CHAPTER 5

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

Abstract

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

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

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

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

5.1 INTRODUCTION

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

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

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

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

5.2 MATERIALS AND METHODS

5.2.1 Experimental site and treatments

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

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

5.2.2 Crop management

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

5.2.3 Measurements

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

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

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

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

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

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

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

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

5.2.4 Data analysis

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

5.3 RESULTS AND DISCUSSION

5.3.1 Specific leaf area, leaf area index and canopy development

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

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

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

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

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

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

5.3.2 Dry matter production and partitioning

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

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

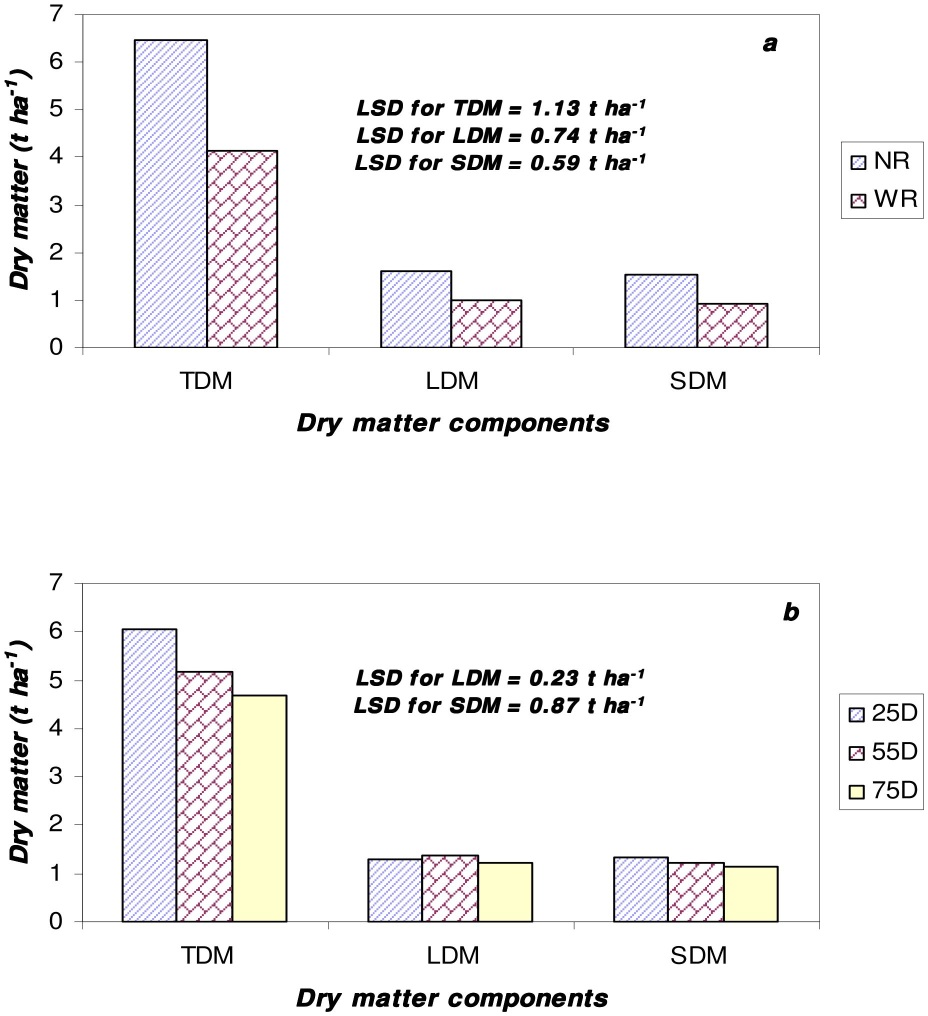

Figure 5.1 Top (TDM), leaf (LDM) and stem (SDM) dry matter as affected by row spacings (a) and irrigation regimes (b). NR: narrow row (0.45 m) and WR: wide row (0.7 m). 25D, 55D, & 75D: irrigation at 20-25, 50-55, and 70-75 % depletion of plant available water, respectively. LSD: least significant difference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

Row spacing and irrigation regime effects on dry matter partitioning to different plant parts are shown in Table 5.2. High irrigation regime resulted in significant increase in the proportion of assimilate partitioned to fruit (harvest index), while it resulted in a significant decrease in the proportion of assimilate partitioned to leaves. However, assimilate partitioned to stem was not significantly affected by the irrigation regime. Neither planting density nor the interaction effect of planting density and irrigation regime markedly affected assimilate partitioning. Jolliffe & Gaye (1995) reported no significant effect on harvest index as plant population changed from 1.4 to 11.1 m^{-2} in bell pepper. Dorji *et al.* (2005) reported no significant difference in dry mass distribution among plant organs due to irrigation treatments. Irrespective of the treatments, fruits remained the major sink (Table 5.2) accounting on average for more than 49 % of the top plant dry mass in the present study. This value is higher than the 39% reported from a split-root pot experiment with pepper (Cantore *et al.*, 2000), whereas it is lower than the 56 % harvest index reported for a deficit irrigation and partial root drying pepper experiment by Dorji *et al.* (2005). The strength of stem and leaf sinks were more or less equal across all treatments (Table 5.2).

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

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

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

5.3.3 Yield, yield components and selected quality measures

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

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

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

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

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

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

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

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

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

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

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

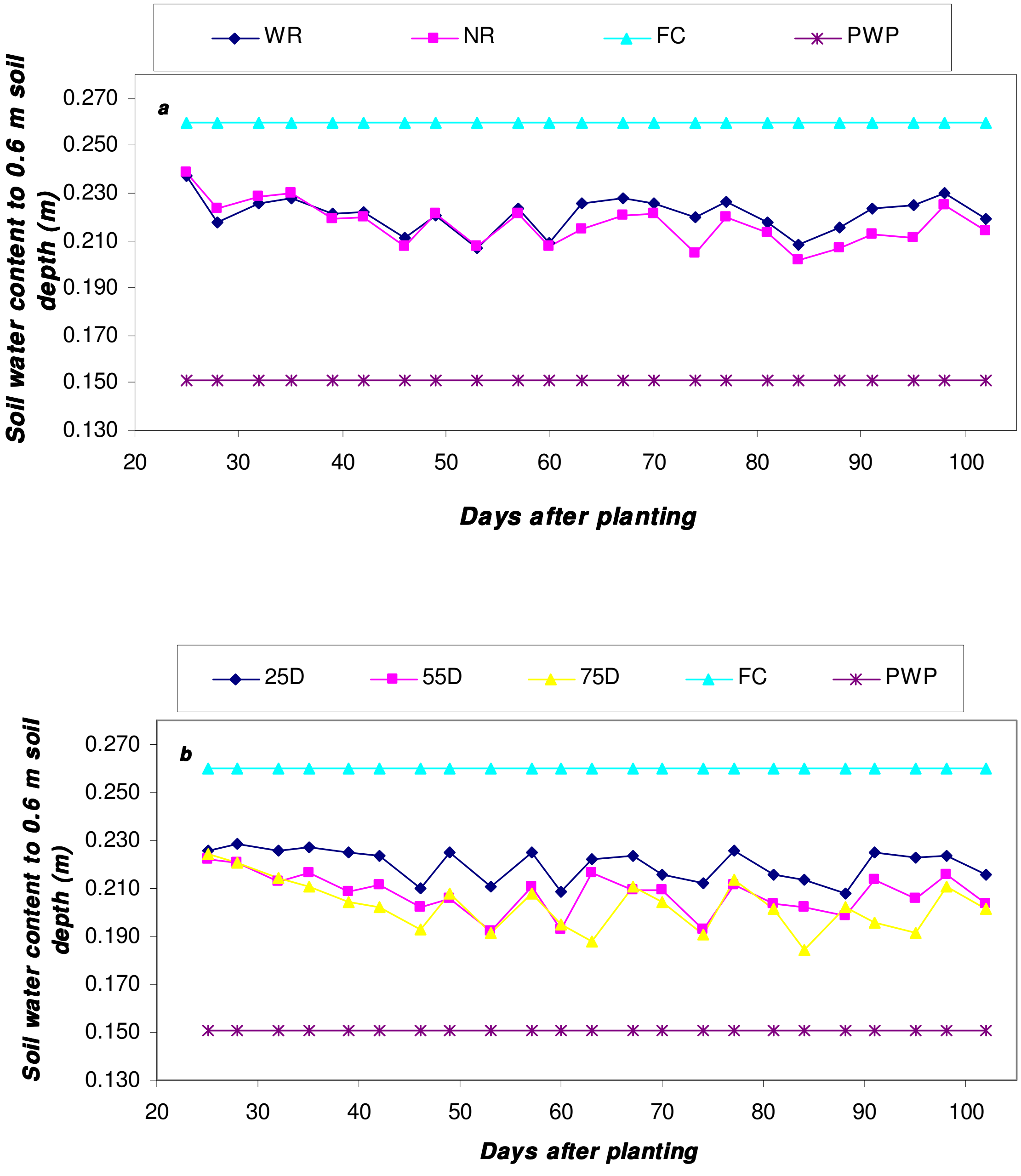

Figure 5.2 Soil water content to 0.6 m soil depth during the growing season as influenced by plant density (a) and irrigation regime (b). HD: high plant density, LD: low plant density. 25D, 55D, & 75D: 20-25, 50-55, and 70-75 % depletion of plant available water, respectively. FC: Field capacity, PWP: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

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

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

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

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

5.4 CONCLUSIONS

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

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

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

CHAPTER 6

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

Abstract

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

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

6.1 INTRODUCTION

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

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

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

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

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

6.2 MATERIALS AND METHODS

6.2.1 Experimental site and treatments

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

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

6.2.2 Crop management and measurements

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

Table 6.1 Soil chemical and physical properties of experimental plots

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

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

Table 6.2 Treatments, experimental design and planting date of experiments

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

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

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

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

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

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

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

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

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

Crop coefficients (Kc) were calculated as follows:

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

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

Crop potential evapotranspiration (PET) is calculated as follows:

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

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

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

or

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

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

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

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

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

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

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

where FI is fractional canopy cover.

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

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

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

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

6.2.3 The Soil Water Balance (SWB) model

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

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

6.3 RESULTS AND DISCUSSION

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

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

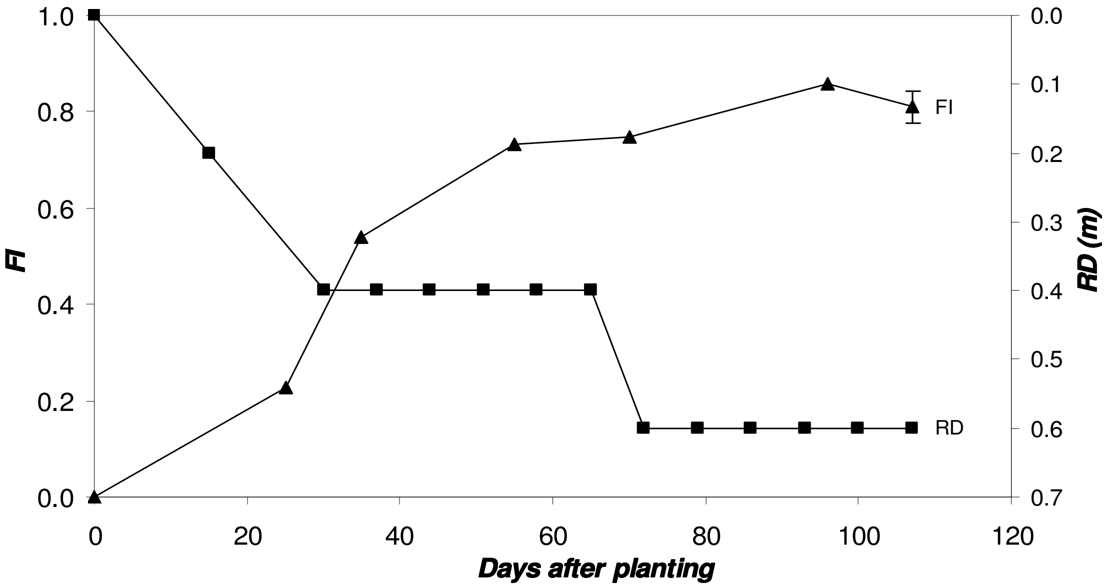

Figure 6.1 Measured values of canopy cover (FI) and estimated root depth (RD) during the growing season of hot pepper cultivar Long Slim. Vertical bar is ± 1 standard error of the measurement.

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

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

6.3.2 Basal crop coefficients and growth periods

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

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

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

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

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

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

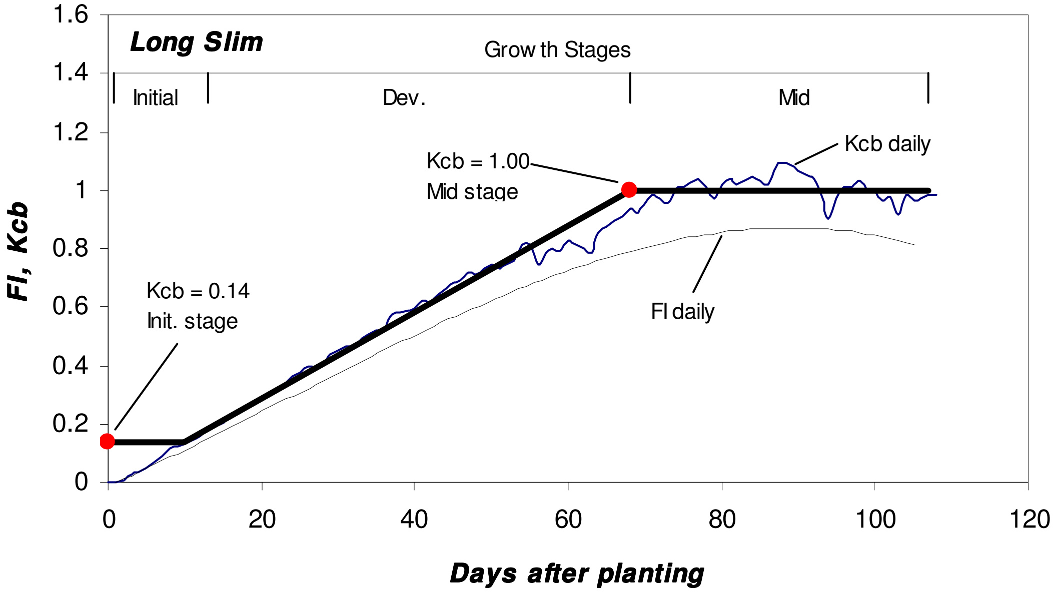

Figure 6.2 Daily values of canopy cover (FI daily) and basal crop coefficient (Kcb daily), and estimated Kcb values for three growth stages of hot pepper cultivar Long Slim under high density and high irrigation treatment (initial, crop development and mid-season stages).

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

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

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

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

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

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

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

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

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

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

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

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

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

6.3.3 Water-use and crop coefficients

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

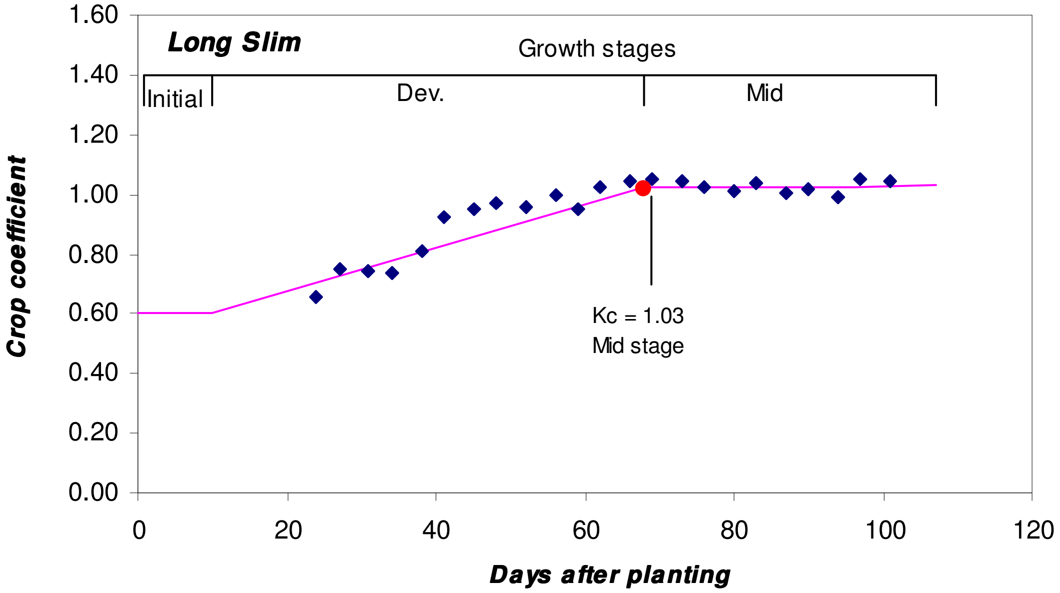

Figure 6.4 Crop coefficient (Kc) calculated for hot pepper cultivar Long Slim. Points are calculated Kc values.

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

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

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

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

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

6.3.4 Model simulation results

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

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

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

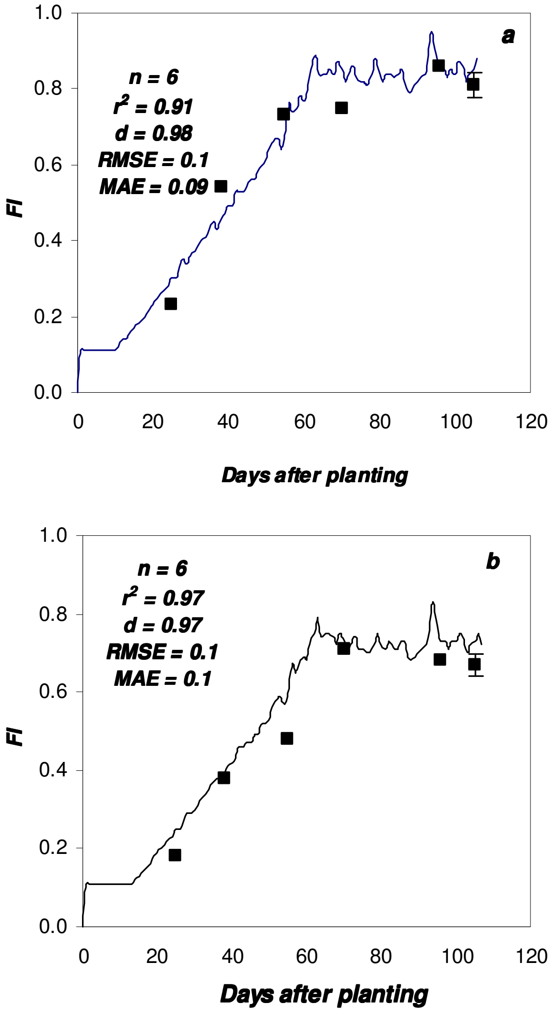

Figure 6.5 Measured (points) and simulated (lines) fractional interception (FI) during the growing season for cultivar Long Slim under high irrigation (calibration, a) and water stress conditions (validation, b). Vertical bars are ± one standard error of the measurement.

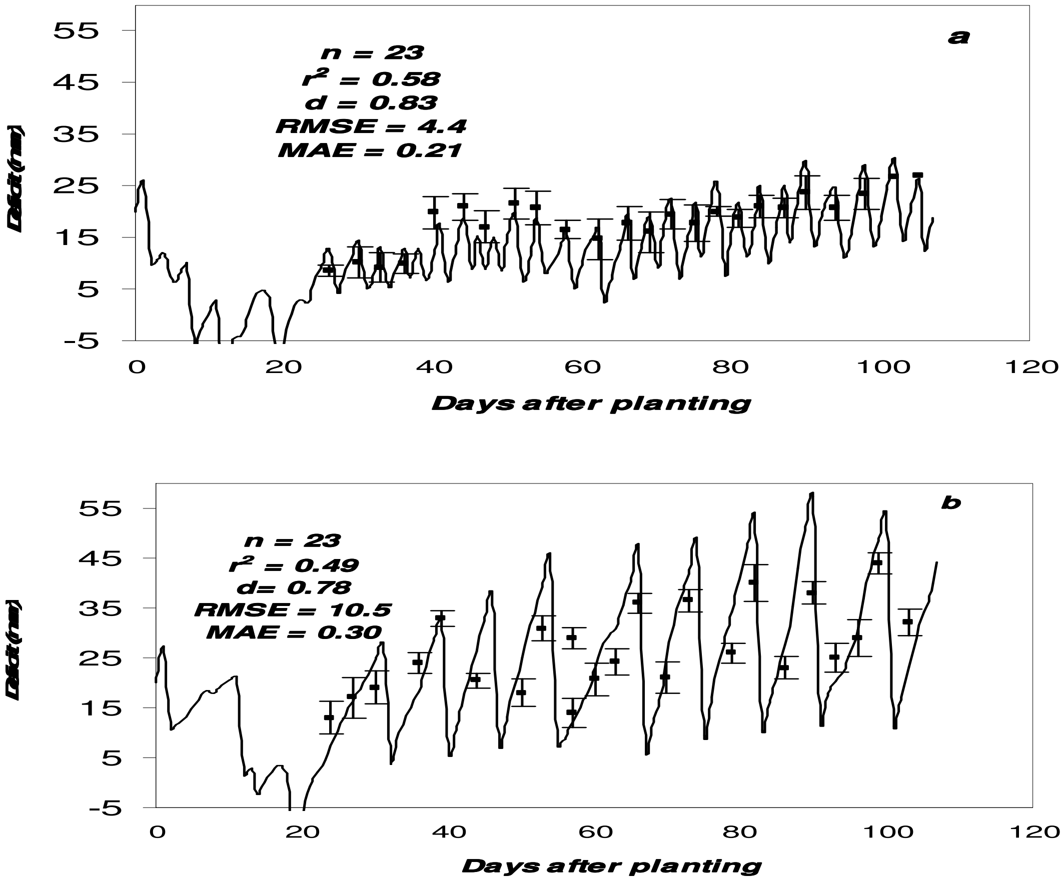

Figure 6.6 Measured (points) and simulated (lines) soil water deficit to field capacity (Deficit) during the growing season for cultivar Long Slim under high irrigation regime (calibration, a) and low irrigation regime (validation, b). Vertical bars are ± one standard error of the measurement.

6.4 CONCLUSIONS

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

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

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