An FAO type crop factor modification to SWB for inclusion of crops with limited data: Examples for vegetable crops

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Abstract

There is a lack of information on crop water requirements of vegetables in South Africa. Six winter and 10 summer irrigated vegetable species were grown in a field trial at Roodeplaat (Gauteng Province) during the 1996/97 season. The objectives were to determine seasonal water requirements of vegetables and to develop a simple, generic crop, irrigation scheduling model that would not require time-consuming and therefore expensive growth analysis data to determine model parameters. Weather data were recorded with an automatic weather station, canopy cover (C) was measured weekly with a sunfleck ceptometer and soil water with a neutron meter. A simple C-based procedure was used to determine FAO (Food and Agriculture Organisation of the United Nations, Rome, Italy) type basal crop coefficients (Kcb) and growth periods for the following stages: initial, development, mid-season and late-season. In addition, initial and maximum rooting depths and crop heights were determined. An FAO-based crop factor approach was combined with the mechanistic irrigation scheduling SWB (Soil-Water Balance) model, thereby allowing evaporation and transpiration to be modelled as supply- and demand-limited processes. FAO type crop parameters were included in SWB and simulations performed. SWB predicted soil-water deficit and canopy cover well. The crop parameters should be extremely useful to irrigators, but caution should be exercised against blind acceptance of these empirical parameters as local conditions, management and cultivars are likely to influence crop growth periods and Kcb's.

Introduction

Interest in the application of computer models in agriculture is rapidly increasing, particularly since PCs have become accessible to crop producers. Crop models have been developed with different levels of complexity depending on the specific requirements (Whisler et al., 1986). For irrigation scheduling purposes, models should simulate growth and development of the crop well. Several mechanistic irrigation scheduling models are available (Bennie et al., 1988; Campbell and Stockle, 1993; Singels and De Jager, 1991a, b and c; Hodges and Ritchie, 1991). Mechanistic crop growth models, however, require specific crop growth input parameters which are not readily available for all crops and conditions. The Food and Agriculture Organisation (FAO) of the United Nations recommended a semi-empirical approach for calculating crop water requirements, based on the fact that crop yield depends on climatic conditions, genetic potential of the crop and irrigation water management (Doorenbos and Pruitt, 1992). The FAO approach was used to develop the crop water requirement models CROPWAT (Smith, 1992a) and, in South Africa, SAPWAT (Crosby, 1996). Doorenbos and Pruitt (1992) give a comprehensive database of FAO crop coefficients (Kc) for different climatic conditions and phenological stages (initial, mid-season and late-season stages). They also stressed the need to collect local data on growing season and rate of crop development of irrigated crops. Green (1985a and b) reviewed Kc values empirically related to pan evaporation and growth periods for crops grown in South Africa.

The Kc's published by the FAO represent mean values for a given irrigation cycle and strongly depend on wetting frequency, wetted area and soil type. Allen et al. (1996) defined Kc as the sum of the basal crop coefficient (Kcb) and the time-averaged effects of evaporation from the soil surface layer. They also reported Kcb values and maximum crop height (Hc_{max}) for a wide range of species. The Kcb values, however, depend on cultivars, management and climatic conditions, in particular during incomplete canopy cover (Jagtap and Jones, 1989). Van Zyl and De Jager (1994) recommended climate-adjusted upper limits of Kcb for potato and maize grown at several locations in South Africa. Very little literature is available on Kcb's for vegetables grown in South Africa. In this study, 6 winter and 10 summer vegetable species were grown at Roodeplaat (Gauteng Province). The objectives were to determine what seasonal crop water consumption growers could expect in that area, and to generate a database of Kcb values, growth periods, root depths (RD) and crop heights (Hc) from the limited data available. A further objective was to develop a simple computer model making use of this database for real time mechanistic irrigation scheduling of vegetables.

Materials and methods

Field trial

A field trial was established at Roodeplaat (Department of Agriculture - Directorate of Plant and Quality Control; 25°35' S, 28°21' E, altitude 1 165 m), 30 km NE of Pretoria. The climate of the region is one of summer rainfall with an average of about 650 $mm \cdot y^{-1}$ (October to March). January is the month with the highest average maximum temperature (30°C), whilst July is the month with the lowest average minimum temperature (1.5°C). Frost occurs frequently during winter months. The soil is a 1.2 m deep clay loam Red Valsrivier (Soil Classification Working Group, 1991), with a clay content of between 27% and 31% and a water-holding capacity of about 300 $mm \cdot m^{-1}$.

Six winter vegetable species were grown during the 1996

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TABLE 1
PLANTING AND HARVEST DATES, AND ROW SPACINGS FOR 6 WINTER AND 19 SUMMER VEGETABLE CULTIVARS (ROODEPLAAT, 1996/97)

Crop	Planting date	Harvest date	Row spacing (m)
Onions (*Allium cepa* cv. Mercedes)	2 May 1996*	20 Sep. 1996	0.15 x 0.2
Cabbage (*Brassica oleracea* cv. Grand Slam)	2 May 1996*	20 Sep. 1996	0.5 x 0.5
Carrots (*Daucus carota* cv. Kuroda)	7 May 1996	11 Oct. 1996	0.3
Beetroot (*Beta vulgaris* cv. Crimson Globe)	7 May 1996	11 Oct. 1996	0.3
Lettuce (*Lactuca sativa* cv. Great Lakes)	7 May 1996*	6 Sep. 1996	0.4 x 0.5
Swisschard (*Beta vulgaris*)	7 May 1996	11 Oct. 1996	0.3
Sweet-corn (*Zea mays Saccharata* cv. Cabaret)	11 Dec. 1996	12 Feb. 1997	1.0
Sweet-corn (*Zea mays Saccharata* cv. Jubilee)	12 Nov. 1996	5 Feb. 1997	1.0
Sweet-corn (*Zea mays Saccharata* cv. Paradise)	12 Nov. 1996	5 Feb. 1997	1.0
Sweet-corn (*Zea mays Saccharata* cv. Dorado)	9 Dec. 1996	12 Feb. 1997	1.0
Beans bush (*Phaseolus limensis* cv. Provider)	12 Nov. 1996	20 Jan. 1997	1.0
Beans bush (*Phaseolus limensis* cv. Bronco)	27 Nov. 1996	27 Jan. 1997	1.0
Beans runner (*Phaseolus coccineus* cv. Lazy Housewife)	27 Nov. 1996	12 Feb. 1997	1.0
Pumpkin (*Cucurbita pepo* cv. Miniboer)	12 Nov. 1996*	5 Feb. 1997	1 x 0.5
Pumpkin (*Cucurbita pepo* cv. Minette)	12 Nov. 1996*	5 Feb. 1997	1 x 0.5
Marrow (*Cucurbita maxima* cv. President)	12 Nov. 1996*	5 Feb. 1997	1 x 0.5
Marrow (*Cucurbita maxima* cv. Long White Bush)	12 Nov. 1996*	5 Feb. 1997	1 x 0.5
Squash (*Cucurbita moschata* cv. Table Queen)	12 Nov. 1996*	5 Feb. 1997	1 x 0.5
Squash (*Cucurbita moschata* cv. Waltham)	12 Nov. 1996*	12 Feb. 1997	1 x 0.5
Tomato table (*Lycopersicon esculentum* cv. Zeal)	29 Nov. 1996*	20 Feb. 1997	1 x 0.5
Tomato processing (*Lycopersicon esculentum* cv. P747)	29 Nov. 1996*	20 Feb. 1997	1 x 0.5
Tomato processing (*Lycopersicon esculentum* cv. HTX14)	29 Nov. 1996*	20 Feb. 1997	1 x 0.5
Eggplant (*Solanum melongena* cv. Black Beauty)	19 Dec. 1996*	4 Mar. 1997	1 x 0.5
Green peppers (*Capsicum annuum* cv. King Arthur)	19 Dec. 1996*	4 Mar. 1997	1 x 0.5
Chilli peppers (*Capsicum annuum* cv. Super Cayenne)	19 Dec. 1996*	4 Mar. 1997	1 x 0.5

* Transplanted

season on 5 m x 12 m plots. During the 1996/97 summer season, 19 cultivars covering 10 crop species were grown on 4 m x 5 m plots. Crops, cultivars, planting and harvest dates, as well as row spacings are summarised in Table 1. Irrigations were carried out weekly with an overhead sprinkler system. The experimental plots were surrounded by irrigated vegetable fields.

Agronomic practices commonly used in the area were followed. The field was ploughed (0.3 m) and a rotovator was used to prepare an 0.15 m deep seedbed. Vegetables planted by seeding were thinned a few weeks after planting. At planting winter crops received 27 kg N·ha^{-1}, 40 kg P·ha^{-1} and 53 kg K·ha^{-1} in the form of 2:3:4 (30), and all but the beetroot received a top dressing of 112 kg·ha^{-1} in the form of LAN (28). Cabbage was treated with metazachlor (Pree) at 2 ℓ·ha^{-1} and onions with oxadiazon (Ronstar) at 4 ℓ·ha^{-1} for weed control, 2 d after transplanting. In addition, cabbage was treated with the insecticide carbofuran (Curaterr) at 2 g·m^{-1} row length. At planting summer crops received 34 kg N·ha^{-1}, 50 kg P·ha^{-1} and 66 kg K·ha^{-1} in the form of 2:3:4 (30). On 23 December, four varieties of sweet-corn, two varieties of bush beans and the runner beans received a top dressing of 84 kg·ha^{-1} in the form of LAN (28). Before planting, all summer plots were sprayed with Dual at 2 ℓ·ha^{-1} for weed control. The eggplant, green and chilli peppers, as well as three varieties of tomato were occasionally sprayed with Karate plus Metasystox for pest control.

Volumetric soil-water content (SWC) was measured with a neutron water meter Model 503DR CPN Hydroprobe (Campbell Pacific Nuclear, California, USA) (*Mention of manufacturers is for the convenience of the reader only and implies no endorsement on the part of the authors, their sponsors nor the University of Pretoria*). The neutron water meter was calibrated for SWC, using gravimetric soil-water contents and bulk densities. Weekly readings were taken in the middle of each plot, for 0.2 m soil layers down to 1.0 m. Measured SWC was used to calculate soil-water deficit (SWD) to field capacity (FC). Rain gauges were installed in order to measure irrigation (I) and precipitation (P).

Canopy cover (C) was measured weekly with a Decagon sunfleck ceptometer (Decagon, Pullman, Washington, USA), making one reference reading above each canopy and 10 readings beneath each canopy. Crop height was measured at the end of the growing season for winter crops, and weekly for summer crops.

Weather data were recorded with an automatic weather station (Mike Cotton Systems, Cape Town, South Africa) located 300 m from the trial site. Solar radiation was measured with an MCS 155-1 pyranometer, wet and dry bulb air temperature with two MCS 152 thermistors and wind speed with an MCS 177 cup anemometer. Hourly averages were stored with an MCS 120-02EX data logger.

Theoretical overview of the model

The SWB model is a daily time step, generic crop, irrigation scheduling model simulating soil-water balance and crop growth from specific crop growth parameters (Annandale et al., 1996; Barnard et al., 1998). Specific crop growth parameters can be determined using weather, soil and growth analysis data. In the absence of such time-consuming and therefore expensive growth analysis data, a simpler modelling approach is required. An FAO-based crop factor procedure has therefore been developed and combined with the mechanistic SWB model, thereby still allowing evaporation and transpiration to be modelled separately as supply- and demand-limited processes. The crop factor model does not grow the canopy mechanistically and therefore the effect of water stress on canopy size is not simulated. The simpler crop factor model should, however, still perform satisfactorily if the estimated canopy cover closely resembles that found in the field.

The SWB model calculates grass reference evapotranspiration (ETo) using the revised FAO Penman-Monteith methodology (Smith et al., 1996). Crop potential evapotranspiration (PET) is calculated as follows:

$$PET = ETo\ Kc_{max} \tag{1}$$

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., 1996):

$$Kc_{max} = \max \begin{cases} 1.2 + [0.04\,(U_2 - 2) - 0.004\,(RH_{min} - 45)]\,(Hc/3)^{0.3} & (2) \\ Kcb + 0.05 & (3) \end{cases}$$

where:

U_2 - Mean daily wind speed at 2 m height ($m \cdot s^{-1}$)
RH_{min} - Daily minimum relative humidity (%)

where the canopy height (Hc) is in m. The upper limit of Kc_{max} is set at 1.45 (Allen et al., 1996).

The SWB model partitions PET into potential crop transpiration (PT) and potential evaporation from the soil surface (PE), and estimates C using the following equations:

$$PT = Kcb\ ETo \quad \text{(Allen et al., 1996)} \tag{4}$$
$$C = PT/PET \tag{5}$$
$$PE = (1 - C)\ PET \tag{6}$$

Water loss by evaporation (E) is assumed to occur only from the top soil layer. It proceeds at the potential rate until SWC reaches the permanent wilting point (PWP). Thereafter, it is equal to the product of PE and the square of the fraction of the remaining evaporable water down to air dryness which is taken as 30% of PWP (Campbell and Diaz, 1988). No root water uptake is calculated for the uppermost soil layer. The SWB model assumes that layer water uptake is weighted by root density when soil-water potential is uniform (Campbell and Diaz, 1988). Water loss by crop transpiration (T) is calculated as a function of maximum transpiration rate (T_{max}) and leaf water potential at T_{max} (Ψ_{lm}) (Campbell, 1985). It represents the lesser of root water uptake or maximum loss rate. The input parameters T_{max} and Ψ_{lm} can be easily estimated from one's experience with the crop. In this way, a mechanistic supply- and demand-limited water uptake calculation was linked to an FAO crop factor approach with a minimal addition of crop input parameters required.

The SWB model assumes Kcb, RD and Hc are equal to the initial values during the initial stage. During the crop development stage, they increase linearly from the end of the initial stage until the beginning of the mid-season stage, when they attain maximum values. They remain constant at this maximum during the mid-season stage. During the late-season stage, Kcb decreases linearly until harvest when it reaches the value for late-season stage, whilst RD and Hc remain constant at their maximum value. The following crop parameters need therefore to be known: T_{max}, Ψ_{lm}, Kcb for the initial, mid-season and late-season stages, crop growth periods in days for initial, development, mid-season and late-season stages, initial and maximum RD, as well as initial Hc and Hc_{max}.

The following input parameters are required to run the model: planting date, latitude, altitude, rainfall and irrigation water amounts, as well as maximum and minimum daily air temperatures. In the absence of measured data, SWB estimates solar radiation, vapour pressure and wind speed according to the FAO recommendations (Smith, 1992b; Smith et al., 1996). It is, however, recommended that these be measured. In addition, SWC at FC and PWP as well as initial SWC are required for each soil layer. Volumetric soil-water contents at FC and PWP were calculated from the content of clay and silt in the soil, using the empirical functions recommended by Bennie et al. (1988).

The SWB model is written in Delphi 4 (Inprise Corporation). A user-friendly Windows 95 version of the SWB model is available from the authors, as is the crop growth, soil-water content and weather database.

Results and discussion

In this study, detailed field measurements and figures are presented and discussed for one winter (onions) and one summer crop (green peppers) as examples. Results obtained for all crops are summarised in Tables.

Canopy development and root depth

Figure 1 represents measured values of canopy cover C and estimated root depth RD during the growing season of onions and green peppers. RD was estimated from weekly measurements of SWC with the neutron meter. It was assumed to be equal to the depth at which 90% of soil-water depletion occurred during weekly periods. Estimated RD values were different from those recommended by Green (1985b) for transplanted onions, in particular for the initial stage. Initial RD values of 0.25 m were used as model input (Smith, 1992a). Maximum RD values estimated from SWC measurements with the neutron water meter were generally in the range of those reported by Green (1985b) and Smith (1992a). These values were included in the SWB database and are summarised in Table 2.

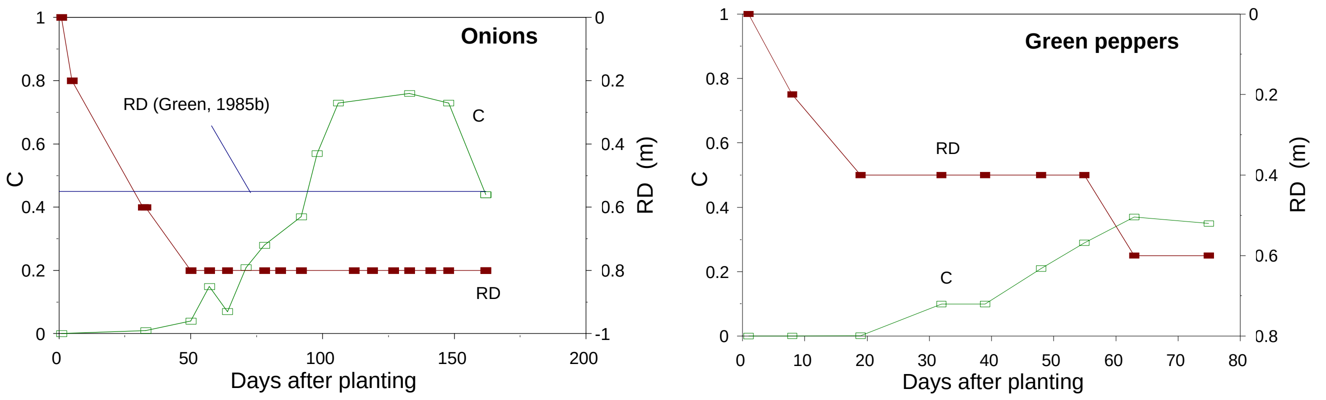

Figure 1
Measured values of canopy cover (C) and estimated root depth (RD, depth at which 90% of weekly soil-water depletion occurred) during the growing season of onions and green peppers. Root depth recommended by Green (1985b) is also presented for onions

TABLE 2
MAXIMUM ROOT DEPTH (RD) AND CROP HEIGHT (Hc_{MAX}), AND 90% OF MAXIMUM CANOPY COVER (C) FOR 6 WINTER AND 19 SUMMER VEGETABLE CULTIVARS

Crop	Maximum RD (m)	Hc_{max} (m)	90% of maximum C
Onions	0.8	0.5	0.60
Cabbage	0.8	0.3	0.90
Carrots	0.8	0.3	0.90
Beetroot	0.8	0.4	0.90
Lettuce	0.6	0.3	0.88
Swisschard	0.8	0.4	0.90
Sweet-corn (cv. Cabaret)	1.0	1.7	0.81
Sweet-corn (cv. Jubilee)	0.6	2.1	0.83
Sweet-corn (cv. Paradise)	0.6	2.1	0.80
Sweet-corn (cv. Dorado)	0.8	1.7	0.61
Bush beans (cv. Provider)	0.4	0.5	0.74
Bush beans (cv. Bronco)	0.8	0.5	0.71
Runner beans	0.6	2.3	0.81
Pumpkin (cv. Miniboer)	0.8	0.6	0.75
Pumpkin (cv. Minette)	0.8	0.7	0.76
Marrow (cv. President)	1.0	0.6	0.61
Marrow (cv. Long White Bush)	0.8	0.65	0.74
Squash (cv. Table Queen)	0.8	0.4	0.47
Squash (cv. Waltham)	0.8	0.3	0.55
Tomato (cv. Zeal)	0.6	0.6	0.48
Tomato (cv. P747)	0.8	0.65	0.69
Tomato (cv. HTX14)	0.8	0.45	0.53
Eggplant	0.6	0.6	0.45
Green peppers	0.6	0.5	0.31
Chilli peppers	0.6	0.6	0.29

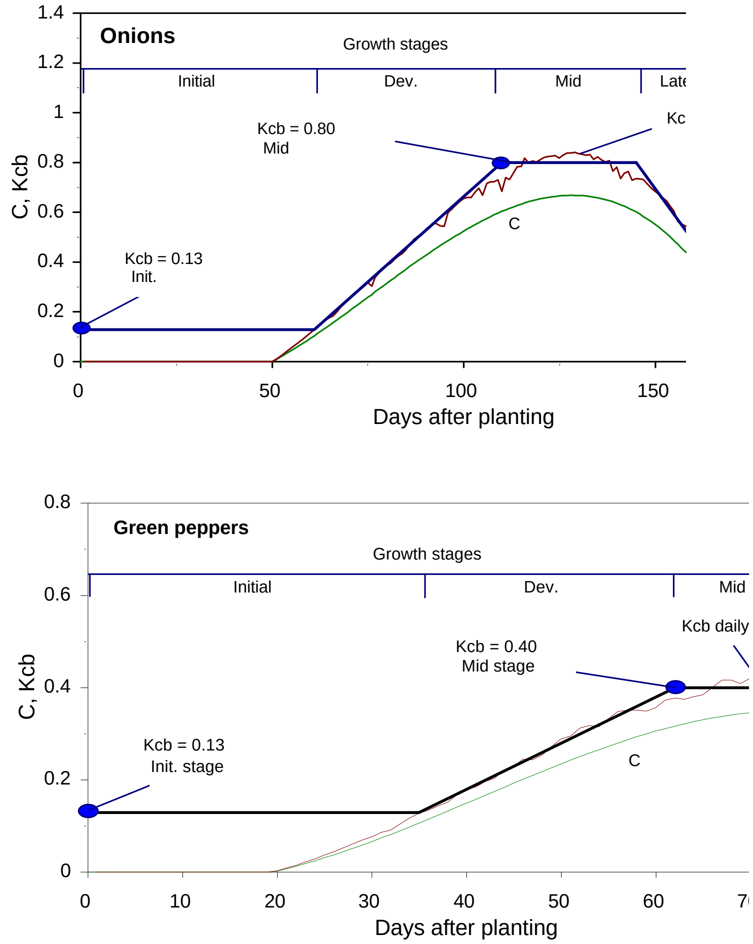

Figure 2
Daily values of canopy cover (C) and basal crop coefficient (Kcb daily), and estimated Kcb values for four growth stages of onions and green peppers (initial, crop development, mid-season and late-season stages)

Crop height and potential evapotranspiration

Grass reference evapotranspiration ETo was calculated using the SWB model and weather input data collected from the weather station, and used to determine PET with Eqs. (1) and (2). In the absence of measurements during the growing season, it was assumed that Hc of onions increased linearly from planting until harvest. A third-order polynomial was fitted through eight measured data points of Hc for green peppers ($r^2 = 0.97$), and used to calculate daily PET. The same procedure was used to calculate PET for the other winter and summer crops. Initial Hc values used as model input were assumed to be 0.01 m for crops planted by seeding and 0.05 m for transplanted crops. Measured Hc_{max} values were included in the SWB database and are summarised in Table 2 for all crops studied.

Basal crop coefficients and growth periods

Figure 2 presents values of C and Kcb for onions and green peppers. A third order polynomial was fitted through the measured data points of C as a function of days after planting for both crops. The coefficients of determination were 0.94 for onions and 0.97 for green peppers. Daily Kcb was calculated from C, Hc and weather data using the following equation derived from Eqs. (4) and (5):

$$Kcb = C\ PET/ETo \qquad (7)$$

The following procedure was used to determine Kcb's for the initial, mid-season and late-season stages, and the lengths of growth stages in days for onions and green peppers (Fig. 2):

- Initial stage: Length of stage from planting until C = 0.1.
  Kcb equal to daily calculated Kcb at C = 0.1.
- Crop development stage: Length of stage from end of initial stage until C is 90% of maximum C (Table 2).
- Mid-season stage: Length of stage from end of development stage until canopy cover drops to the same value it had at the beginning of the mid-season period (90% of maximum C).
  Kcb equal to average daily Kcb calculated with Eq. (7) during the mid-season stage.
- Late-season stage: Length of stage from end of mid-season stage until end of growing season.
  Kcb equal to daily calculated Kcb at end of growing season.

Doorenbos and Pruitt (1992) stated that the beginning of the mid-season stage can be recognised in the field when the crop has attained 70 to 80% ground cover. They also stated that full ground cover occurs when Kc approaches a maximum. Many vegetables do not reach 70% groundcover during the growing season. The mid-season stage was therefore assumed to have started when C became equal to 90% of maximum C value attained (Table 2).

TABLE 3
BASAL CROP COEFFICIENTS (Kcb) AND GROWTH PERIODS (INITIAL, DEVELOPMENT, MID-SEASON AND LATE-SEASON STAGES) FOR 6 WINTER AND 19 SUMMER VEGETABLE CULTIVARS

	Kcb			Growth period (days)				
Crop	Init.	Mid	Late*	Init.	Dev.	Mid	Late*	Total
Onions	0.13	0.80	0.38	61	49	35	20	165
Cabbage	0.13	1.22	-	5	62	98	-	165
Carrots	0.12	1.22	-	46	64	50	-	160
Beetroot	0.13	1.18	1.04	26	79	50	5	160
Lettuce	0.14	1.14	-	52	46	27	-	125
Swisschard	0.13	1.21	-	36	73	51	-	160
Sweet-corn (cv. Cabaret)	0.14	1.04	0.99	18	27	17	1	63
Sweet-corn (cv. Jubilee)	0.14	1.03	0.86	22	37	23	3	85
Sweet-corn (cv. Paradise)	0.14	1.00	0.61	33	26	19	7	85
Sweet-corn (cv. Dorado)	0.14	0.76	0.53	16	26	17	6	65
Bush beans (cv. Provider)	0.13	0.94	0.55	19	26	17	7	69
Bush beans (cv. Bronco)	0.13	0.90	0.70	6	30	20	5	61
Runner beans	0.14	1.02	0.78	6	37	26	8	77
Pumpkin (cv. Miniboer)	0.14	0.94	-	9	53	23	-	85
Pumpkin (cv. Minette)	0.14	0.96	0.48	34	24	18	9	85
Marrow (cv. President)	0.12	0.77	0.30	28	27	19	11	85
Marrow (cv. Long White Bush)	0.13	0.93	0.73	30	30	21	4	85
Squash (cv. Table Queen)	0.12	0.60	0.60	10	47	28	-	85
Squash (cv. Waltham)	0.13	0.70	-	18	46	28	-	92
Tomato (cv. Zeal)	0.12	0.62	0.48	32	27	20	4	83
Tomato (cv. P747)	0.13	0.90	-	27	38	18	-	83
Tomato (cv. HTX14)	0.14	0.68	0.27	34	22	17	10	83
Eggplant	0.12	0.58	0.52	20	32	22	1	75
Green peppers	0.13	0.40	-	35	27	13	-	75
Chilli peppers	0.13	0.37	0.28	28	22	20	5	75

* Not determined for crops harvested during the mid-season stage, before leaf senescence occurred

The duration of the late-season stage and Kcb for this stage were not determined for green peppers as the crop was harvested during the mid-season stage, before leaf senescence had occurred (Fig. 2).

Table 3 summarises Kcb values for initial, mid-season and late-season stages, as well as lengths of the stages in days for 25 crops. Initial Kcb's were generally in the range of those recommended by Allen et al. (1996). Mid-season Kcb's were generally higher for the winter species, and lower for the summer vegetables compared to those reported by Allen et al. (1996). Kcb's for the late-season stage and the duration of this stage were not determined for crops harvested during the mid-season stage, before leaf senescence occurred. Differences in length of crop growth stages were observed between the data obtained in this trial and those published by the FAO (Doorenbos and Pruitt, 1992; Smith, 1992a) for most crops, due to the different cultivars and conditions under which the experiments were carried out. The total lengths of growth periods were similar to those reported by Green (1985b) for transplanted onions, beans and cucurbits grown at Roodeplaat. In his work, Green (1985b) included data for cabbage planted in March, September and December with shorter growing seasons (90 to 110 d) compared to this trial. The growth periods recommended in this trial for tomatoes (83 d) were much shorter than those reported by Green (1985b), probably due to a difference in cultivars.

Model simulations

Crop input parameters were entered in the SWB database and data from the field trial compared to simulations for 25 crops. Maximum transpiration rate T_{max} was estimated to be 9 mm·d^{-1} and Ψ_{lm} equal to -1 500 J·kg^{-1} for all crops. Figure 3 represents measured and simulated values of SWD, and Fig. 4, canopy cover for onions and green peppers. Statistical analysis of measured and simulated data was carried out by SWB to assess the model's accuracy, as recommended by De Jager (1994). The parameters

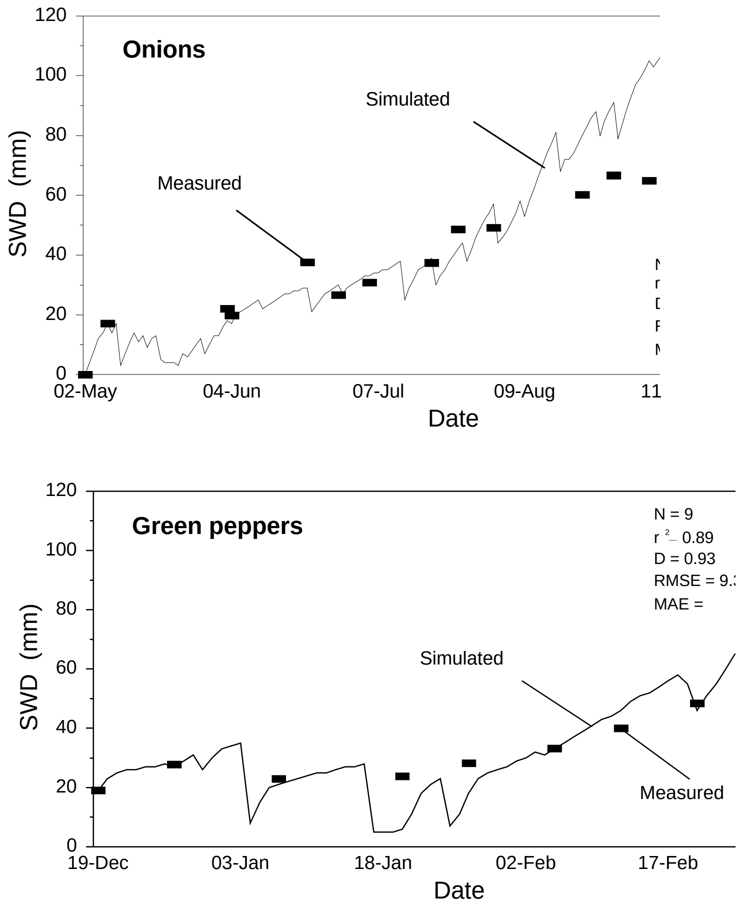

Figure 3
Measured and simulated soil-water deficit (SWD) during the growing season of onions and green peppers. The parameters of the statistical analysis of measured and simulated data are number of observations (N), coefficient of determination (r^2), Willmott's index of agreement (D), root mean square error (RMSE) and mean absolute error (MAE).

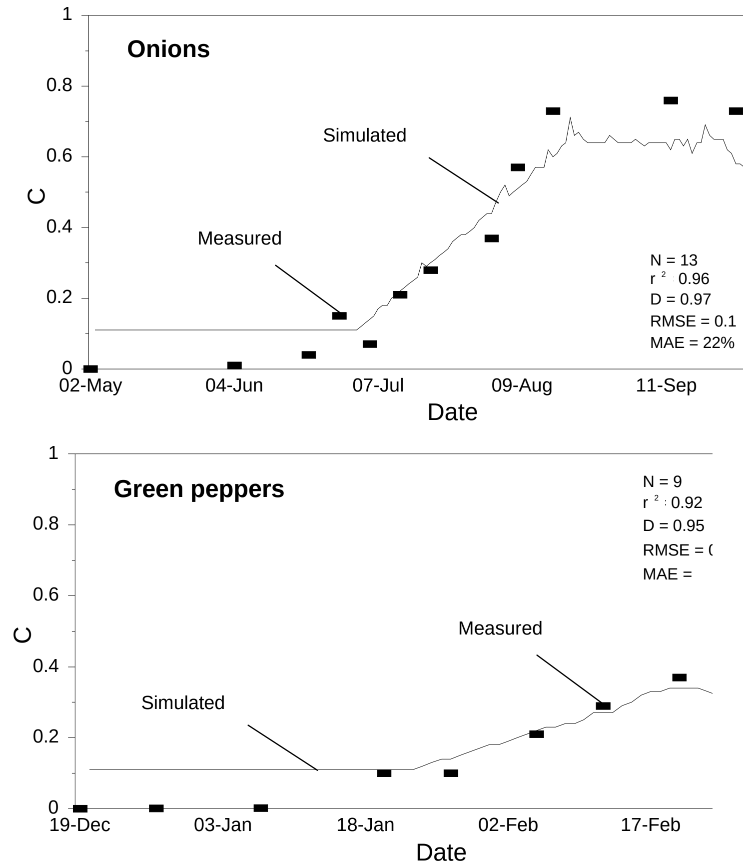

Figure 4
Measured and simulated canopy cover (C) during the growing season of onions and green peppers. The parameters of the statistical analysis of measured and simulated data are number of observations (N), coefficient of determination (r^2), Willmott's index of agreement (D), root mean square error (RMSE) and mean absolute error (MAE).

TABLE 4 CALCULATED SEASONAL VALUES OF EVAPORATION FROM THE SOIL SURFACE (E), TRANSPIRATION (T) AND EVAPOTRANSPIRATION (ET), AND MEASURED SEASONAL EVAPOTRANSPIRATION (ET_m)				
Crop	Calculated E (mm)	Calculated T (mm)	Calculated ET (mm)	ET_m (mm)
Onions	229	123	352	350
Cabbage	106	232	338	350
Carrots	153	246	399	390
Beetroot	147	212	359	383
Lettuce	141	131	272	281
Swisschard	142	248	390	390
Sweet-corn (cv. Cabaret)	137	171	308	-
Sweet-corn (cv. Jubilee)	168	212	380	-
Sweet-corn (cv. Paradise)	203	187	390	-
Sweet-corn (cv. Dorado)	148	149	297	-
Bush beans (cv. Provider)	151	158	309	-
Bush beans (cv. Bronco)	142	188	330	-
Runner beans	146	207	353	-
Pumpkin (cv. Miniboer)	177	235	412	-
Pumpkin (cv. Minette)	205	199	404	-
Marrow (cv. President)	213	178	391	-
Marrow (cv. Long White Bush)	208	199	407	-
Squash (cv. Table Queen)	220	173	393	-
Squash (cv. Waltham)	220	192	412	-
Tomato (cv. Zeal)	207	114	321	-
Tomato (cv. P747)	195	154	349	-
Tomato (cv. HTX14)	206	136	342	-
Eggplant	147	91	238	-
Green peppers	148	78	226	-
Chilli peppers	145	81	226	-

of the statistical analysis are shown on the graphs in Figs. 3 and 4. They are number of observations (N), coefficient of determination (r^2), Willmott's index of agreement (D), root mean square error (RMSE) and mean absolute error (MAE). Model predictions were very good, but one should bear in mind that the comparison is not with independent data. A lack of water treatments in the field trial prevented testing the model for different conditions of soil-water supply. Similar results were obtained for the other crops.

Crop water use

Table 4 shows seasonal modelled values of soil evaporation (E) and crop transpiration (T), as well as actual evapotranspiration (ET) calculated with SWB for 25 vegetable crops. Measured seasonal evapotranspiration values (ET_m) were obtained for six winter species using the following equation:

$$ET_m = P + I - R - Dr - \Delta Q \qquad (8)$$

The components of the soil-water balance are rainfall (P), irrigation (I), runoff (R) and drainage (Dr). ΔQ represents soil-water storage. All terms are expressed in mm. R was assumed to be negligible. Dr was also assumed to be 0 as irrigations were carried out to refill the soil profile to below FC and no heavy rainfall occurred during the growing season. A positive ΔQ indicates a gain in soil-water storage. ΔQ was estimated from soil-water content measurements with the neutron meter. Simulated ET values were very close to those measured. During the rainy summer 1996/97 season, it was not possible to apply Eq. (8) as R and Dr were not measured. Simulated ET values were in the range of those calculated by Green (1985b) for onions, cabbage and beans. Different values of seasonal evapotranspiration were estimated by Green (1985b) for cucurbits and tomatoes compared to this trial, as the total length of the growing season was different for these crops.

Conclusions

Kcb's and growth periods were determined for 25 vegetable cultivars using a simple canopy cover-based equation. Weather data and crop height were used to calculate crop PET, whilst canopy cover was used to calculate Kcb values, and to determine the start of the initial stage, as well as the start and end of the mid-season stage. The procedure can be easily and cheaply applied to determine FAO type crop parameters for any species.

A simple FAO crop factor-based water balance model, accounting for supply- and demand-limited crop water use, has been incorporated in the user-friendly, mechanistic SWB irrigation scheduling model. This facilitates irrigation scheduling of 25 vegetable cultivars for which a database of experimentally determined crop parameters has been generated. Good model predictions of soil-water deficit and canopy cover were observed. Caution should, however, be exercised against blind acceptance of the FAO parameters as local conditions, management and cultivars are likely to influence crop growth periods and Kcb's. Validation of the model with independent data sets would be desirable.

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