

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 annuum* 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 environment 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:

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

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 $\text{m}^2 \text{kg}^{-1}$.

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

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

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 ($\text{m}^2 \text{m}^{-2}$) and SLA is the specific leaf area in $\text{m}^2 \text{kg}^{-1}$.

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

$$DWR = (DM \ VPD) / PT \quad (7.10)$$

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 (T_{max}), minimum air temperature (T_{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):

$$VPD = \left(\frac{e_{sT_{\text{max}}} + e_{sT_{\text{min}}}}{2} \right) - e_a \quad (7.11)$$

where $E_{sT_{\text{max}}}$ is saturated vapour pressure at maximum air temperature (kPa), $E_{sT_{\text{min}}}$ is saturated vapour pressure at minimum air temperature (kPa) and e_a is actual vapour pressure (kPa).

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

$$e_s = 0.6108 \exp \left[\frac{17.27 T}{T + 237.3} \right] \quad (7.12)$$

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

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

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

$$GDD = (T_{avg} - T_b)\Delta t \quad (7.14)$$

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.

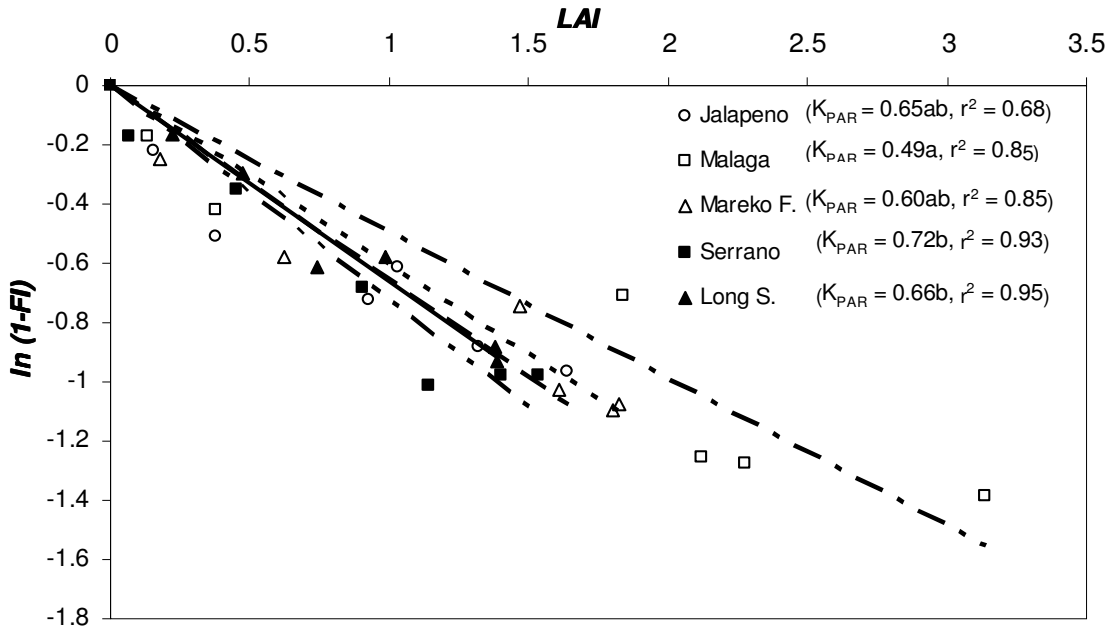


Figure 7.1 Regression between leaf area index (LAI) and natural logarithm of transmitted PAR for five hot pepper cultivars under the medium irrigation regime (55D) and 0.70 m row spacing. The slope of the regression line (K_{PAR}) and the coefficient of determination (r^2) are shown in brackets. K_{PAR} 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.

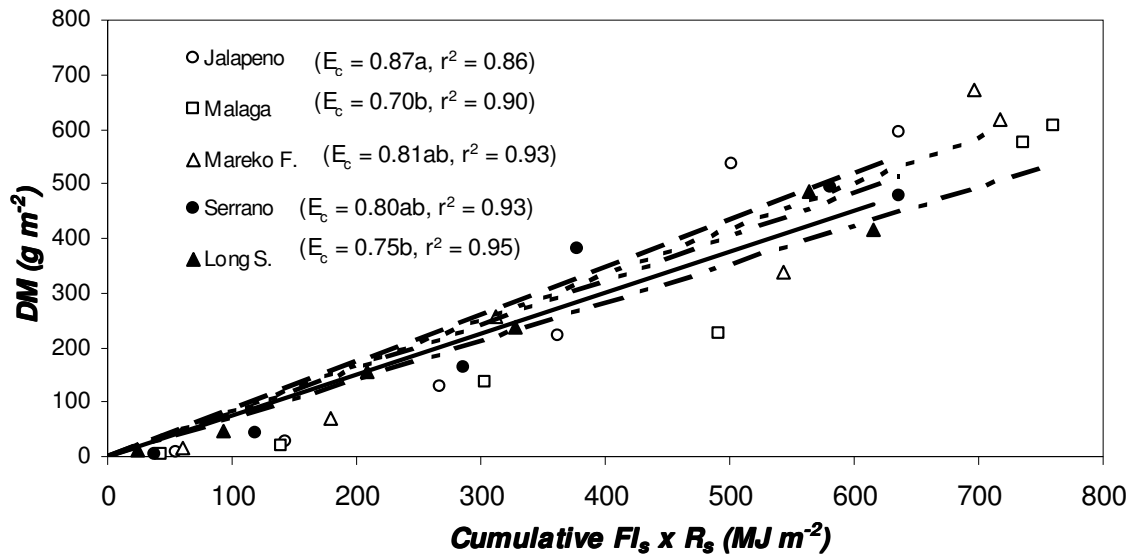


Figure 7.2 Top dry matter (DM) production of five hot pepper cultivars, under medium irrigation regime (55D) and 0.7 m row spacing, as a function of the cumulative product of fractional interception (FI) and total solar radiation (R_s). Radiation conversion efficiency (E_c) and the coefficient of determination (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 (r²) 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 ($9.70 \text{ m}^2 \text{ kg}^{-1}$) 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 spacing 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 ($1.04 \text{ m}^2 \text{ kg}^{-1}$) and green pepper ($1.07 \text{ m}^2 \text{ kg}^{-1}$). 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.

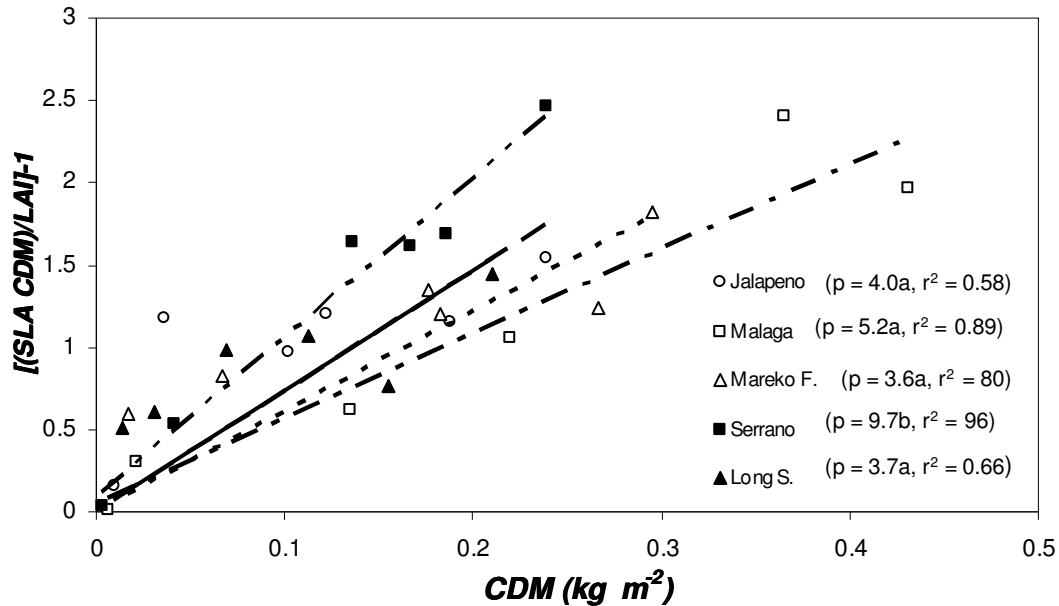


Figure 7.3 Determination of the leaf-stem dry matter partitioning parameter (p) as a function of canopy dry matter (CDM), specific leaf area (SLA) and leaf area index (LAI) for five hot pepper cultivars under medium irrigation and 0.7 m row spacing. The slope of the regression line (p , $m^2 kg^{-1}$) 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 ($20.78 \text{ m}^2 \text{ kg}^{-1}$) had the higher SLA followed by Serrano ($18.51 \text{ m}^2 \text{ kg}^{-1}$), Mareko Fana ($17.48 \text{ m}^2 \text{ kg}^{-1}$), Jalapeno ($17.07 \text{ m}^2 \text{ kg}^{-1}$), and Long Slim ($16.36 \text{ m}^2 \text{ kg}^{-1}$).

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 ($\text{m}^2 \text{ kg}^{-1}$)	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 $>0.9 \text{ g MJ}^{-1}$. 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 E_c 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 E_c 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 $7.59 \text{ m}^2 \text{ kg}^{-1}$, 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 $7.59 \text{ m}^2 \text{ kg}^{-1}$. 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 $8.5 \text{ m}^2 \text{ kg}^{-1}$.

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 (*Capsicum 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):

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

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

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

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).

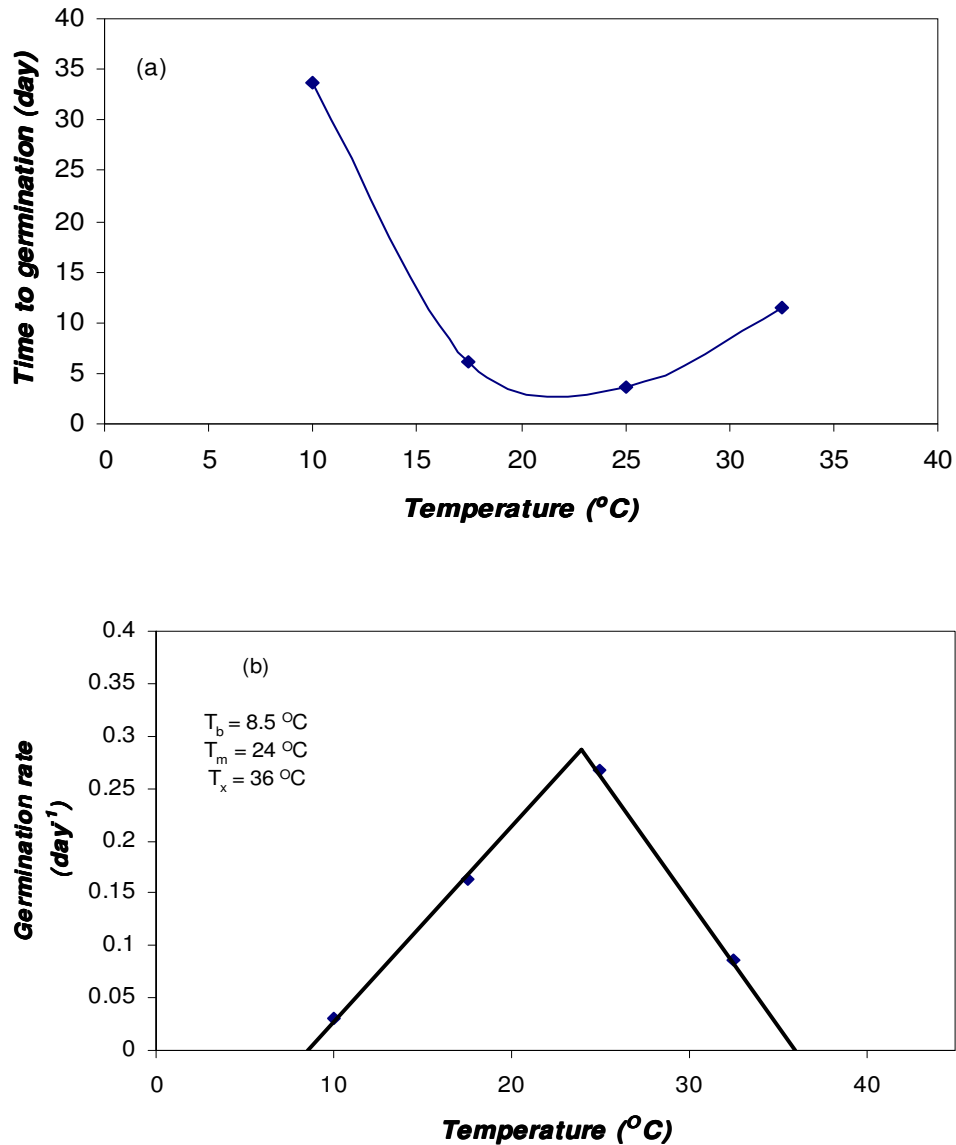


Figure 8.1 Temperature response of time for 50% germination for the cultivar Jalapeno (a), determination of the cardinal temperatures for 50% germination for the cultivar Jalapeno (b).

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 ($SE = 1.9\text{ }^{\circ}\text{C d}$) 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.

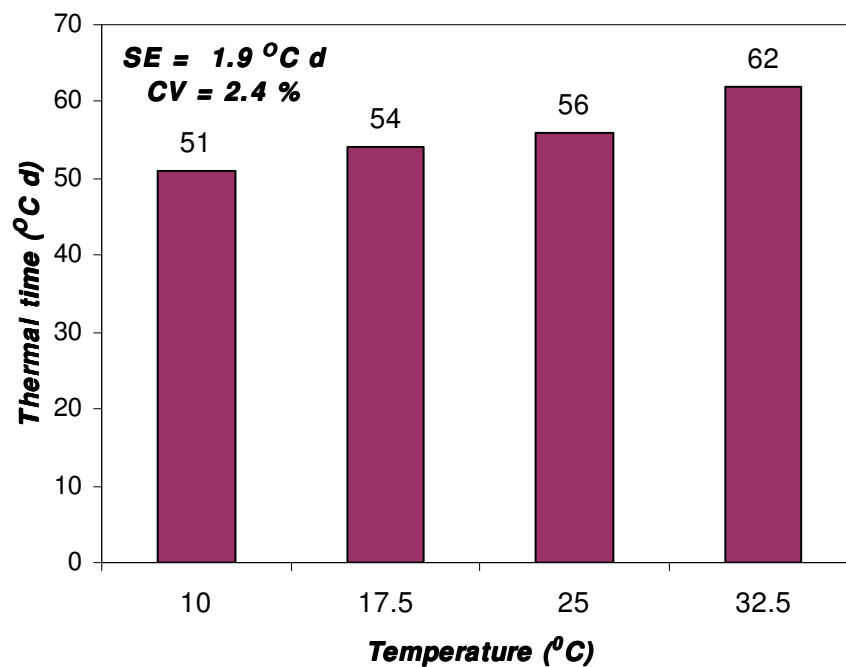


Figure 8.2 Thermal time requirement for 50% germination, calculated at four constant temperatures for the cultivar Jalapeno.

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).

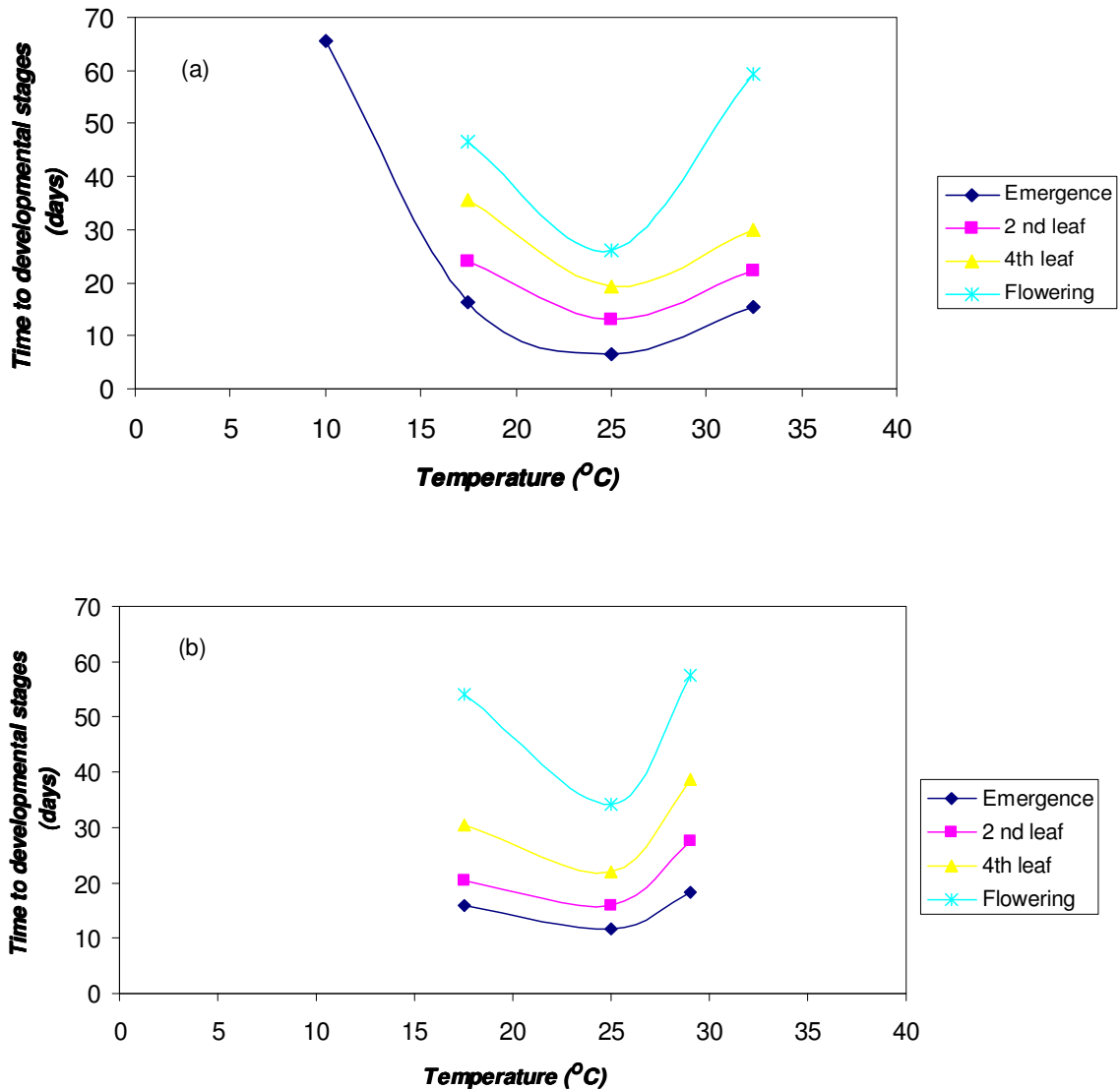


Figure 8.3 Temperature response of time from sowing/transplanting to developmental stages for the cultivar Jalapeno (a) and Mareko Fana (b).

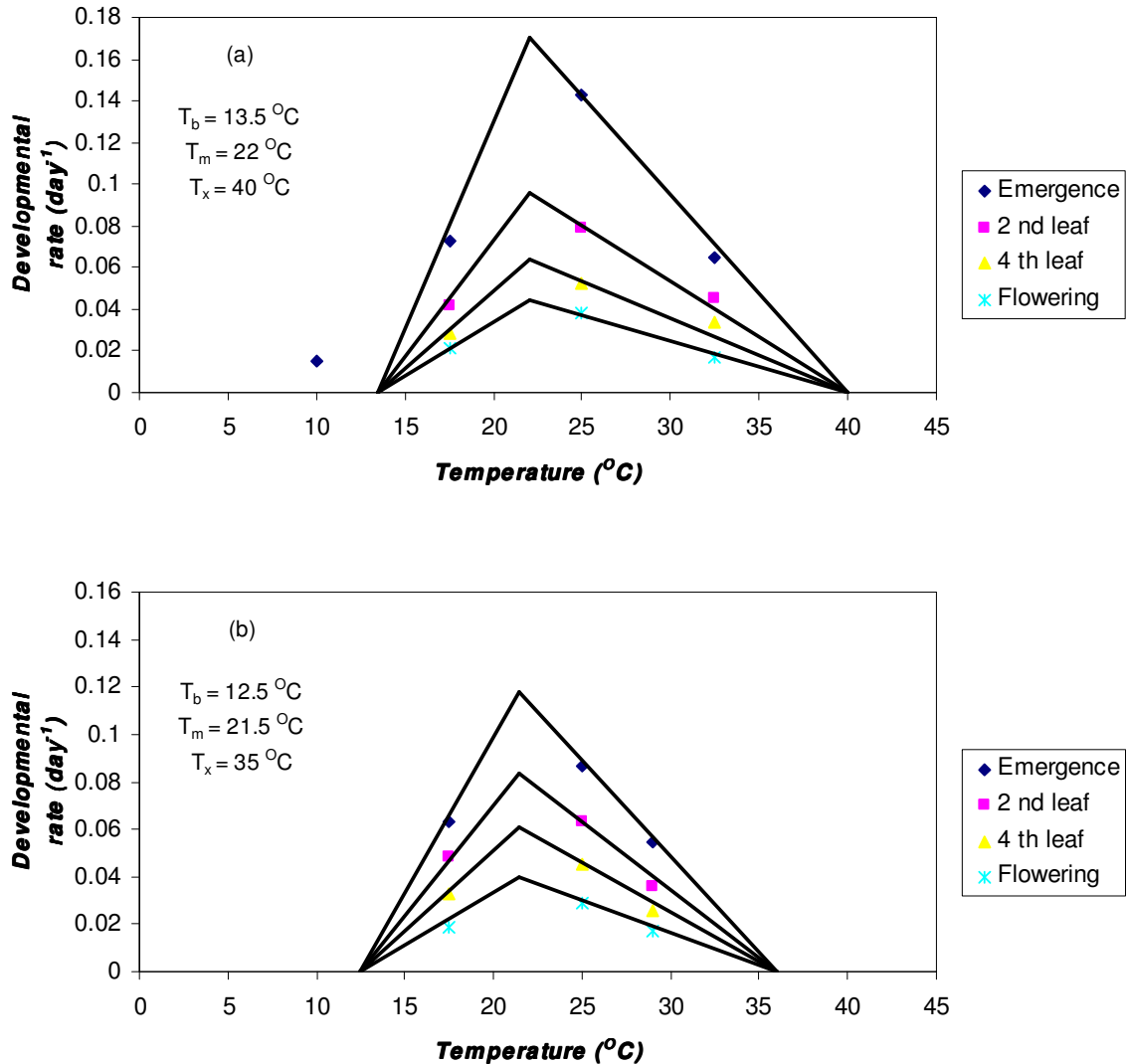


Figure 8.4 Determination of the cardinal temperatures for various developmental stages for the cultivar Jalapeno (a) and Mareko Fana (b).

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 than 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.

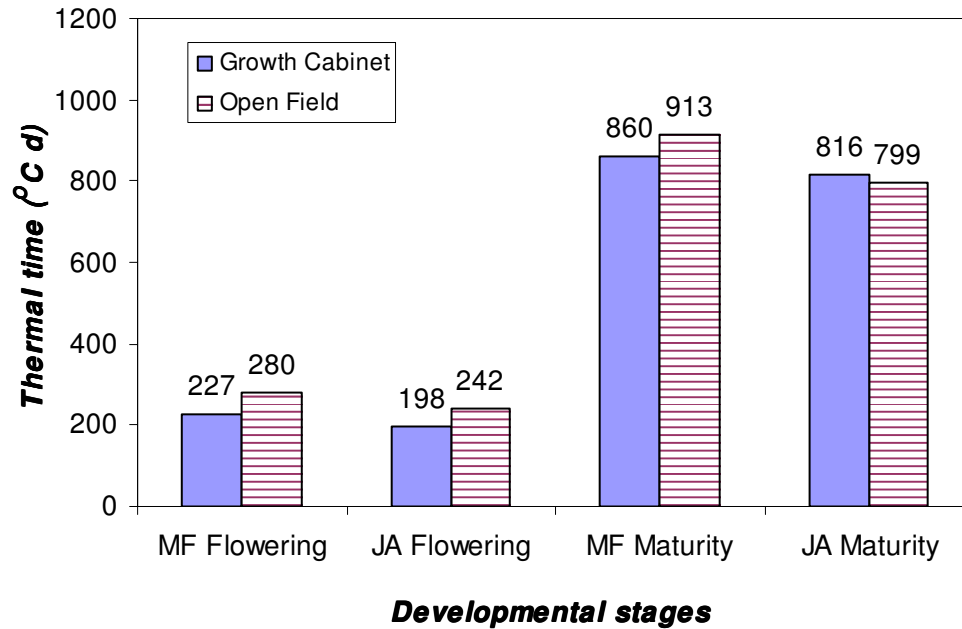


Figure 8.5 Comparison of growth cabinet and field thermal time requirements of flowering and maturity for the cultivars Mareko Fana (MF) and Jalapeno (JA) using growth cabinet determined cardinal temperatures.

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.