FAO-type crop factor determination for irrigation scheduling of hot pepper (*Capsicum annuum* L.) cultivars

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Accepted 1 July 2009

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

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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.

Material and methods

Experimental site and treatments

Detailed weather, soil and crop data were collected from three field trials conducted in the 2004/2005 growing season on 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. Soil analysis results for the experimental site are shown in Table 1.

Table 1 Soil chemical and physical properties of experimental plots

Soil chemical properties						
Experiment	pH (H_2O)	P (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	Na (mg kg^{-1})
Open field 1, 2	6.5	60.5	79	572	188	29
Rainshelter	6.4	192.3	155	2340	976	196
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

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

Field trials were conducted under a manually operated rainshelter (7.7 m x 12.6 m) and in two open fields. In all three experiments, a plot consisted of five 2.4 m long rows, with an intra-row spacing of 0.4 m. Treatments were replicated 3 times. The experimental procedures followed are summarized in Table 2.

Table 2 Treatments, experimental design and planting date of experiments

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

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.

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 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 Metasytox® (oxydemeton–methyl) applied at the recommended doses.

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 was collected at 15 to 25 day intervals. The fractional canopy interception (FI) of photosynthetically active radiation (PAR) was measured using a model AccuPAR sunfleck ceptometer (Decagon Devices, Pullman, Washington, USA). The PAR measurements for each 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. The FI was calculated by subtracting the ratio of PAR below canopy to PAR above canopy from one (Jovanovic & Annandale, 1999).

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 (Jovanovic & Annandale, 1999). Crop coefficients (Kc) were calculated according to Allen *et al*. (1998). Potential crop transpiration, potential soil evaporation, and potential crop evapotranspiration (PET) were calculated following procedures described by Jovanovic and Annandale (1999). The daily basal crop coefficient (Kcb) was calculated from FI, PET and grass reference evapotranspiration (ETo) (Jovanovic & Annandale, 1999).

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 was 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, a cup anemometer (MET One, Inc., USA) to measure average wind speed, a tipping bucket rain gauge (RIMCO, R/TBR, Rauchfuss Instruments Division, Australia), a CS500 relative humidity and temperature sensor, and a CR10X datalogger (Campbell Scientific, Inc., Logan, Utah, USA).

The Soil Water Balance (SWB) model

The FAO-based model in SWB (Annandale *et al*., 1999) was run for cultivar Long Slim, using the FAO crop factors determined from the field experiments and collected weather data. The FAO-based SWB model requires the following input parameters to run the model: soil water characteristics (field capacity, wilting point and initial water content per soil layer), planting date, basal crop coefficient values for initial, mid-season and late-season stages, crop growth periods in days, initial and maximum root depth and plant height, potential yield, stress index, maximum transpiration (T_{max}), leaf water potential at T_{max} and canopy interception water storage.

Statistical analysis

Student's t test was conducted for replicated observations to test the presence of statistical differences between paired means. Statistical parameters such as index of agreement (d), the root mean square error (RMSE), mean absolute error (MAE) and adjusted coefficient of determination (r^2 adj) were calculated to evaluate the performance of the SWB model.

Results and discussion

Canopy development, rooting depth, leaf area index and plant height

Figure 1 shows measured values of fractional canopy cover (FI) and estimated rooting 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 to 25% depletion of plant available water) treatment. Weekly measurements of soil water content (SWC) from neutron meter data were used to estimate RD, following Jovanovic and Annandale (1999). It was assumed to be equal to the depth at which 90% of soil water depletion occurred during weekly periods. Maximum RD values estimated from SWC measurements were generally in agreement with those reported by Smith (1992) and Jovanovic and Annandale (1999).

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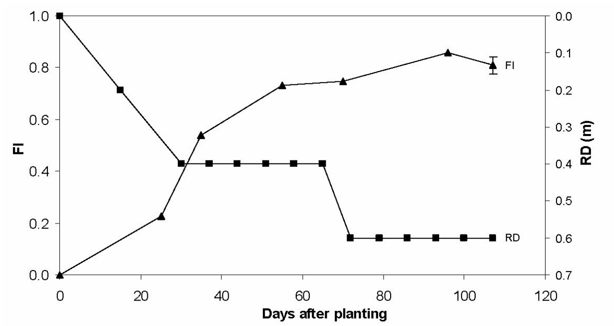

Figure 1 Measured values of canopy cover (FI) and estimated root depth (RD, depth at which 90% of weekly soil-water depletion occurred) during the growing season of hot pepper cultivar Long Slim. Vertical bar is ± one standard error of the measurement.

Table 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 level 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 level (HI) 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 3, there exists a very strong correspondence between LAI and FI. The measured seasonal FI values for Long Slim (Figure 1), and $0.9FI_{max}$

values (Table 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.

Table 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 (HI)	0.6	0.64a	0.56a	1.16a
Jalapeno (LI)	0.6	0.63a	0.45a	0.98a
SE		0.022	0.038	0.109
Long Slim (0.45)[a] & HI	0.6	0.82a	0.74a	2.02a
Long Slim (0.45)[a] & LI	0.6	0.81a	0.68b	1.54b
SE		0.040	0.015	0.039
Malaga (HI)	0.6	0.84a	0.76a	2.24a
Malaga (LI)	0.6	0.73b	0.58b	1.91a
SE		0.031	0.024	0.200
Mareko Fana (HI)	0.6	0.71a	0.73a	1.74a
Mareko Fana (LI)	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; HI or LI: 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<0.05). SE: standard error.

Basal crop coefficients and growth periods

Figure 2 presents values of FI and Kcb for hot pepper cultivar Long Slim under high density and high irrigation treatment. The lengths of initial, development and mid-season growth stages are also indicated in Figure 2. 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 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 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 initial 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 and Annandale (1999) for green and chilli peppers.

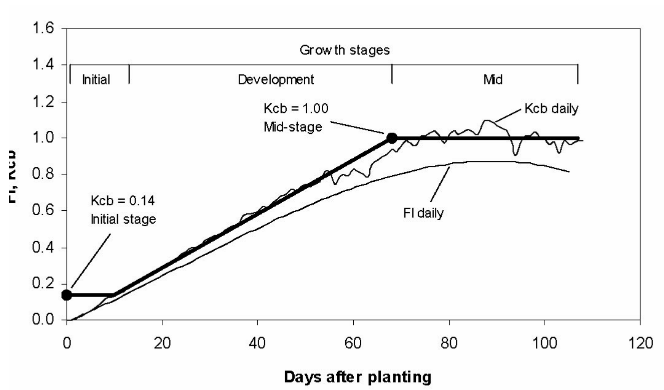

Figure 2 Daily values of canopy cover (FI daily) and basal crop coefficient (Kcb daily), and estimated Kcb values for three growth stages of hot pepper cultivar Long Slim under high density and high irrigation treatment (initial, crop development and mid-season stages).

Table 4 Basal crop coefficients (Kcb), and growth periods (initial, development, mid-season and late-season stages) for five hot pepper cultivars

Cultivar and treatment	Kcb			Growth period (days)				
	Initial	Mid	Late	Initial	Dev.	Mid	Late	Total
Jalapeno (HI)	0.12	0.72	-	16	60	30	-	106
Jalapeno (LI)	0.12	0.70	-	19	56	31	-	106
Long Slim (0.45)[a] and HI	0.14	1.00	-	10	56	41	-	107
Long Slim (0.45) [a] and LI	0.13	0.86	-	13	53	44	-	107
Long Slim (0.7)[b] and HI	0.13	0.78	-	16	61	33	-	107
Malaga (HI)	0.12	0.97	0.85	20	63	40	6	129
Malaga (LI)	0.12	0.94	0.84	24	60	41	5	129
Mareko Fana (HI)	0.12	0.93	-	14	62	43	-	119
Mareko Fana (LI)	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]

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

The Kcb value is a reflection of plant height and plant canopy development (Allen *et al*., 1998). Therefore, Kcb values depend on cultivar, management practices and climatic conditions (Jagtap & Jones, 1989; Jovanovic & Annandale, 1999). The present study indicated that management factors such as row spacing and irrigation regimes, 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 regimes increased the 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 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).

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 regimes 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 regimes and/or low density planting gave mid-season Kcb values less than 0.9.

All the cultivars and treatments produced mid-season Kcb values that are markedly greater than mid-season Kcb values reported by Jovanovic and 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 and Annandale (1999). High density planting and early November planting may have contributed to the greater Kcb values obtained in the present study.

In all cultivars and treatments, the duration of the development stage was longer than that of mid-season stage, which is in agreement with results reported by Jovanovic and 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 and Annandale (1999), the end of the development stage was marked when the crop attained an FI value of $0.9FI_{max}$, 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 for 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.

Table 5 Some morphological characteristics of the hot pepper cultivars used in the experiments

	Features		
Cultivar	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

New cultivars are released regularly due to market demand and the broad genetic basis of the species. It will, therefore, be useful to be able to predict FAO type crop factors for new cultivars. Table 5 presents 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 smaller FI, LAI and/or Hc_{max} values. Furthermore, high density planting and high irrigation regimes 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 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).

Water use and crop coefficients

Figure 3 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 the irrigation amount did not exceed the measured deficit when refilling the soil profile to FC.

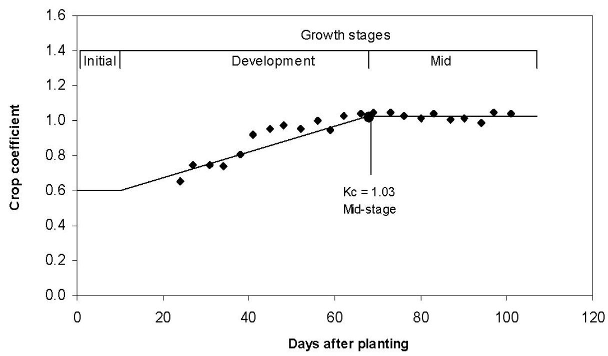

Figure 3 Crop coefficient (Kc) calculated for hot pepper cultivar Long Slim. Points are calculated Kc values.

Development stage Kc values increased from 0.65 to 1.05 for Long Slim. The calculated mid-stage Kc value (1.03) is slightly less than that 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 dictates the reference evapotranspiration and evapotranspiration potential, which are the two variables determining Kc.

Table 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 S 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 (PET) calculated in a given environment is a function of plant height and length of the 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 70 mm from the ET_{meas} for cultivar Long Slim. All evapotranspiration values reported here fall outside the range reported by Doorenbos and Kassam (1979) for pepper, which varies from 600 to 1250 mm, depending on the region, climate and variety. Growing conditions, climate and cultivar differences may have contributed to the observed differences between the present results and those of Doorenbos and 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 and 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 Soil water storage (S), 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 various cultivars

Cultivar	S (mm)	E_{sim}	T_{sim}	ET_{sim}	ET_{meas}
Jalapeno	11	136	254	390	
Long Slim	-6	115	392	507	577
Malaga	4	138	408	546	
Mareko Fana	-3	139	386	525	
Serrano	-5	147	365	512	

Model simulation results

Figure 4 shows measured and simulated values of fractional interception (FI), and Figure 5, soil water deficit to field capacity (deficit) for cultivar Long Slim under full irrigation (a, calibration) and deficit irrigation (b, validation) conditions, using the new Kcb values determined for cultivar Long Slim under full irrigation. 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. Instead of the normal r^2, adjusted r^2 (r^2adj) values were calculated, since the sample size was different for various regressions. 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.

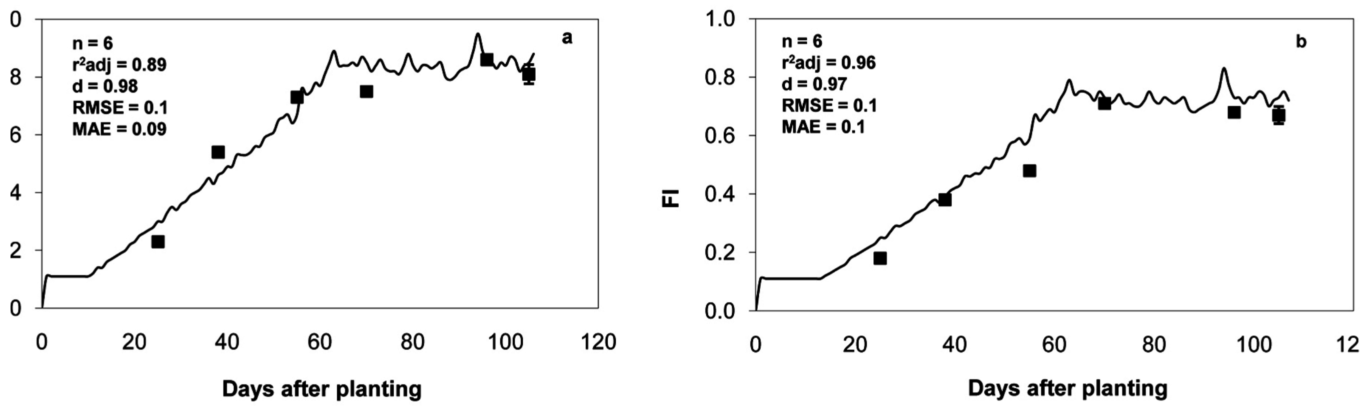

Figure 4 Measured (points) and simulated (lines) fractional interception (FI) during the growing season for cultivar Long Slim under full irrigation (calibration, a) and water stress conditions (validation, b). Vertical bars are ± one standard error of the measurement.

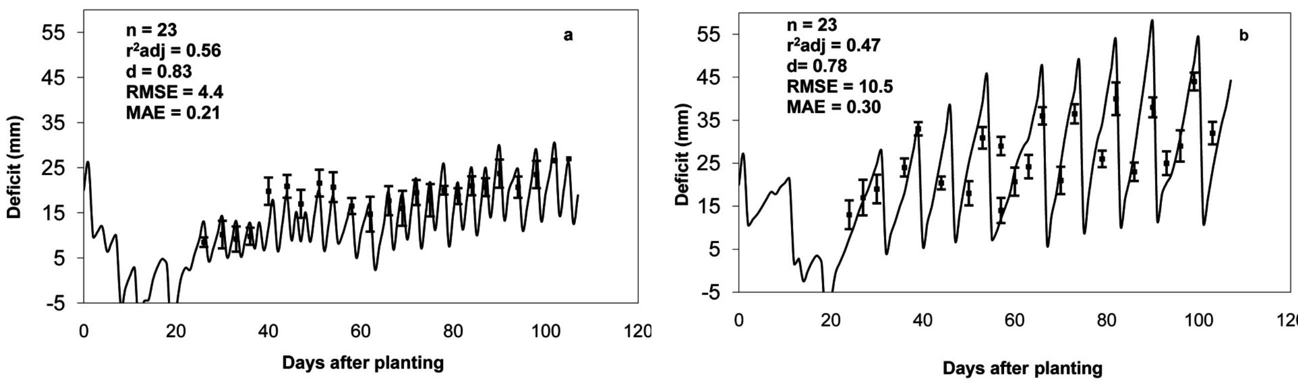

Figure 5 Measured (points) and simulated (lines) soil water deficit to field capacity (Deficit) during the growing season for cultivar Long Slim under full irrigation (calibration, a) and water stress conditions (validation, b). Vertical bars are ± one standard error of the measurement.

The model predicted FI well for both full (calibration data) and deficit (validation data) irrigation treatments. However, the soil water deficit to field capacity (deficit) was predicted with reduced 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 (Steyn, 1997). In the present study, a slight over-estimation 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 value of -1500 J kg^{-1} at T_{max} (ψ_{lm}) were used as input parameters to run the model (Jovanovic & Annandale, 1999). The satisfactory model test results obtained for both FI and deficit simulations suggest that the chosen T_{max} and ψ_{lm} values are reasonably acceptable.

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 morphology. 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 0.9 under 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 optimum soil water regime and/or high planting density. If 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 appear to be acceptable for most hot pepper cultivars (depending on the initial canopy size).

Cultivar Long Slim had a crop coefficient value of 1.03 for the mid-season stage and seasonal evapotranspiration of 577 mm. Simulated evapotranspiration ranged from 390 to 546 mm across cultivars. Simulation results showed that the simple FAO crop factor approach, embedded in the SWB model, could reasonably well simulate fractional canopy cover and the soil water deficits to field capacity.

Acknowledgments

The authors acknowledge the Haramaya University for financial support and the University of Pretoria for provision of field, rainshelter and laboratory facilities.

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