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.

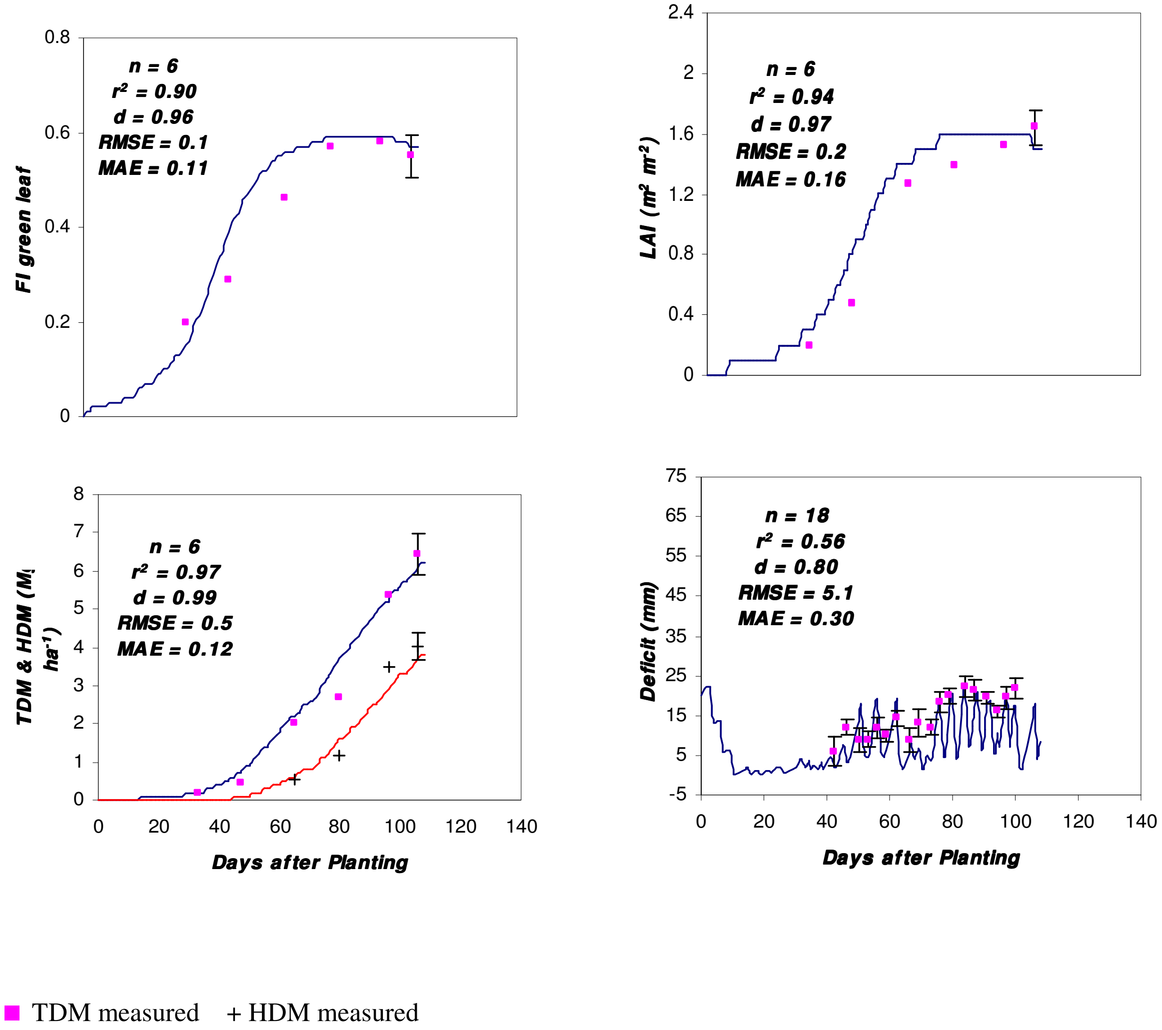

Figure 9.1 Simulated (solid lines) and measured values (points) of fractional interception (FI), leaf area index (LAI), soil water deficit (Deficit), top dry matter (TDM) and harvestable dry matter (HDM) [Jalapeno calibration, well irrigated]. Vertical bars are ± 1 standard error of the measurement.

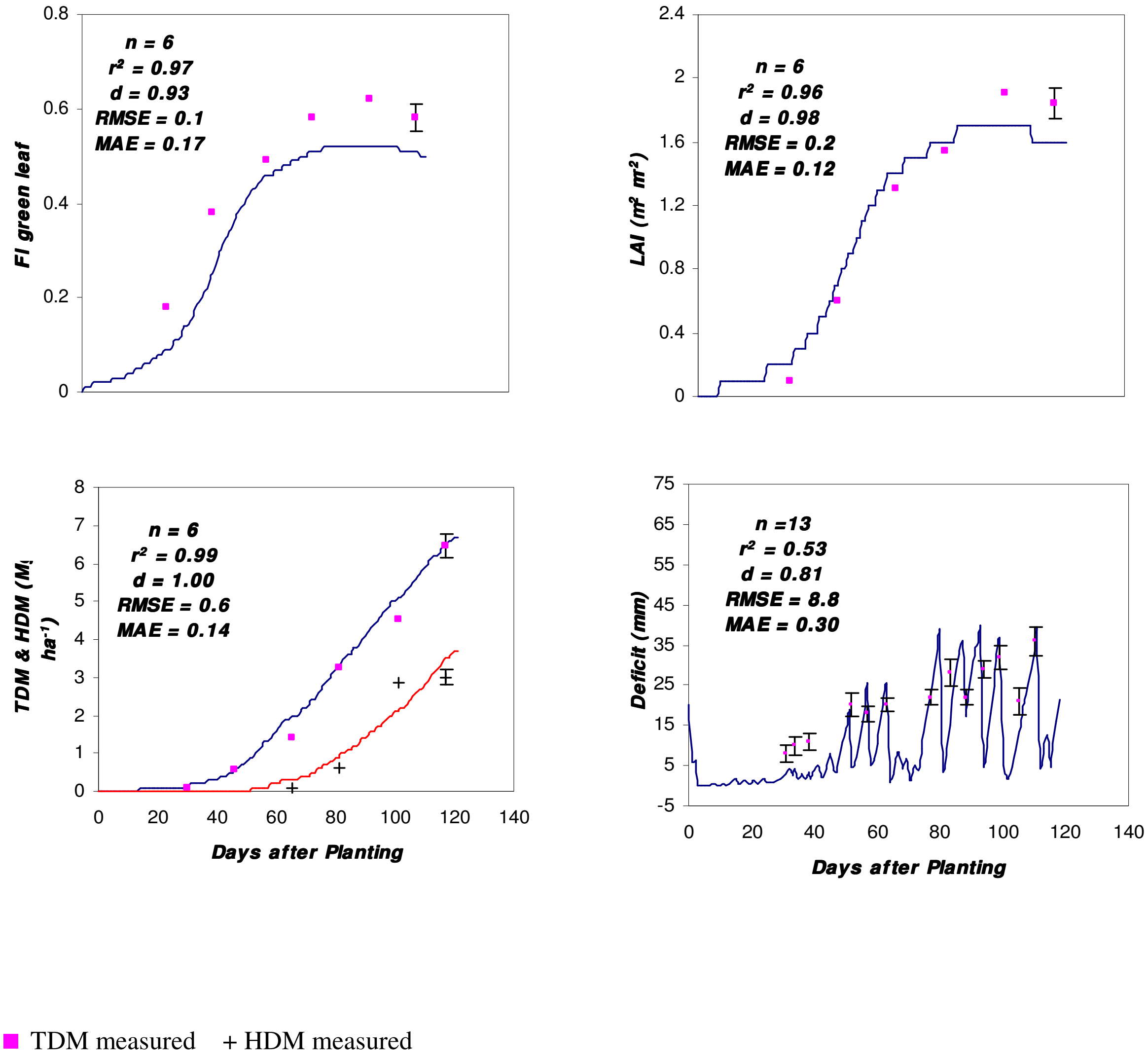

Figure 9.2 Simulated (solid lines) and measured values (points) of fractional interception (FI), leaf area index (LAI), soil water deficit (Deficit), top dry matter (TDM) and harvestable dry matter (HDM) [Serrano calibration, high density planting]. Vertical bars are ± 1 standard error of the measurement.

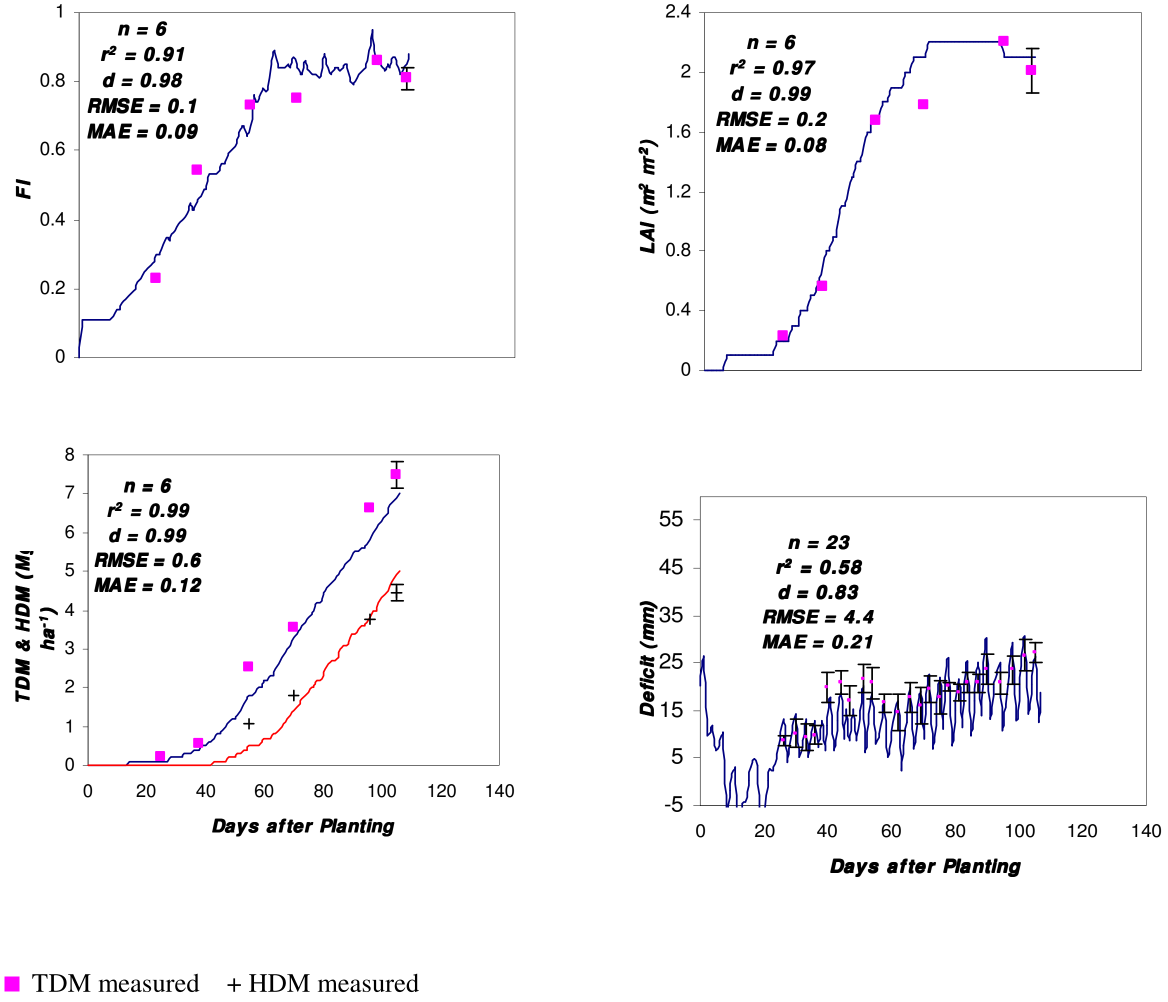

Figure 9.3 Simulated (solid lines) and measured values (points) of fractional interception (FI), leaf area index (LAI), soil water deficit (Deficit), top dry matter (TDM) and harvestable dry matter (HDM) [Long Slim calibration, well irrigated and high density planting]. Vertical bars are ± 1 standard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

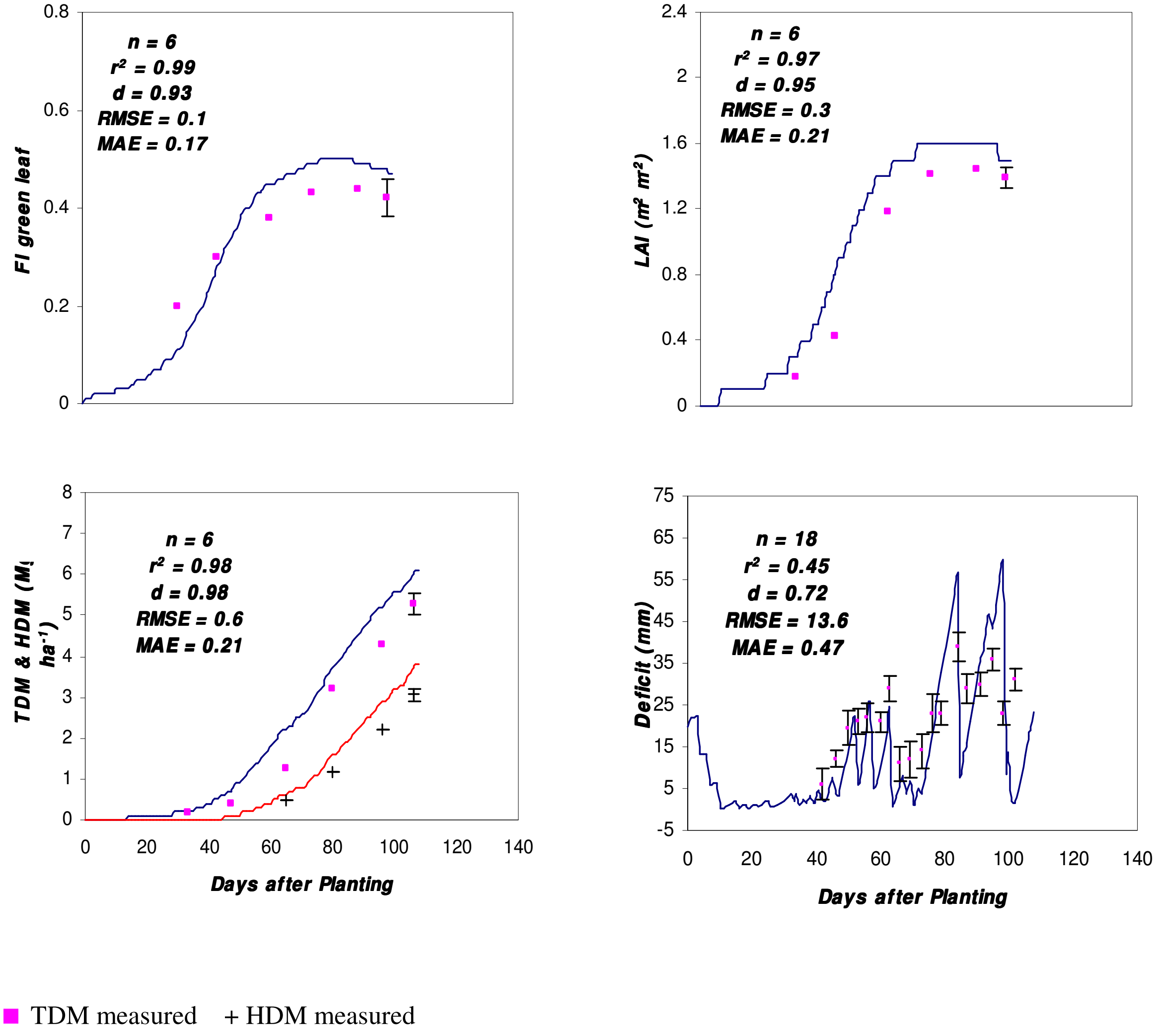

Figure 9.4 Simulated (solid lines) and measured values (points) of fractional interception (FI), leaf area index (LAI), soil water deficit (Deficit), top dry matter (TDM) and harvestable dry matter (HDM) [Jalapeno validation, deficit irrigation]. Vertical bars are ± 1 standard error of the measurement.

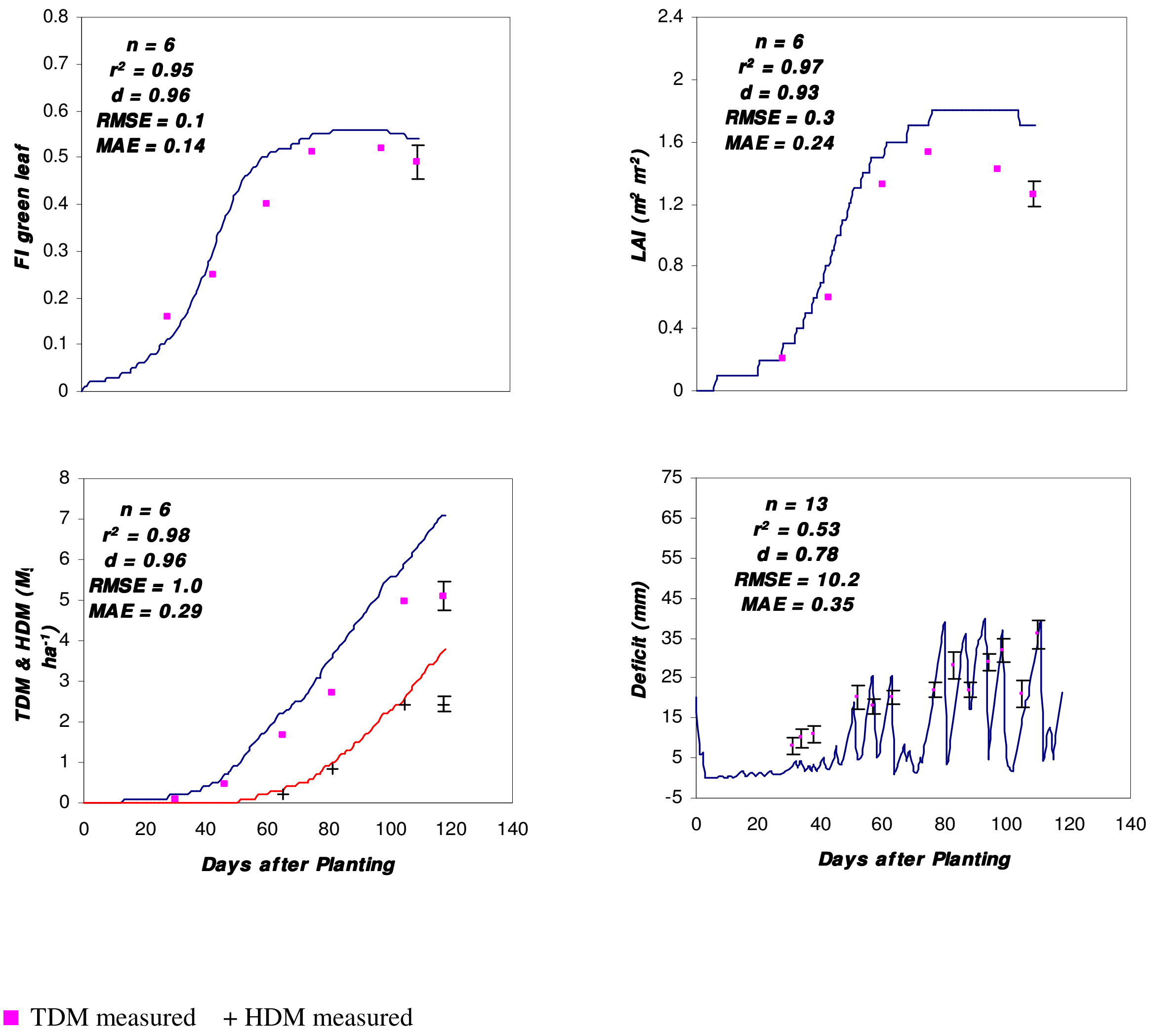

Figure 9.5 Simulated (solid lines) and measured values (points) of fractional interception (FI), leaf area index (LAI), soil water deficit (Deficit), top dry matter (TDM) and harvestable dry matter (HDM) [Serrano validation, low density planting]. Vertical bars are ± 1 standard error of the measurement.

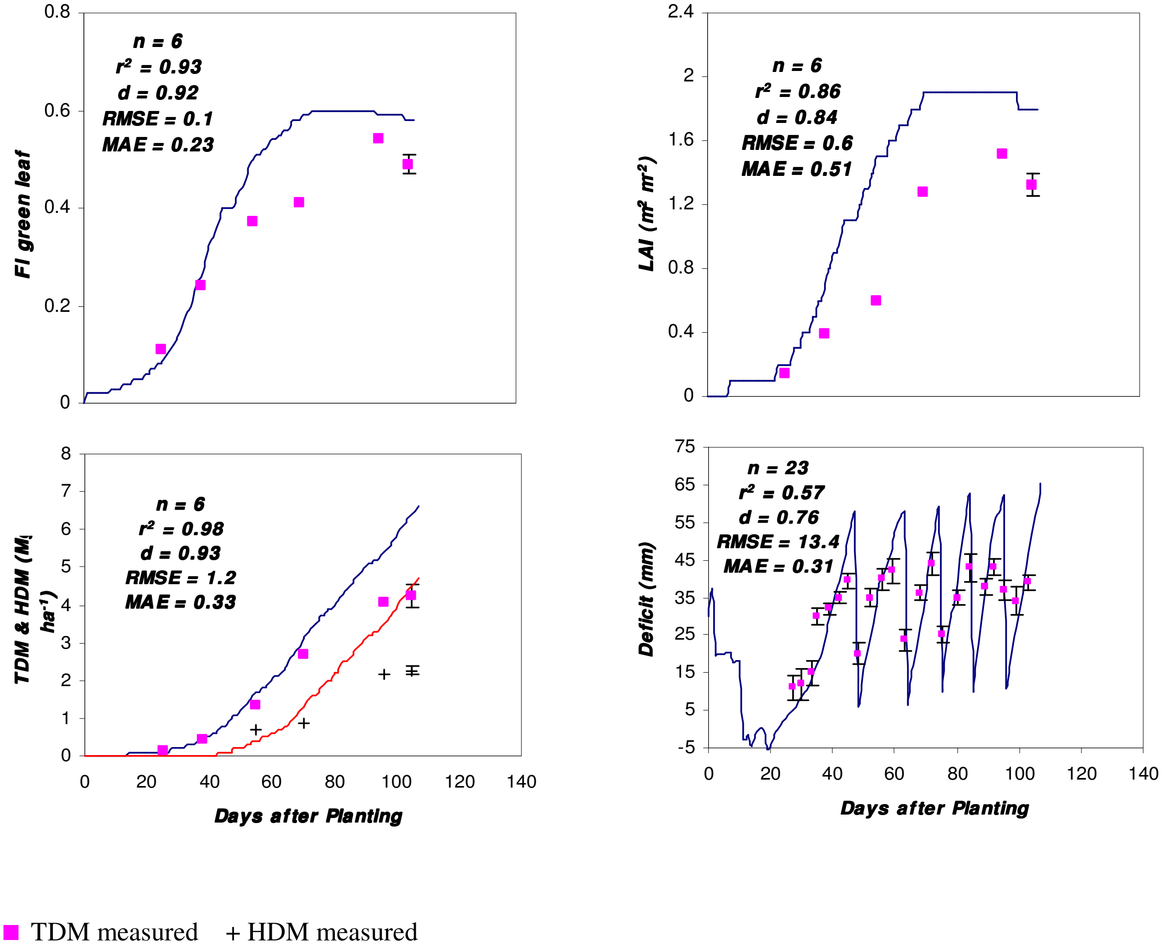

Figure 9.6 Simulated (solid lines) and measured values (points) of fractional interception (FI), leaf area index (LAI), soil water deficit, top dry matter (TDM) and harvestable dry matter (HDM) [Long Slim validation, deficit irrigation and low density planting]. Vertical bars are ± 1 standard error of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

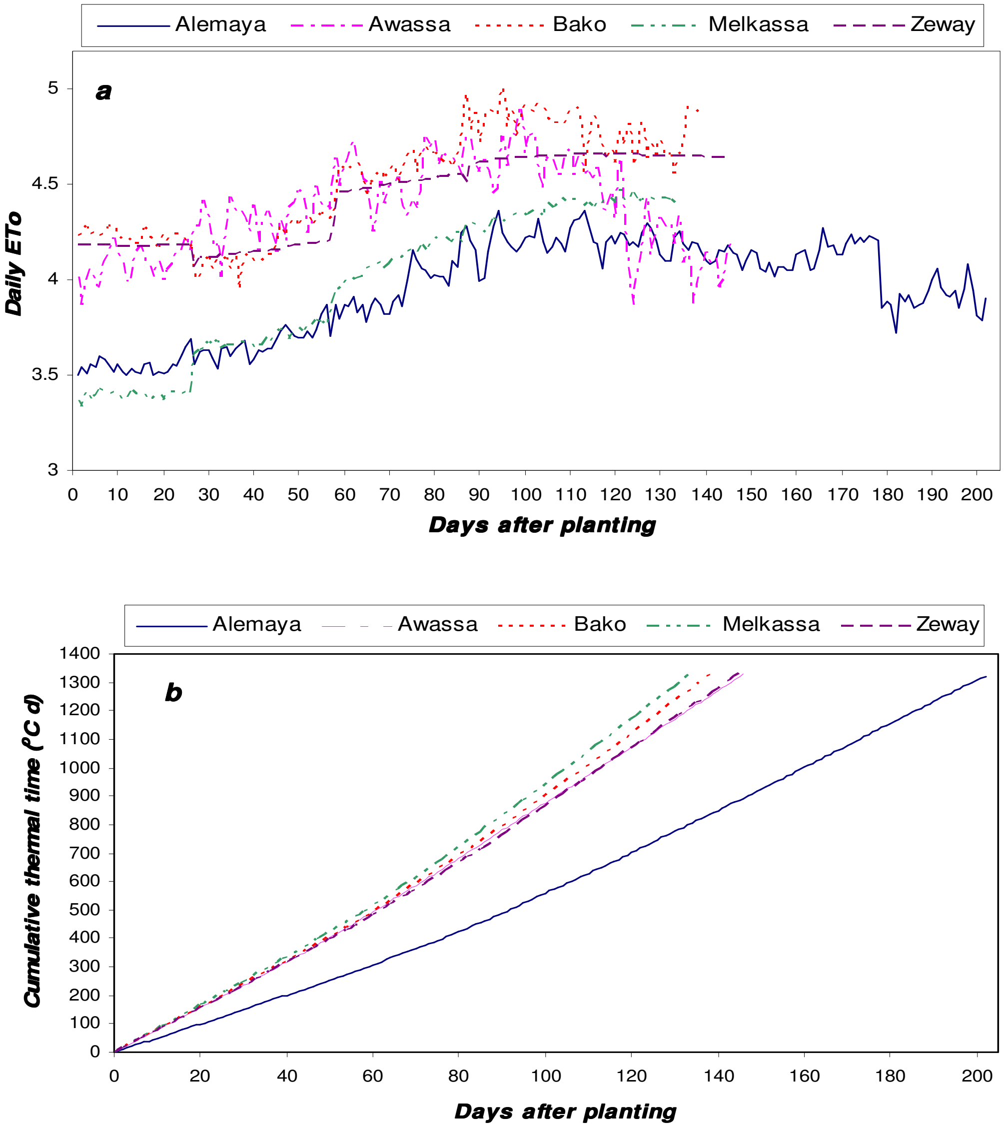

Figure 10.2 Penman-Monteith grass reference daily evapotranspiration (ETo) (a) and cumulative thermal time to maturity (b) for Mareko Fana under five ecological regions of Ethiopia.

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.

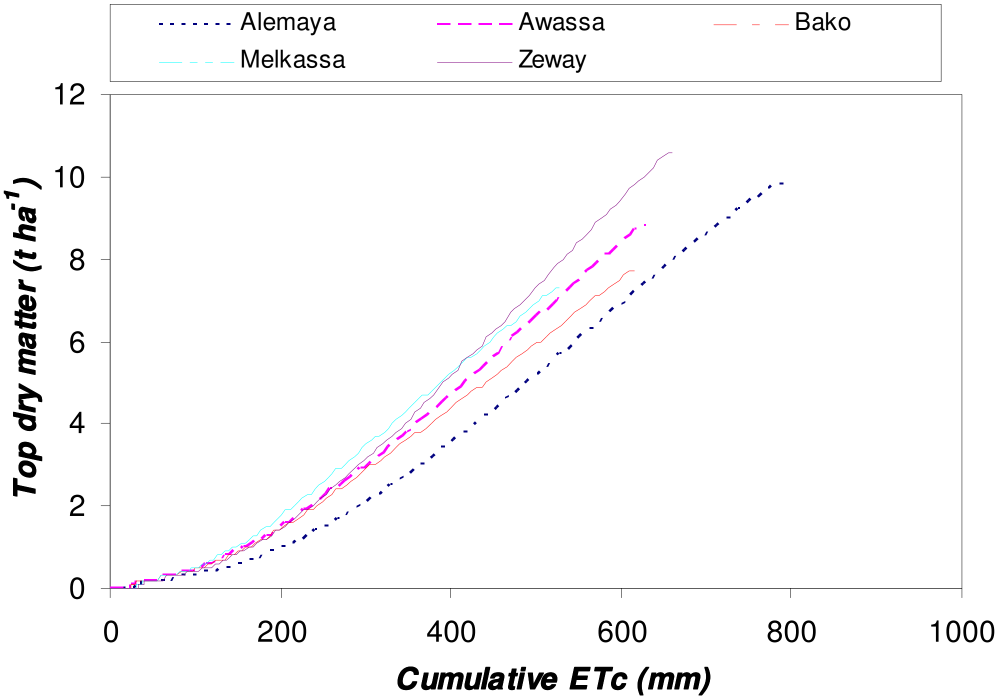

Figure 10.3 Relationship between cumulative crop evapotranspiration (ETc) and top dry matter production of Mareko Fana for five ecological regions of Ethiopia.

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.