soil and management data. Such fixed

irrigation calendars developed by the SWB model for a crop can be upgraded to flexible irrigation calendars by making use of real-time rainfall data so as to modify the irrigation calendar.

- Separate base, optimum temperature and cut-off temperatures need to be used to model vegetative and reproductive growth, as reproductive growth appeared to be arrested by relatively low and high temperatures, whereas vegetative growth seemed to withstand relatively low and high temperatures.

11.3 RECOMMENDATIONS FOR FURTHER RESEARCH

- Where the cost of fresh water is high, further research is recommended to establish irrigation regimes between 20 and 55% depletion of plant available water. This undertaking must seek to quantify the trade-offs between the yield loss that would be incurred because of low irrigation regime and the economic and ecological advantages of low irrigation regime.

- Row spacings below 0.45 m need to be tested for optimum hot pepper yields and WUE.

- In future the SWB model needs to be improved by accounting for the effect of row spacing on crop-specific model parameters such as K_{PAR} and E_c.

- Cardinal temperatures for vegetative and reproductive growth stages and different cultivars need to be determined by setting up growth cabinet studies. The numbers of growth cabinets have to be more than five and the different temperatures have to be in small increments that are not more than 7.5 °C. The lowest temperature has to also greater than 10 °C and less than 17.5 °C.

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APPENDICES

Figure A1 The automatic weather station at Hatfield Experimental Farm, Pretoria.

Figure A2 The Hydro probe neutron water meter, model 503DR CPN, used in the Experiments.

Figure A3 The sunfleck ceptometer, model AccuPAR, used to measure PAR.

Figure A3 Partial view of the open field experiment 1 (Outdoor irrigation regime study).

Figure A4 Partial View of the open field experiment 2 (Outdoor row spacing study).

Figure A2 Partial view of the rainshelter experiment.

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Table A1 Weather data (Hatfield Experimental Farm, Pretoria) 2004/05 growing season

	RF (mm)	Ta_{max} (°C)	Ta_{min} (°C)	Solar (MJ m^{-2} day^{-1})	U (m s^{-1})	VPD (KPa)	RH_{min} (%)	RH_{max} (%)
2004/11/01	0	30	11.2	33.7	1.9	0.9	18	76
2004/11/02	0	30.2	13.2	33.4	1.8	0.8	16	58
2004/11/03	0	31.8	15	29.2	2.5	1	18	58
2004/11/04	0	29.3	15	31.3	2.3	1.3	27	85
2004/11/05	0	31.6	16.6	30.6	2.6	1.3	27	73
2004/11/06	0	30.1	17.2	26.6	3.4	1.7	33	92
2004/11/07	2	30.4	15.5	26.2	2.4	1.6	31	100
2004/11/08	0	31.4	18.2	27.1	3.3	1.6	30	89
2004/11/09	0.2	31.9	14.4	32.5	1.8	1.6	27	100
2004/11/10	0	33	16.6	30.9	2	1.5	25	86
2004/11/11	24.5	30.1	15.9	24.2	3.6	2	48	100
2004/11/12	4	27	15.5	26.6	2.1	2	57	100
2004/11/13	0	27.7	18.4	19.8	2.3	2.1	40	100
2004/11/14	0.5	28.1	17.3	25.1	2.5	2	48	100
2004/11/15	10	29.2	16.8	27.2	2.5	2.1	48	100
2004/11/16	0	30.4	15.5	26.2	2.4	1.6	31	100
2004/11/17	0.6	24.8	23.6	0	1.6	2.2	69	78
2004/11/18	8.5	29.2	16.8	27.2	2.5	2.1	48	100
2004/11/19	0	31.9	19.3	21.4	3.3	1.6	30	89
2004/11/20	0	33.2	21.8	20.3	1.8	1.6	27	100
2004/11/21	18.5	30.2	20.3	19	2	1.5	25	86
2004/11/22	0.3	28.2	16.9	20.3	3.6	2	48	100
2004/11/23	0	29.8	16.3	22.2	2.1	2	57	100
2004/11/24	0	28.4	20	36.4	1.9	1.7	33	89
2004/11/25	0	31.2	20.8	43.9	2.1	1.7	32	91
2004/11/26	0	31.9	18.6	31.7	2.1	1.7	28	78
2004/11/27	4	31.7	18.3	30.6	3.1	2.1	40	100
2004/11/28	0	28.6	18.8	30.2	3.4	1.9	43	85
2004/11/29	1.1	26.5	17.7	16.3	2.4	1.9	51	93
2004/11/30	22.3	28.4	16.2	22.4	2.3	1.9	47	100
2004/12/01	0	21.7	16.2	16.3	2.3	2.1	69	100
2004/12/02	0	29.7	17.6	21.2	2	1.5	25	86
2004/12/03	7.4	30	19.3	19.9	3.6	2	48	100
2004/12/04	0	29.7	19.3	19.7	2.1	2	57	100
2004/12/05	0.1	30	21.2	18.1	1.9	1.7	33	89
2004/12/06	1.5	29.7	19.3	19.7	2.1	1.7	32	91
2004/12/07	4.5	30.6	18.5	21.2	2.1	1.7	28	78
2004/12/08	28.5	29.3	18.9	19.7	3.3	2.1	58	100
2004/12/09	5	33.7	16.5	25.4	2.3	2.1	48	100
2004/12/10	0	23.2	13.9	18.7	1.8	2.1	51	100
2004/12/11	0	19.5	17.9	7.7	1.6	2	45	100
2004/12/12	0	28.1	16.5	20.8	2.7	2	57	100
2004/12/13	0	28.8	18.8	24.9	3.2	1.8	47	83
2004/12/14	4	30.6	15.4	25.1	1.6	1.9	40	100
2004/12/15	0	29.8	17.4	31.5	2.7	2.1	37	100
2004/12/16	4.5	27.3	17	26.8	2.5	2.1	61	100
2004/12/17	0	26.1	17.1	21.7	1.6	2.2	69	100
2004/12/18	11.5	30.2	18.1	24.7	2	2.1	40	100

2004/12/19	0	26.5	17.3	25.3	3.3	2.1	58	100
2004/12/20	41	27.3	16	25.2	2.3	2.1	48	100
2004/12/21	0.4	27.3	15.6	24.6	1.8	2.1	51	100
2004/12/22	2	28.9	16.1	33	1.6	2	45	100
2004/12/23	5	26.8	15.8	21.9	2.7	2	57	100
2004/12/24	11.5	26.6	15.7	26.1	2.7	2	62	100
2004/12/25	0	27.1	14.3	24.6	1.8	2.2	61	100
2004/12/26	0	31.4	18.1	32.9	2.3	2.1	34	100
2004/12/27	9.5	31.6	18.9	34.5	2.1	2.3	44	100
2004/12/28	21.5	28.9	17.1	27.4	2.7	2.2	54	100
2004/12/29	0	28.9	17.2	30.3	2	2.1	52	100
2004/12/30	0	31.5	18.3	32.6	2	2.1	42	94
2004/12/31	0	30.7	18.7	23.4	0.9	2.3	53	100
2005/01/01	0.4	30.8	20.4	33.4	1.5	2.3	46	97
2005/01/02	0	30.4	19.4	31.3	2	2.3	46	100
2005/01/03	21.2	30.6	18.2	32.9	2.1	2.1	41	100
2005/01/04	0	30.5	14.6	33.9	1.6	2.2	43	100
2005/01/05	0	32.4	19.5	32.7	1.9	2.4	37	100
2005/01/06	0	31.9	18	32	1.4	2.3	48	97
2005/01/07	0.5	32.9	20.7	31.5	1.7	2.3	43	94
2005/01/08	25.5	32.1	17.6	27.2	2	2.3	45	100
2005/01/09	2.7	26.9	16.8	24.1	1.9	2.2	64	100
2005/01/10	0	26.8	17.2	24.6	1.7	2.2	62	100
2005/01/11	0	28.2	17.7	28.1	1.1	2.3	54	100
2005/01/12	0.5	30	18.3	27.7	3.3	2.2	47	100
2005/01/13	0	29.5	18	29.3	3	2.3	54	100
2005/01/14	29.7	22	17.1	6	2	2.2	93	100
2005/01/15	1.1	27	16.8	16.1	1	2.2	64	100
2005/01/16	0	24.3	18.1	12.8	1.9	2.2	73	100
2005/01/17	0	24.1	16.1	16.6	1.2	2.1	74	100
2005/01/18	67.4	27.6	16.4	26.4	1.2	2.2	60	100
2005/01/19	0	25.1	16.9	17.9	1.3	2.3	75	100
2005/01/20	27.5	23.8	18	11.5	0.7	2.3	84	100
2005/01/21	28.9	21.1	17.7	7	1.3	2.2	100	100
2005/01/22	0	27.8	17.6	25	1.1	2.4	66	100
2005/01/23	12.5	28.9	17.1	22	1.2	2.4	62	100
2005/01/24	0	29	15.6	33.3	1.1	2.3	54	100
2005/01/25	0	29.5	18.7	25.4	1.1	2.4	51	100
2005/01/26	0	30.9	17.7	28.9	1.4	2.4	44	100
2005/01/27	0	28.2	17.9	21.9	2	2.3	63	100
2005/01/28	0	30.3	15.8	33.1	1.9	2.3	52	100
2005/01/29	0	29.8	18.8	29.3	2.7	2.2	47	100
2005/01/30	0	29.3	18.7	24.3	2.1	2.3	51	100
2005/01/31	0	26.9	19.3	20.2	1.9	2.3	60	100
2005/02/01	0	31.1	17.4	27.4	1.9	2.1	41	100
2005/02/02	0	30.5	17.9	29.7	2.2	2.1	40	100
2005/02/03	0	31.9	17.7	33.1	1.4	1.9	30	95
2005/02/04	0	34	15.9	31	1.5	1.9	29	95
2005/02/05	0	28.7	18.6	25.7	3.3	2.3	59	100
2005/02/06	0	25.1	17.3	14.3	2.4	2.1	71	100
2005/02/07	0	29.1	14.1	31.9	1.5	1.9	43	100
2005/02/08	0.7	30.6	16.8	27.7	2.2	2.1	42	100
2005/02/09	0	29.2	18.1	28.1	2	2.1	51	100
2005/02/10	0	30.6	15.3	29.6	1.5	2	43	100

2005/02/11	3.7	32.7	16.5	26.4	1.2	2	34	100
2005/02/12	0	27.8	17.7	16.9	2.6	2.1	56	100
2005/02/13	0	29.3	17.6	29.5	1.5	2.1	51	100
2005/02/14	0	31.6	16.1	30.5	2.1	1.7	30	100
2005/02/15	0	30.8	18.1	29.6	2.5	1.8	28	100
2005/02/16	0	29.2	17	32.3	2.9	1.7	36	90
2005/02/17	0	29.7	16.1	31.2	1.7	1.8	33	95
2005/02/18	0	29.9	18.2	27.9	1.9	1.9	42	86
2005/02/19	0.5	30.1	19.3	24.6	1.8	2.1	44	98
2005/02/20	25	24.9	18.1	7.7	2	2.2	72	100
2005/02/21	15.7	21.8	17.1	7.3	0.7	2.1	92	100
2005/02/22	0	27.2	16.6	20.3	1.3	2.3	67	100
2005/02/23	0.3	28.5	16.4	22.1	1.9	2.2	55	100
2005/02/24	0	29.4	15.1	27.1	1	2.1	42	100
2005/02/25	0	30.2	17.7	26.1	2	2	41	100
2005/02/26	3.4	29.2	17.4	24.6	2	2.2	56	100
2005/02/27	0	28.6	17.3	25.5	1.7	2.2	48	100
2005/02/28	0.5	27.8	17.6	22	2	2.2	63	100
2005/03/01	0	28.5	14.7	27.2	1.2	2	49	100
2005/03/02	0	28.8	17	27	2.9	2	45	97
2005/03/03	7	27.7	16.1	26	2	1.9	46	100
2005/03/04	0	25.9	15.1	25.3	2.2	1.9	56	100
2005/03/05	0	26.7	15.3	21.6	1.3	2	60	100
2005/03/06	0	27.9	15.9	26.9	2.1	1.9	47	100
2005/03/07	0	28.3	14.2	29.5	2.1	1.5	33	95
2005/03/08	0	31.5	15.2	28	1.8	1.5	28	91
2005/03/09	0	32.4	15.9	28.6	1.5	1.4	27	70
2005/03/10	0	30.1	18.1	22.5	1.8	2.3	57	100
2005/03/11	0.2	26.3	14.8	20.5	4.1	1.9	65	100
2005/03/12	0	23.2	14.1	14.7	2.3	1.7	66	99
2005/03/13	0	24.6	13.4	18.9	1.1	1.8	54	100
2005/03/14	0	23.7	14.5	16.1	1.3	1.8	61	100
2005/03/15	0	26.3	13.4	20.4	2.3	1.8	49	100
2005/03/16	19.5	25.7	14.6	22.4	2.4	1.9	56	100
2005/03/17	0	26.3	13.9	22.1	1.4	2	56	100
2005/03/18	0.7	26.6	14.8	25.2	2.3	1.9	45	100
2005/03/19	0	25.9	14.3	23.5	1.8	1.8	42	100
2005/03/20	0	26.2	14.3	18.7	1	1.9	53	100
2005/03/21	0	25.8	15.8	19.9	2.6	1.9	59	100
2005/03/22	17.9	21.3	14.7	4.5	2.7	1.9	82	100
2005/03/23	0	22.7	14.9	14.2	3.4	1.9	67	100
2005/03/24	0	24.8	14.5	24.1	2	1.9	61	100
2005/03/25	0	24.5	13	16.4	1.2	1.9	63	100
2005/03/26	0	27.9	14.6	21.1	1.3	1.9	49	100
2005/03/27	0	24.8	17.4	15.8	1.7	2.2	73	100
2005/03/28	0	28.5	14.4	25.8	1.9	1.6	28	100
2005/03/29	1	26.7	16.5	16	2.1	2.1	59	100
2005/03/30	1	26.3	16.2	19.3	1	2	54	100
2005/03/31	0	28.4	13.5	24	0.8	1.9	46	100
2005/04/01	0	28.1	17.5	21.1	1.9	2	52	100
2005/04/02	1	23.3	17.9	8.7	1	2.2	77	100
2005/04/03	43.8	18.2	14.1	2.6	2.3	1.8	100	100
2005/04/04	4.5	24.3	14.3	18.9	1	1.9	70	100
2005/04/05	0	23.6	15.4	19.8	2.7	2	73	100

2005/04/06	0	23.3	13.5	21.3	1.8	1.7	56	100
2005/04/07	0	19	12.7	9.8	1.7	1.6	74	100
2005/04/08	0	24.2	13.8	19.7	1.6	1.7	51	100
2005/04/09	0	24.2	12.1	18.8	0.8	1.7	52	100
2005/04/10	0	25	14.1	19.6	1.5	1.8	57	100
2005/04/11	0	26	12.7	19.3	0.8	1.7	49	100
2005/04/12	0	26.6	12.7	19.6	1.3	1.6	46	100
2005/04/13	0	27.9	13.9	21.6	2.3	1.4	38	88
2005/04/14	0	22.4	15.6	9	1.6	1.9	78	100
2005/04/15	2.5	23.5	14	13.1	1.8	1.9	68	100
2005/04/16	5	18.4	13	4.1	0.9	1.7	91	100
2005/04/17	0	24.3	10.3	21.1	0.9	1.8	61	100
2005/04/18	0	27.5	12.3	21.3	0.9	1.8	44	100
2005/04/19	0	28	13.6	20.3	1.4	1.8	43	100
2005/04/20	1.5	23.2	15.2	11.4	1.9	1.9	66	100
2005/04/21	0	25.1	11.7	20.2	1.8	1.7	54	100
2005/04/22	13.4	20.9	12.2	7.5	1.7	1.7	79	100
2005/04/23	0.5	18.3	10.4	7.9	0.7	1.6	89	100
2005/04/24	0	22.7	10.7	17	1.4	1.8	76	100
2005/04/25	0	24.6	10.8	20.1	2	1.5	36	100
2005/04/26	0	22.6	10.2	16.8	2	1.4	45	100
2005/04/27	0	21.1	11.4	16.7	3.2	1.4	47	100
2005/04/28	0	21.3	9.1	16.9	1.4	1.3	46	100
2005/04/29	0	21.6	8.3	18.3	1.5	1.3	44	100
2005/04/30	0	21.8	7.5	17.6	1.1	1.3	47	100
2005/05/01	0	21.3	9.8	14.6	0.8	1.3	50	100
2005/05/02	0	23.5	8.1	19.2	0.6	1.2	34	100
2005/05/03	0	22.6	9.2	16.7	1.5	1.3	43	100
2005/05/04	0	23.2	11.1	18.9	1.7	1.4	48	100
2005/05/05	0	24.7	11.5	18.3	1.8	1.5	46	100
2005/05/06	0	26.1	9.8	18.7	1.6	1.3	36	100
2005/05/07	0	27.1	12.3	15.8	2.3	1.1	35	82
2005/05/08	0	25.5	11	18.7	1.7	1.4	43	94
2005/05/09	0	25	12	16.3	1.1	1.6	45	100
2005/05/10	0	24.5	9.9	18.3	0.8	1.5	46	100
2005/05/11	0	23.4	8.8	18	0.7	1.4	46	100
2005/05/12	0	22	10.2	18.2	1.2	1.2	41	100
2005/05/13	0	23	7.3	18.3	0.8	1.1	31	100
2005/05/14	0	24.1	8.3	17.9	3.1	1.2	35	95
2005/05/15	0	22	12.2	15.5	1.6	1.6	60	100
2005/05/16	0	22.5	9	16.5	1.8	1.3	49	100
2005/05/17	0	24.4	7.1	17.7	0.8	1	21	100
2005/05/18	0	26.1	6	17.2	0.9	0.9	24	92
2005/05/19	0	26.2	8.8	14	1.5	1	30	88
2005/05/20	0	22.9	11.5	17.2	2.8	1.4	44	100
2005/05/21	0	20.2	10.1	9.5	0.4	1.5	67	100
2005/05/22	0	22.5	7.3	16.9	0.5	1.3	41	100
2005/05/23	0	21.9	7.3	16.8	0.8	1.2	34	100
2005/05/24	0	24.3	8.3	16	1.9	1.1	31	93
2005/05/25	0.5	19.9	9.2	14.6	2.7	1.3	50	100
2005/05/26	0	19.5	8.2	17	1.3	1.2	46	100
2005/05/27	0	21.2	4.8	16.8	0.6	1.1	41	100
2005/05/28	0	24.4	6.1	15.8	0.7	1.1	30	100
2005/05/29	0	23.4	9	14.8	2	0.9	32	77

Table A2 Penman-Monteith reference grass evapotranspiration (ETo) for Pretoria, Hatfield Experimental Farm, during field experiment execution period

Date	ETo	Date	ETo	Date	ETo
2004/11/11	0	2004/12/25	6.51	2005/02/07	6.53
2004/11/12	5.56	2004/12/26	6.81	2005/02/08	6.9
2004/11/13	5.6	2004/12/27	6.61	2005/02/09	6.15
2004/11/14	5.09	2004/12/28	6.54	2005/02/10	5.76
2004/11/15	4.94	2004/12/29	6.63	2005/02/11	5.27
2004/11/16	7.14	2004/12/30	6.68	2005/02/12	2.37
2004/11/17	8.69	2004/12/31	6.13	2005/02/13	1.86
2004/11/18	7.2	2005/01/01	4.91	2005/02/14	3.63
2004/11/19	6.94	2005/01/02	4.69	2005/02/15	4.36
2004/11/20	6.7	2005/01/03	5.29	2005/02/16	5.1
2004/11/21	4.14	2005/01/04	5.92	2005/02/17	5.37
2004/11/22	4.94	2005/01/05	5.95	2005/02/18	5.03
2004/11/23	3.05	2005/01/06	1.76	2005/02/19	4.98
2004/11/24	4.95	2005/01/07	3.12	2005/02/20	4.42
2004/11/25	5.45	2005/01/08	2.81	2005/02/21	5.1
2004/11/26	4.91	2005/01/09	3.3	2005/02/22	5.8
2004/11/27	4.94	2005/01/10	4.8	2005/02/23	5.2
2004/11/28	5.32	2005/01/11	3.49	2005/02/24	4.7
2004/11/29	5.48	2005/01/12	2.4	2005/02/25	5.37
2004/11/30	5.09	2005/01/13	1.66	2005/02/26	5.03
2004/12/01	6.06	2005/01/14	4.44	2005/02/27	4.98
2004/12/02	3.73	2005/01/15	4.37	2005/02/28	4.42
2004/12/03	1.68	2005/01/16	6.18	2005/03/01	5.12
2004/12/04	4.35	2005/01/17	4.91	2005/03/02	5.42
2004/12/05	5.93	2005/01/18	5.77	2005/03/03	5.14
2004/12/06	5.49	2005/01/19	4.61	2005/03/04	4.73
2004/12/07	6.39	2005/01/20	6.27	2005/03/05	4
2004/12/08	5.37	2005/01/21	6.01	2005/03/06	5.09
2004/12/09	4.24	2005/01/22	5.13	2005/03/07	5.84
2004/12/10	5.21	2005/01/23	4.25	2005/03/08	5.77
2004/12/11	5.15	2005/01/24	5.74	2005/03/09	5.93
2004/12/12	4.91	2005/01/25	6.21	2005/03/10	4.67
2004/12/13	4.76	2005/01/26	6.66	2005/03/11	4.52
2004/12/14	6.19	2005/01/27	6.62	2005/03/12	3.2
2004/12/15	4.61	2005/01/28	5.41	2005/03/13	3.36
2004/12/16	5.01	2005/01/29	3.35	2005/03/14	3.02
2004/12/17	4.53	2005/01/30	5.9	2005/03/15	3.93
2004/12/18	6.55	2005/01/31	5.61	2005/03/16	4.06
2004/12/19	7.05	2005/02/01	5.71	2005/03/17	3.93
2004/12/20	5.74	2005/02/02	5.92	2005/03/18	4.57
2004/12/21	5.98	2005/02/03	5.41	2005/03/19	4.31
2004/12/22	6.67	2005/02/04	4.17	2005/03/20	3.45
2004/12/23	4.95	2005/02/05	5.68		
2004/12/24	6.72	2005/02/06	6.55		