Field water balance and SWB parameter determination of six winter vegetable species

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Abstract

Mechanistic, user-friendly crop growth models are useful and accurate tools for irrigation scheduling. They require, however, specific crop growth input parameters which are not readily available for all crops and conditions. Six irrigated vegetable species (onions, cabbage, carrots, beetroot, lettuce and swisschard) were grown in a field trial at Roodeplaat (Gauteng, South Africa) during the 1996 dry winter season. The objective was to determine specific crop growth parameters required by the SWB (Soil-Water Balance) irrigation scheduling, generic crop growth model. Weather data were recorded with an automatic weather station, phenological stages monitored and growth analyses carried out fortnightly. Fractional interception of radiation was measured weekly with a sunfleck ceptometer as was soil water with a neutron water meter. Field measurements were used to generate a database of crop water and radiation use efficiencies, specific leaf areas, stem-leaf partitioning parameters, canopy extinction coefficients, maximum rooting depths, and thermal time requirements for crop development. These data are invaluable for generating the parameters required to accurately simulate the soil-water balance with mechanistic crop models.

Introduction

In the absence of winter rainfall in the Gauteng Province, irrigation is required in order to achieve optimal yields of winter crops. Optimisation of irrigation water management is necessary for structural (irrigation system design), economic (saving of water and energy), and environmental reasons (risks of salinisation, fertiliser and nutrient leaching). The direct objectives of irrigation water management are to determine the amount of irrigation water to supply the crop and the timing of this irrigation. Several methods for irrigation scheduling are reviewed in the literature. They can be classified as soil-, plant- and atmosphere-based approaches. Examples are monitoring soil water by means of tensiometers (Cassel and Klute, 1986), electrical resistance and heat dissipation soil-water sensors (Campbell and Gee, 1986; Bristow et al., 1993), or neutron water meters (Gardner, 1986). Crop water requirements can also be determined by monitoring atmospheric conditions (Doorenbos and Pruitt, 1992), and plant water status is often used as an indicator of when to irrigate (Clark and Hiler, 1973; Bordovsky et al., 1974; Stegman et al., 1976; O'Toole et al., 1984).

The interest in scheduling irrigations with crop growth computer models is rapidly increasing, particularly since PCs have become accessible to crop producers (Bennie et al., 1988; Smith, 1992a; Campbell and Stockle, 1993; Annandale et al., 1996a). This provides a mechanistic description of the soil-plant-atmosphere continuum without the user requiring specialist knowledge to make the intricate calculations. It is, however, essential that the model interface be user-friendly.

Mechanistic crop growth models require specific crop input parameters which are not readily available for all crops and conditions. In particular, there is a lack of information on crop-specific parameters for vegetables. The objective of this study was to determine crop growth parameters of six vegetable species, and include them in the database of the SWB (Soil-Water Balance) irrigation scheduling model (Annandale et al., 1996b; Barnard et al., 1998). These specific crop growth parameters could also be used in other models, or the data could be used to calculate other parameters. Field measurements were used to determine the following parameters: vapour pressure deficit-corrected dry matter/water ratio (DWR), radiation conversion efficiency (E_c), specific leaf area (SLA), stem-leaf dry matter partitioning parameter (p), canopy extinction coefficient for solar radiation (K_s) and growing day degrees (GDD) for the completion of phenological stages.

Materials and methods

Experimental set-up

A field trial was established at Roodeplaat (Department of Agriculture - Directorate of Plant and Quality Control; 25°35' S, 28°21' E, altitude 1165 m), 30 km NE of Pretoria. The climate of the region is one of summer rainfall with an average of about 650 mm 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). Frequent occurrence of frost is experienced during winter months. The soil is a 1.2 m deep clay loam Red Valsrivier (Soil Classification Working Group, 1991), with a clay content between 27% and 31% and a water-holding capacity of about 300 mm·m^{-1}.

Six winter vegetable species were grown during the 1996 season: onions (*Allium cepa* cv. Mercedes), cabbage (*Brassica oleracea* cv. Grand Slam), carrots (*Daucus carota* cv. Kuroda), beetroot (*Beta vulgaris* cv. Crimson Globe), lettuce (*Lactuca sativa* cv. Great Lakes) and swisschard (*Beta vulgaris*). The experimental field was 30 m x 12 m in size. Each plot was 5 m x 12 m. Transplanting, seeding and harvest dates, as well as

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TABLE 1
TRANSPLANTING, SEEDING AND HARVEST DATES, AND SPACING OF SIX WINTER VEGETABLES (ROODEPLAAT, 1996)

Crop	Transplanting or seeding date	Harvest date	Spacing (m)
Onions	Transplanted 2 May	20 September	0.15 x 0.2
Cabbage	Transplanted 2 May	20 September	0.5 x 0.5
Carrots	Seeded 7 May	11 October	0.3
Beetroot	Seeded 7 May	11 October	0.3
Lettuce	Transplanted 2 May	6 September	0.4 x 0.5
Swisschard	Seeded 7 May	22 August; 11 October	0.3

spacing are summarised in Table 1. Weekly irrigations were carried out with an overhead sprinkler system. No water stress occurred during the growing season. 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 a 0.15 m deep seedbed. Vegetables planted by seeding were thinned a few weeks after planting. At planting all 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 N ha^{-1} in the form of LAN (28). Cabbage was treated with metazachlor (Pree) at 2 $\ell \cdot ha^{-1}$ and onions with oxadiazon (Ronstar) at 4 $\ell \cdot ha^{-1}$ for weed control, 2 d after transplanting. In addition, cabbage was treated with the insecticide carbofuran (Curaterr) at 2 $g \cdot m^{-1}$ row length.

Field measurements

Soil-water deficit to field capacity 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 the site. Weekly readings were taken in the middle of each plot, at one position between rows, for 0.2 m soil layers down to 1.0 m. Rain gauges were installed in order to measure irrigation (I) and rainfall (P).

Fractional interception (FI) of photosynthetically active radiation (PAR, 0.4-0.7 m) 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. Growth analyses were carried out fortnightly, by harvesting plant material above 1 m^2 of ground surface at representative sites, with no replications due to the small plot size. Harvestable fresh mass was measured directly after sampling, and dry matter of plant organs after drying in an oven at 60°C for 4 to 5 d. Leaf area index (LAI) was calculated after measuring leaf area with an LI 3100 belt-driven leaf area meter (LiCor, Lincoln, Nebraska, USA). Outer, green leaves of lettuce and cabbage were assumed to be photosynthetically active. Phenological development was also monitored for each crop.

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

Results and discussion

Yield and crop water requirements

Table 2 presents dry matter (DM) and harvestable dry matter (HDM) production, as well as fresh yield at the end of the season and seasonal average gravimetric water content of the harvestable organ for the six vegetables. DM includes all above-ground biomass and, in the case of the root crops, the underground harvestable organ. Root dry matter was not measured and is therefore not included.

Seasonal crop evapotranspiration (ET), rainfall and irrigation are shown in Table 2. ET was obtained using the following equation for weekly time intervals:

$$ET = P + I - R - D - \Delta Q \qquad (1)$$

where R is runoff, D is drainage and ΔQ represents the soil-water storage for 1 m soil depth. All terms are expressed in mm. R was assumed to be negligible as no high intensity rain occurred and the irrigation system application rate did not exceed the soil infiltration rate. D was neglected as irrigations (I) were carried out refilling the soil profile to below field capacity and no heavy rains (P) occurred during the growing season. A positive sign for ΔQ indicates a gain in soil-water storage. ΔQ was calculated from soil-water content measurements with the neutron water meter.

Vapour pressure-corrected dry matter/water ratio

DWR is a crop-specific parameter determining water use efficiency. Tanner and Sinclair (1983) recommended that the relation between DM production and crop transpiration should be corrected to account for atmospheric conditions, in particular for vapour pressure deficit (VPD). DWR of six well-irrigated vegetables was calculated as follows:

$$DWR = (DM\ VPD) / ET \qquad (2)$$

DM ($kg \cdot m^{-2}$) was measured at harvest, whilst VPD represents the seasonal average. Both VPD and DWR are in Pa (Table 2). ET in mm is equivalent to $kg \cdot m^{-2}$. Evaporation from the soil surface should not actually be included in the calculation of DWR, as unlike transpiration, it is not tightly linked to photosynthesis and therefore dry matter production. The portion of soil-water lost by evaporation could be substantial in vegetables, particularly at the beginning of the season when canopy cover is partial. Root dry matter was also not measured and was therefore also not included in the calculation of DWR. For these reasons, the DWR values calculated with Eq. (2) and presented in Table 2, should be seen as lower limits and need to be increased to give reliable simulations in SWB. This is because the SWB model calculates transpiration-limited DM production as follows:

$$DM = DWR\ Tr / VPD \qquad (3)$$

where:
Tr - Crop transpiration (mm)

Daily VPD was calculated from measurements of T_w and T_d, adopting the following procedure recommended by the Food and Agriculture Organisation (FAO) of the United Nations (Smith, 1992b):

TABLE 2
YIELD, SOIL-WATER BALANCE AND SPECIFIC CROP GROWTH PARAMETERS FOR SIX WINTER VEGETABLES (ROODEPLAAT, 1996)

Yield, water use and crop parameters	Species					
	Onions	**Cabbage**	**Carrots**	**Beetroot**	**Lettuce**	**Swisschard**
Dry matter production DM ($kg \cdot m^{-2}$)	0.70	1.50	1.07	1.40	0.37	1.07
Harvestable dry matter HDM ($kg \cdot m^{-2}$)	0.31	0.92	0.76	0.76	0.20	0.56
Fresh yield ($kg \cdot m^{-2}$)	2.84	4.29	5.76	4.97	1.85	6.14
Gravimetric water content of harvestable organ (%)	82.6	73.1	87.3	82.5	90.5	90.1
Evapotranspiration ET (mm)	350	350	390	383	281	390
Rainfall P (mm)	55	55	61	61	42	61
Irrigation I (mm)	234	234	287	287	199	287
Vapour pressure deficit VPD (Pa)	859	859	940	940	805	940
Dry matter/evapotranspiration ratio corrected for vapour pressure deficit DWR (Pa)	1.72	3.68	2.57	3.44	1.06	2.58
Radiation conversion efficiency E_c ($g \cdot MJ^{-1}$)	1.08	1.29	0.60	1.28	1.26	1.56
r^2	0.99	0.91	0.91	0.77	0.99	0.88
Specific leaf area SLA ($m^2 \cdot kg^{-1}$)	8.11	6.93	14.28	10.09	20.27	12.64
Stem-leaf partitioning parameter p	1.12	0.44	3.08	1.44	8.28	1.46
r^2	0.81	0.63	0.71	0.86	0.88	0.48
Canopy extinction coefficient for PAR K_{PAR}	1.06	1.17	1.85	1.31	0.80	0.63
r^2	0.76	0.81	0.87	0.78	0.50	0.75
Canopy extinction coefficient for total solar radiation K_s	0.75	0.83	1.31	0.93	0.56	0.44
Maximum rooting depth (m)	0.8	0.8	0.8	0.8	0.6	0.8
Base temperature T_b* (°C)	7.2	4.4	7.2	4.4	7.2	4.4
Optimum temperature T_{opt}* (°C)	29.4	23.9	23.9	23.9	23.9	23.9
Day degrees for emergence	-	-	100	100	-	50
Day degrees until harvest	837	1234	1067	1509	656	840

* Knott (1988)

$$VPD = [e_{sTmax} + e_{sTmin})]/2 - e_a \quad (4)$$

where:

- e_{sTmax} - Saturated vapour pressure at maximum air temperature (kPa)
- e_{sTmin} - Saturated vapour pressure at minimum air temperature (kPa)
- e_a - Actual vapour pressure (kPa)

Saturated vapour pressure (e_s) at maximum (T_{max}) and minimum air temperature (T_{min}) was calculated by replacing T with T_{max} and T_{min} (°C) in the following equation (Tetens, 1930):

$$e_s = 0.611 \exp[17.27\ T/(T + 237.3)] \quad (5)$$

e_a was calculated from measured daily average T_w and T_d (°C), using the following equation (Bosen, 1958):

$$e_a = e_{sTw} - 0.0008\ (T_d - T_w)\ P_a \quad (6)$$

where:

- e_{sTw} - Saturated vapour pressure at T_w (kPa)
- P_a - Atmospheric pressure (kPa)

Saturated vapour pressure at T_w was calculated by replacing T with T_w in Eq. (5). P_a was calculated as follows (Burman et al., 1987):

$$P_a = P_0\ [(T_0 - \alpha Alt)/T_0]^{g/(\alpha R_g)} \quad (7)$$

where:

- P_0 - Standard atmospheric pressure at sea level (101.3 kPa)
- T_0 - Standard temperature at sea level (293 K)
- α - Adiabatic lapse rate ($K \cdot m^{-1}$)
- Alt - Altitude (m)
- g - Gravitational acceleration (9.8 $m \cdot s^{-2}$)
- R_g - Specific gas constant for dry air (286.9 $J \cdot kg^{-1} \cdot K^{-1}$)

The adiabatic lapse rate was assumed to be 0.0065 $K \cdot m^{-1}$ for saturated air.

Radiation conversion efficiency

E_c is a crop-specific parameter used to calculate dry matter production under conditions of radiation-limited growth (Monteith, 1977) as follows:

$$DM = E_c\ FI\ R_s \quad (8)$$

Figure 1 represents DM of cabbage as a function of the daily cumulative product of FI and R_s. FI was measured with the ceptometer and R_s with the MCS 155-1 pyranometer. E_c is the slope of the regression line forced through the origin. The high coefficients of determination of these functions indicate that E_c is a relatively constant and predictable parameter under conditions of good water supply (Table 2). E_c values also represent a lower limit, as root dry matter is once again not accounted for. This also caused the over-estimation of DM calculated with Eq. (8) during the first part of the season for cabbage (Fig. 1; cumulative FI x R_s < 750 MJ m^{-2}). Calculated E_c values for onions and beetroot are in the range of those reported by Monteith (1988) for root crops. The lowest E_c was calculated for carrots, as the horizontal leaf-canopy intercepts high radiation levels on upper leaves, but has less total sunlit leaf area compared to inclined leaf-canopies, making the photosynthesis process less efficient. Caution should be exercised in the use of a constant E_c throughout the entire growing season (Demetriades-Shah et al., 1992). Variability in E_c was reported depending on plant phenology (Garcia et al., 1988; Arkebauer et al., 1994), water supply, nutrient status and disease (Monteith, 1994).

Specific leaf area and stem-leaf partitioning parameter

SWB calculates daily increments of DM as being either transpiration-limited (Eq. 3) or radiation-limited processes (Eq. 8), with water stress affecting the partitioning of assimilates to the different plant organs. DM is preferentially partitioned to reproductive sinks and roots. The remaining DM is partitioned to canopy dry matter (CDM, dry matter of leaves plus stems). SWB calculates leaf (LDM) and stem dry matter (SDM) as follows:

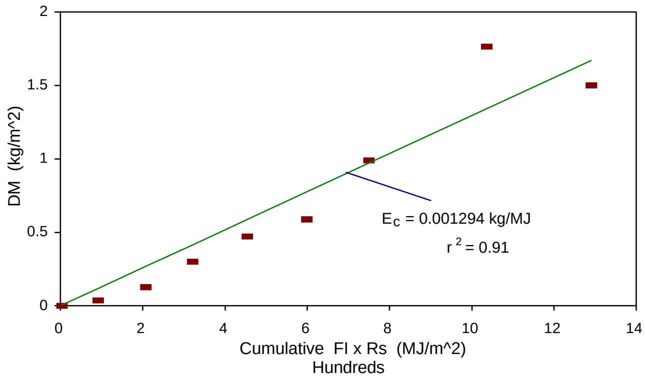

Figure 1

Dry matter (DM) production of cabbage as a function of the cumulative product of fractional interception and solar radiation (FI x R_s). Radiation conversion efficiency (E_c) and the coefficient of determination (r^2) are shown

$$LDM = CDM / (1 + p\ CDM) \quad (9)$$

$$SDM = CDM - LDM \quad (10)$$

LDM is used to calculate LAI as follows:

$$LAI = SLA\ LDM \quad (11)$$

where SLA is the specific leaf area in $m^2 \cdot kg^{-1}$. LAI is then used to calculate FI, which is required for partitioning of potential evapotranspiration into potential transpiration and potential evaporation from the soil surface.

SLA and the stem-leaf dry matter partitioning parameter (p) have to be known in order to calculate DM partitioning with SWB. Growth analysis data were used to determine these parameters. SLA was calculated as the seasonal average of the ratio of LAI and LDM. SLA values for six vegetables are shown in Table 2. Caution should be exercised in the use of seasonal average SLA as this parameter typically has a decreasing trend during the season as is illustrated for cabbage in Fig. 2. The partitioning parameter "p" was determined as a function of SLA, LAI and CDM, by combining Eqs. (9) and (11). Figure 3 represents the correlation between CDM and (SLA CDM)/LAI - 1 for cabbage. The slope of the regression line which is forced through the origin, represents p in $m^2 \cdot kg^{-1}$. Values of p and the coefficients of determination for six winter vegetables are summarised in Table 2.

Canopy radiation extinction coefficient

The basic equation describing transmission of a beam of solar radiation through the plant canopy is similar to Bouguer's law (Campbell and Van Evert, 1994):

$$FI = 1 - \exp(-K_{PAR}\ LAI) \quad (12)$$

where K_{PAR} is the canopy extinction coefficient for PAR. Values of K_{PAR} have been calculated using field measurements of LAI and FI. Guidelines for determining K_{PAR} in the field are given by Jovanovic and Annandale (1998). Figure 4 represents FI of PAR measured with the ceptometer as a function of LAI for cabbage. The calculated value of K_{PAR} was 1.17, and the coefficient of determination of the exponential function (r^2) was 0.81.

K_{PAR} can be used to calculate photosynthesis as a function of intercepted PAR. The canopy extinction coefficient for solar radiation (K_s) is, however, required for predicting radiation-limited dry matter production (Monteith, 1977) and for partitioning ET into evaporation from the soil surface and crop transpiration (Ritchie, 1972). The procedure recommended by Campbell and Van Evert (1994) was used to convert K_{PAR} into K_s:

$$K_s = K_{bd} \sqrt{a_s} \quad (13)$$

$$K_{bd} = K_{PAR} / \sqrt{a_p} \quad (14)$$

$$a_s = \sqrt{a_p\, a_n} \quad (15)$$

where:

K_{bd} - Canopy radiation extinction coefficient for 'black' leaves with diffuse radiation
a_s - Leaf absorptance of solar radiation
a_p - Leaf absorptance of PAR
a_n - Leaf absorptance of near infrared radiation (NIR, 0.7-3 m)

The value of a_p was assumed to be 0.8, whilst a_n was assumed to be 0.2 (Goudriaan, 1977). a_s is the geometric mean of the absorptances in the PAR and NIR spectrums.

Calculated values of K_{PAR}, K_s and the coefficients of determination of the FI-LAI correlation for six vegetable species are shown in Table 2. High canopy extinction coefficients were calculated for carrots due to its particular canopy structure, which reaches full canopy cover at a low LAI. The canopy of carrots tends to have a horizontal shape, and absorbs a somewhat greater fraction of the incident radiation than other canopy structures at low LAI.

Rooting depth and thermal time requirements

Root depth was estimated from weekly measurements of soil-water extraction with the neutron meter. It was assumed to be equal to the depth at which 90% of soil-water depletion occurred during weekly periods. Maximum rooting depths for the six vegetables are shown in Table 2.

GDD (d·°C) was determined from daily average air temperature (T_{avg}), after Monteith (1977):

$$GDD = (T_{avg} - T_b)\, \Delta t \quad (16)$$

where T_b is the base temperature in °C and Δt is one day. Values of T_b recommended by Knott (1988) were used in this study (Table 2). Thermal time accumulation occurred every day of the season for all crops, as T_{avg} was never lower than the minimum temperature required for development (T_b). T_{avg} also never exceeded the optimum temperature for crop development (T_{opt}). T_{opt} values were recommended by Knott (1988) and are also shown in Table 2. GDD required for emergence was calculated for crops planted by seeding (carrots, beetroot and swisschard), whilst GDD until harvest was determined for all crops (Table 2). Day degrees required for flowering and maturity were not determined as all crops were harvested during the vegetative stage.

Conclusions

Soil-water measurements with a neutron probe indicated the seasonal crop water requirements farmers could expect from six irrigated vegetable species grown during the winter season at Roodeplaat (Gauteng). Seasonal crop water use varied between 281 mm for lettuce and 390 mm for carrots and swisschard.

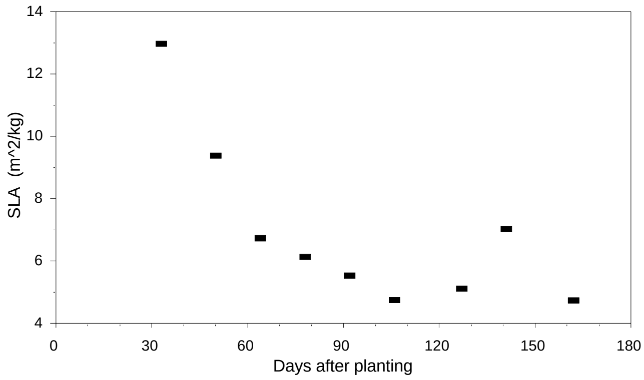

Figure 2
Measured values of specific leaf area (SLA) during the growing season of cabbage

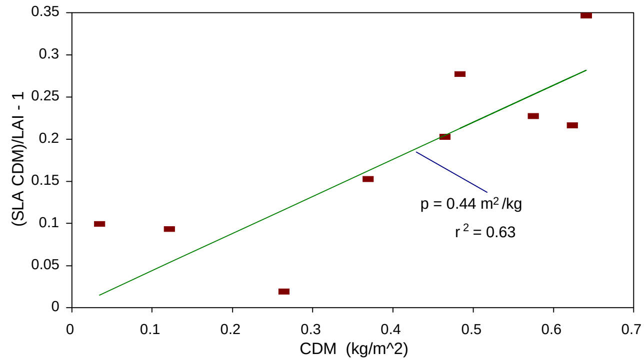

Figure 3
Determination of the stem-leaf dry matter partitioning parameter (p) as a function of canopy dry matter (CDM), specific leaf area (SLA) and leaf area index (LAI) for cabbage. The slope of the regression line (p) and the coefficient of determination (r^2) are shown.

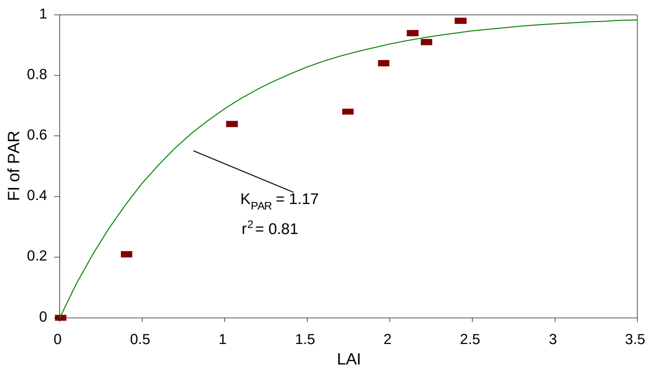

Figure 4
Correlation between leaf area index (LAI) and fractional interception (FI) of PAR measured with the ceptometer for cabbage. Canopy extinction coefficient (K_{PAR}) and the coefficient of determination of the exponential regression function (r^2) are shown.

Several of the parameters needed by crop modellers to simulate growth and water use of the vegetable crops have been calculated. A database of specific crop growth parameters required by the SWB model has been generated. Some modelling approaches, however, may require the calculation of other parameters and for this purpose the growth analysis, soil water and weather data are available from the authors.

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