Crop growth model parameters of 19 summer vegetable cultivars for use in mechanistic irrigation scheduling models

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Abstract

Mechanistic, generic crop, irrigation scheduling models require crop-specific growth parameters which are not readily available for many crops and conditions. The objective of this work was to determine growth parameters for 19 summer vegetable cultivars, and to calibrate the SWB (soil-water balance) model. These vegetable crops were grown in a field trial at Roodeplaat (Gauteng, South Africa) during the 1996/97 summer rainy season. Weather data were recorded with an automatic weather station, phenological stages monitored and growth analyses carried out weekly. Fractional interception of radiation was measured with a sunfleck ceptometer and soil water content was monitored 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 crop heights, as well as 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

The interest in computer models for agriculture is rapidly increasing, particularly since PCs have become accessible to crop producers. Computer models operated from offices could facilitate irrigation water management by making frequent field visits and measurements less essential. Several crop growth and water balance models have been developed with different levels of complexity depending on specific requirements (Whisler et al., 1986; Bennie et al., 1988; Singels and De Jager, 1991a, b and c; Smith, 1992; Annandale et al., 1996; Crosby, 1996). Walker et al. (1995) published a comprehensive review of wheat models, and Mottram and De Jager (1994) an overview of soil-water balance and reference evapotranspiration models. Advantages and disadvantages of several models were also described by Hanks and Ritchie (1991).

The soil -water balance (SWB) model was developed as a real-time, user-friendly, irrigation scheduling tool (Benadé et al., 1997). It is based on the improved generic crop version of NEWSWB (Campbell and Diaz, 1988). A cascading soil-water balance is used once canopy interception and surface runoff have been accounted for. Each soil layer is assumed to be filled to field capacity and then pass on a fraction of the remaining water to the layer below. Any water which passes beyond the bottom layer is assumed lost as deep percolation. Potential evapotranspiration (PET) is calculated as a function of daily average air temperature, vapour pressure deficit, radiation and wind speed, adopting the internationally standardised FAO (Food and Agriculture Organisation of the United Nations, Rome, Italy) Penman-Monteith methodology (Allen et al., 1998). The two components of PET (potential evaporation and potential transpiration) are estimated using canopy cover (Ritchie, 1972). Water loss by evaporation is assumed to occur only from the top soil layer, which thickness is an input. Actual evaporation proceeds at the potential rate until the water content in the top soil layer reaches the permanent wilting percentage. Thereafter, it is equal to the product of potential evaporation and the square of the remaining evaporable water down to the air-dry soil-water content (Campbell and Diaz, 1988). Similarly, actual transpiration is determined on a daily basis as either being limited by soil water supply or evaporative demand (Campbell and Norman, 1998). Total soil-water potential is used to determine the amount of water available for crop transpiration from each soil layer. The daily dry matter increment is taken as the minimum of the transpiration-limited (Tanner and Sinclair, 1983) and radiation-limited (Monteith, 1977) dry matter production, with water stress affecting the partitioning of assimilates to the different plant organs. A detailed description of SWB can be found in Annandale et al. (1999).

The mechanistic approach used in SWB to estimate crop water use has several advantages over the more empirical methods often used. Using thermal time to describe crop development removes the need to use different crop factors for different planting dates and regions. Splitting evaporation and transpiration solves the problem of taking irrigation frequency into account. Deficit irrigation strategies, where water use is supply-limited, can also be more accurately described. The SWB model gives a detailed description of the soil-plant-atmosphere continuum, making use of weather, soil and crop databases. The crop database includes several crop-specific growth parameters: vapour pressure deficit-corrected dry matter/water ratio, radiation conversion efficiency, specific leaf area, stem-leaf dry matter partitioning parameter, canopy extinction coefficient for solar radiation, maximum root depth, maximum crop height, cardinal temperatures and growing day degrees for the completion of phenological stages.

Since SWB is a generic crop growth model, parameters specific for each crop have to be experimentally determined. In previous work, a database of crop-specific growth parameters was generated for annual crops and pasture species (Barnard et al., 1998), as well as for winter vegetables (Jovanovic et al., 1999). Very little literature is available on growth parameters for summer vegetables. The objective of this study was to collect field data to generate crop-specific growth parameters, and calibrate the SWB model for 19 summer vegetable cultivars. This study is, therefore, complementary to the paper published by Jovanovic et al. (1999).

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TABLE 1
PLANTING DATES AND ROW SPACINGS FOR 19 SUMMER VEGETABLE CROPS (ROODEPLAAT, 1996/97)

Crop	Transplanting or seeding date (1996)	Spacing (m)
Bush beans (*Phaseolus limensis* cv. Bronco)	27 November	1.0
Bush beans (*Phaseolus limensis* cv. Provider)	12 November	1.0
Chilli pepper (*Capsicum annuum* cv. Super Cayenne)*	19 December	1 x 0.5
Eggplant (*Solanum melongena* cv. Black Beauty)*	19 December	1 x 0.5
Green pepper (*Capsicum annuum* cv. King Arthur)*	19 December	1 x 0.5
Marrow (*Cucurbita maxima* cv. Long White Bush)*	12 November	1 x 0.5
Marrow (*Cucurbita maxima* cv. President)*	12 November	1 x 0.5
Pumpkin (*Cucurbita pepo* cv. Minette)*	12 November	1 x 0.5
Pumpkin (*Cucurbita pepo* cv. Miniboer)*	12 November	1 x 0.5
Runner beans (*Phaseolus coccineus* cv. Lazy Housewife)	27 November	1.0
Squash (*Cucurbita moschata* cv. Table Queen)*	12 November	1 x 0.5
Squash (*Cucurbita moschata* cv. Waltham)*	12 November	1 x 0.5
Sweet-corn (*Zea mays Saccharata* cv. Cabaret)	11 December	1.0
Sweet-corn (*Zea mays Saccharata* cv. Dorado)	9 November	1.0
Sweet-corn (*Zea mays Saccharata* cv. Jubilee)	12 November	1.0
Sweet-corn (*Zea mays Saccharata* cv. Paradise)	12 December	1.0
Tomato processing (*Lycopersicon esculentum* cv. HTX14)*	29 November	1 x 0.5
Tomato processing (*Lycopersicon esculentum* cv. P747)*	29 November	1 x 0.5
Tomato table (*Lycopersicon esculentum* cv. Zeal)*	29 November	1 x 0.5

* Transplanted

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·a^{-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). The soil is a 1.2 m deep clay loam Red Valsrivier (Soil Classification Working Group, 1992), with a clay content of between 27% and 31% and a water-holding capacity of about 300 mm·m^{-1}.

During the 1996/97 summer season, 19 cultivars covering 9 crop species were grown on 4 m x 5 m plots, surrounded by irrigated vegetable fields. Crops, cultivars, planting dates and row spacings are summarised in Table 1. Agronomic practices commonly used in the area were followed. The field was ploughed (0.3 m) and a rotavator was used to prepare a 0.15 m deep seedbed. Vegetables planted by direct seeding in the field (beans and sweet-corn) were thinned a few weeks after planting. Irrigations close to field capacity were carried out weekly with an overhead sprinkler system. No water stress occurred during the growing season. At planting, crops received 34 kgN·ha^{-1}, 50 kgP·ha^{-1} and 66 kgK·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 kgN·ha^{-1} in the form of LAN (28). Before planting, all 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 insect control [[#]*Mention of products and 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*].

Field measurements

Soil-water deficit to field capacity was measured with a neutron water meter Model 503DR CPN Hydroprobe (Campbell Pacific Nuclear, California, USA)[#]. The instrument was calibrated for the soil. Weekly readings were taken in the middle of each plot, at one position between rows, and at five soil layers each 0.2 m thick down to 1.0 m. Rain gauges were installed in order to measure irrigation and rainfall.

Fractional interception (FI) of photosynthetically active radiation (PAR, 0.4 to 0.7 µm) 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. Readings were taken between 9:00 and 10:00. Growth analyses were carried out weekly, 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)[#]. Crop height was measured weekly. Root depth was estimated from soil water measurements with the neutron water meter. It was assumed to be equal to the depth at which 90% of soil-water depletion occurred after dry spells. Phenological development was also monitored for each crop.

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 data were stored with an MCS 120-02EX data logger.

Results and discussion

Crop-specific growth parameters

Weather, soil and crop data collected in the field trial were used to determine crop-specific growth parameters for 19 well-irrigated vegetable cultivars. These are summarised in Table 2. Complete weather and growth analysis data are shown in the appendix. The following parameters were determined according to the procedure described by Jovanovic et al. (1999):

- canopy extinction coefficient for solar radiation (K_s)
- vapour pressure deficit-corrected dry matter/water ratio (DWR)
- radiation conversion efficiency (E_c)
- growing day degrees (GDD) required for emergence, flowering and maturity
- maximum root depth (RD_{max})
- specific leaf area (SLA)
- leaf-stem dry matter partitioning parameter (p).

The canopy extinction coefficient for total solar radiation is a crop-specific parameter describing the canopy structure, and determining the partitioning of PET into soil evaporation and crop transpiration. The values of K_s presented in Table 2 can be easily converted into the extinction coefficient for photosynthetically active radiation using the procedure recommended by Campbell and Van Evert

TABLE 2
CROP-SPECIFIC GROWTH PARAMETERS FOR SUMMER VEGETABLE CROPS (ROODEPLAAT, 1996/97)

Crop	Bush bean (cv. Bronco)	Bush bean (cv. Provider)	Runner beans	Sweet-corn (cv. Cabaret)	Sweet-corn (cv. Dorado)	Sweet-corn (cv. Jubilee)	Sweet-corn (cv. Paradise)
Canopy extinction coefficient for total solar radiation K_s^*	0.79	0.79	0.33	0.50	0.40	0.36	0.30
Dry matter/transpiration ratio corrected for vapour pressure deficit DWR* (Pa)	6	2.5	6	9	8	9	9
Radiation conversion efficiency E_c^* ($kg \cdot MJ^{-1}$)	0.0012	0.0012	0.0009	0.0026	0.0027	0.0038	0.0022
Base temperature (°C)	10**	10**	10**	11***	11***	11***	11***
Optimum temperature (°C)	18.3**	18.3**	18.3**	20****	20****	20****	20****
Cut-off temperature (°C)	26.6**	26.6**	26.6**	30****	30****	30****	30****
Emergence day degrees* (d °C)	80	50	50	50	50	50	50
Day degrees at end of vegetative growth* (d °C)	300	400	600	500	700	800	800
Day degrees for maturity* (d °C)	700	800	950	800	1150	1400	1400
Transition period day degrees**** (d °C)	400	200	50	200	200	200	200
Day degrees for leaf senescence**** (d °C)	250	300	450	300	350	800	500
Maximum crop height H_{max}***** (m)	0.5	0.5	2.3	1.7	1.7	2.1	2.1
Maximum root depth RD_{max}^* (m)	0.6	0.4	0.6	1	0.8	0.6	0.6
Specific leaf area SLA* ($m^2 \cdot kg^{-1}$)	12.2	16.8	23.1	15.1	17.8	14.1	16.6
Leaf-stem partition parameter p* ($m^2 \cdot kg^{-1}$)	0.57	1.01	0.8	2	1.5	2	2
Root growth rate**** ($m^2 \cdot kg^{-0.5}$)	4	4	4	4	4	4	4

Crop	Marrow (cv. Long White Bush)	Marrow (cv. President)	Pumpkin (cv. Minette)	Pumpkin (cv. Miniboer)	Squash (cv. Table Queen)	Squash (cv. Waltham)
Canopy extinction coefficient for total solar radiation K_s^*	0.50	0.58	0.52	0.70	0.71	0.95
Dry matter/transpiration ratio corrected for vapour pressure deficit DWR* (Pa)	3	3	5.5	5.5	3.5	3.5
Radiation conversion efficiency E_c^* ($kg \cdot MJ^{-1}$)	0.0014	0.0014	0.0010	0.0005	0.0007	0.0004
Base temperature** (°C)	10	10	10	10	10	10
Optimum temperature** (°C)	21.1	21.1	21.1	21.1	21.1	21.1
Cut-off temperature** (°C)	32.2	32.2	32.2	32.2	32.2	32.2
Emergence day degrees* (d °C)	0	0	0	0	0	0
Day degrees at end of vegetative growth* (d °C)	250	400	400	200	400	400
Day degrees for maturity* (d °C)	1000	1000	1000	1000	1000	1100
Transition period day degrees**** (d °C)	750	600	600	800	600	700
Day degrees for leaf senescence**** (d °C)	300	400	300	400	400	500
Maximum crop height H_{max}***** (m)	0.65	0.6	0.7	0.6	0.4	0.3
Maximum root depth RD_{max}^* (m)	0.8	1	0.8	0.8	0.8	0.8
Specific leaf area SLA* ($m^2 \cdot kg^{-1}$)	16.6	11.6	16	17.5	9.7	9.9
Leaf-stem partition parameter p* ($m^2 \cdot kg^{-1}$)	1.3	1.18	1.1	1.1	1.2	1
Root growth rate**** ($m^2 \cdot kg^{-0.5}$)	4	4	5	5	4	5

Table 2 (Continued)						
Crop	**Chilli pepper**	**Green pepper**	**Eggplant**	**Tomato processing (cv. HTX14)**	**Tomato processing (cv. P747)**	**Tomato table (cv. Zeal)**
Canopy extinction coefficient for total solar radiation K_s*	0.42	0.35	0.74	0.32	0.32	0.26
Dry matter/transpiration ratio corrected for vapour pressure deficit DWR* (Pa)	4.5	4.5	2.4	7	7	7
Radiation conversion efficiency E_c* ($kg \cdot MJ^{-1}$)	0.0016	0.0015	0.0009	0.0022	0.0018	0.0016
Base temperature*** (°C)	11	11	11	11	11	11
Optimum temperature** (°C)	22.5	22.5	25.3	22.5	22.5	22.5
Cut-off temperature** (°C)	26.6	26.6	35	26.6	26.6	26.6
Emergence day degrees* (d °C)	0	0	0	0	0	0
Day degrees at end of vegetative growth* (d °C)	350	350	350	50	100	100
Day degrees for maturity* (d °C)	900	900	900	330	330	330
Transition period day degrees**** (d °C)	550	550	550	280	230	230
Day degrees for leaf senescence**** (d °C)	350	550	350	130	100	100
Maximum crop height H_{max}***** (m)	0.6	0.5	0.6	0.45	0.65	0.6
Maximum root depth RD_{max}* (m)	0.6	0.6	0.6	0.8	0.8	0.6
Specific leaf area SLA* ($m^2 \cdot kg^{-1}$)	11.2	12.2	15.4	14.3	12.1	15.5
Leaf-stem partition parameter p* ($m^2 \cdot kg^{-1}$)	1.04	1.07	0.98	2	2	2
Root growth rate**** ($m^2 \cdot kg^{0.5}$)	6	6	6	4	4	4

* Calculated according to Jovanovic et al. (1999)
** Knott (1988)
*** Campbell and Norman (1998)
**** Estimated by calibration against measurements of growth, phenology, yield and water use
***** Measured

(1994), and set out in Jovanovic and Annandale (1998). Only data until leaf senescence were considered in the calculation of K_s. High canopy extinction coefficients were calculated for horizontal leaf-canopies (bush beans, eggplant, pumpkin cv. Miniboer and squash) due to their particular canopy structure, which reaches full canopy cover at a low LAI.

The values of DWR and E_c shown in Table 2, were calculated from several observations during the growing season. Both represent lower limits as root dry matter was not accounted for in the calculation of transpiration-limited and radiation-limited dry matter production. Only dry matter accumulation data until flowering were considered in the estimation of DWR and E_c. This was done to avoid errors caused by plants losing leaves, and by multiple harvests for some crops. In addition, leaf senescence, which generally occurs after flowering, reduces the amount of absorbed energy and would cause an underestimation of E_c. Sweet-corn and tomato had substantially higher water-use efficiencies (DWR) compared to the other vegetables. The lowest E_c values were calculated for horizontal leaf-canopies (beans, eggplant, pumpkin and squash), which intercept high radiation levels on upper leaves, but have less total sunlit leaf area compared to inclined leaf-canopies, making the photosynthesis process less efficient.

Growing day degrees for emergence were assumed to be 0 for transplanted crops to facilitate comparison with those planted by seeding. Maximum root depth was estimated from measurements of soil water content with the neutron meter. Values of RD_{max} were generally in the range of those reported by Green (1985) and Smith (1992). SLA and p are parameters describing the morphology of a specific crop. The values of SLA presented in Table 2, are seasonal averages obtained before leaf senescence. Caution should be exercised in the adoption of constant values for SLA and p in crop growth modelling, as these parameters may vary considerably during the growing season.

Base temperature, temperature for optimal crop growth and cut-off temperature were taken from Knott (1988), and Campbell and Norman (1998). Optimum and cut-off temperatures for sweet-corn were estimated by calibration against measurements of air temperature and phenology. Growing day degrees for the transition period between vegetative and reproductive growth and for leaf senescence, as well as root growth rate were estimated by calibration against field measurements of crop growth, phenology and water use for all crops. Maximum crop height (H_{max}) was measured in the field.

Crop growth and the soil-water balance were simulated with SWB for each crop. An example of output is shown in Fig. 1 for sweet-corn (cv. Cabaret). Figure 1 presents measured and simulated root depth, leaf area index, above-ground dry matter and harvestable dry matter, soil-water deficit to field capacity, as well as fractional interception of solar radiation. Parameters of the statistical analysis of measured and simulated data are shown in the top right corner of the output graphs. These are number of observations (N), coefficient of determination (r^2), Willmott's (1982) index of agreement (D), root mean square error (RMSE) and mean absolute error (MAE). These statistical parameters were recommended by De Jager (1994) to assess a model's accuracy. The statistical analysis shown in the dry matter production graph is for measured and simulated total above-ground dry matter. No spatial variability analysis was performed as no replications were taken for growth analysis. The model predicted crop growth and the soil-water balance well for all crops. Simulations and statistical analyses for all crops can be found in Annandale et al. (1999).

Crop yield and soil-water balance

Table 3 presents harvestable dry matter (HDM) production, as well as fresh yield at the end of the season. Root dry matter was not measured. HDM and fresh yield are not available for those crops which were harvested several times during the growing season by

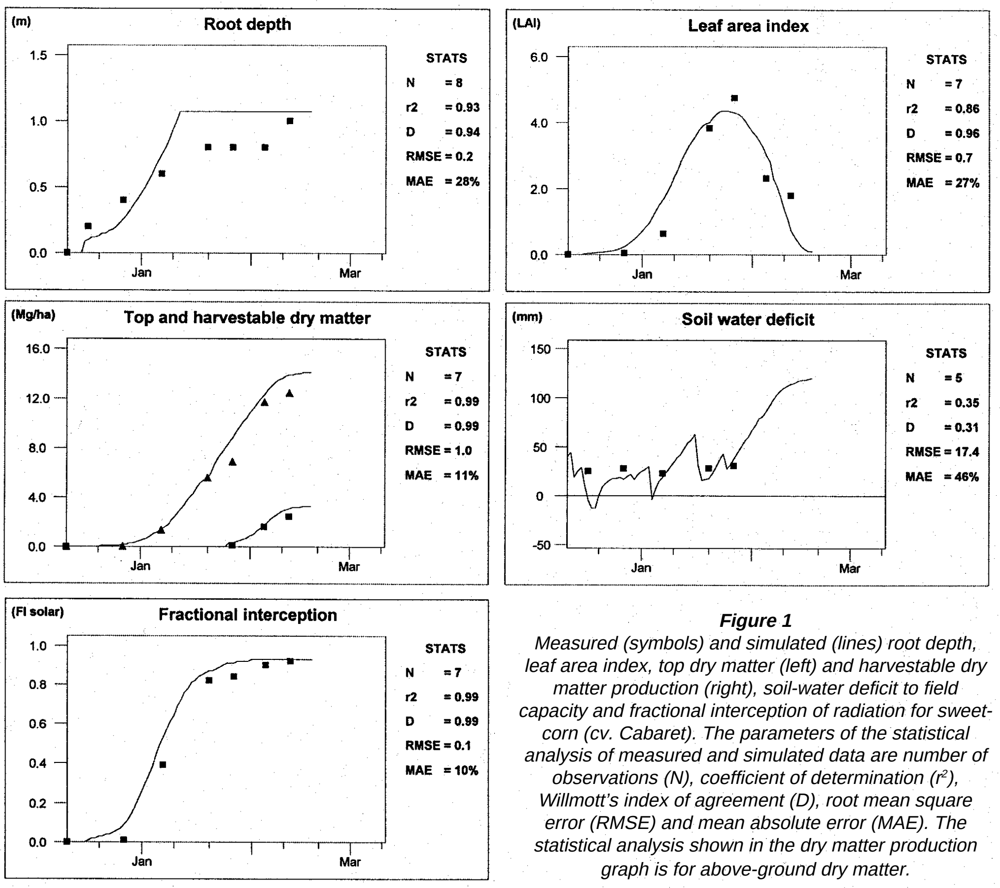

Figure 1
Measured (symbols) and simulated (lines) root depth, leaf area index, top dry matter (left) and harvestable dry matter production (right), soil-water deficit to field capacity and fractional interception of radiation for sweet-corn (cv. Cabaret). The parameters of the statistical analysis of 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). The statistical analysis shown in the dry matter production graph is for above-ground dry matter.

TABLE 3
YIELD AND SOIL-WATER BALANCE FOR 19 SUMMER VEGETABLE CROPS (ROODEPLAAT, 1996/97)

Crop	Measured harvestable dry matter HDM (kg·m^{-2})	Measured fresh yield (kg·m^{-2})	Simulated soil evaporation (mm)	Simulated transpiration (mm)	Simulated crop water use (mm)	Measured rainfall + irrigation (mm)	Simulated drainage (mm)
Bush beans (cv. Bronco)	0.17	1.11	157	137	294	369	100
Bush beans (cv. Provider)	0.21	1.37	129	152	281	419	106
Chilli pepper	-	-	149	54	203	208	39
Eggplant	-	-	148	87	235	208	41
Green pepper	-	-	153	43	196	208	48
Marrow (cv. Long White Bush)	-	-	183	175	358	443	96
Marrow (cv. President)	-	-	213	159	372	443	98
Pumpkin (cv. Minette)	-	-	166	202	368	443	104
Pumpkin (cv. Miniboer)	-	-	165	229	395	443	95
Runner beans	0.22	1.24	190	144	334	372	104
Squash (cv. Table Queen)	-	-	226	136	362	443	109
Squash (cv. Waltham)	-	-	235	148	383	443	109
Sweet-corn (cv. Cabaret)	0.24	1.19	130	179	309	332	86
Sweet-corn (cv. Dorado)	0.27	1.24	128	166	294	332	92
Sweet-corn (cv. Jubilee)	0.62	2.1	158	223	381	443	95
Sweet-corn (cv. Paradise)	0.55	2.07	187	168	355	443	121
Tomato processing (cv. HTX14)	-	-	207	112	319	390	113
Tomato processing (cv. P747)	-	-	213	70	283	390	133
Tomato table (cv. Zeal)	-	-	212	75	287	390	132

intruders. Seasonal soil evaporation, crop transpiration and drainage simulated with the SWB model, as well as measured irrigation and rainfall are also shown in Table 3. It was not possible to measure irrigation and rainfall separately. Runoff was assumed to be negligible as no high intensity rain occurred and the irrigation system application rate did not exceed the soil infiltration rate.

Localised irrigation (micro, drip) could reduce the soil evaporation component of the soil-water balance, and improve water-use efficiency.

Conclusions

Several of the parameters needed by crop modellers to simulate growth and water use of 19 summer vegetable cultivars have been determined. A database of crop-specific growth parameters required by the SWB model has also been generated. These growth parameters could also be used with other models, or the data presented in this study could be used to calculate other parameters.

The SWB model was successfully calibrated for 19 summer vegetable cultivars grown at Roodeplaat, and used to estimate seasonal crop water requirements. Seasonal crop water use of summer vegetables was estimated to vary from just under 200 mm for green pepper to around 400 mm for pumpkin (cv. Miniboer). Water use was estimated to be ≈200 mm for both peppers, and between 350 mm and 400 mm for cucurbits. Water use of beans, sweet-corn and tomato varied depending on the cultivar. Due to the mechanistic, dynamic approach followed, accurate estimates of irrigation requirements are expected for these crops under a wide range of soil and climatic conditions. This needs, however, to be tested experimentally.

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Appendix

TABLE A1
DAILY RAINFALL AND IRRIGATION (R + I), MAXIMUM (TMAX) AND MINIMUM TEMPERATURE (TMIN), SOLAR RADIATION (RS), WIND SPEED (U), AND AVERAGE DRY (Td) AND WET BULB TEMPERATURE (TW) DURING THE 1996/97 SEASON AT ROODEPLAAT

Date	R + I (mm)	Tmax (°C)	Tmin (°C)	Rs ($MJ\cdot m^{-2}$)	U ($m\cdot s^{-1}$)	Td (°C)	Tw (°C)	Date	R + I (mm)	Tmax (°C)	Tmin (°C)	Rs ($MJ\cdot m^{-2}$)	U ($m\cdot s^{-1}$)	Td (°C)	Tw (°C)
09/11	0	31.5	13.0	29.5	1.6	22.1	17.0	06/01	0	28.8	16.2	22.1	1.8	22.4	18.5
10/11	0	33.4	14.4	29.1	2.9	23.0	18.4	07/01	0	26.1	19.4	16.0	1.0	22.4	18.7
11/11	0	35.4	15.9	29.9	2.2	22.3	17.8	08/01	0	28.9	18.3	20.8	1.4	21.8	19.3
12/11	0	33.5	17.1	29.1	2.0	23.9	18.6	09/01	0.2	32.6	15.7	26.3	1.4	24.0	20.4
13/11	0	33.2	15.9	30.3	2.1	22.5	18.3	10/01	0	28.6	17.1	24.7	1.4	22.5	20.2
14/11	0	28.8	16.1	29.1	3.5	17.9	16.2	11/01	0	31.9	17.4	30.1	2.4	21.3	19.2
15/11	0	27.1	16.7	24.0	3.5	17.8	15.5	12/01	3.8	28.7	16.0	29.9	1.4	19.1	18.1
16/11	0	28.4	17.6	17.3	2.8	17.5	16.4	13/01	0	29.2	16.8	28.7	1.7	18.7	16.8
17/11	0	30.2	13.4	27.4	1.7	18.9	16.5	14/01	0	30.2	15.7	29.4	1.1	21.6	18.3
18/11	0	31.0	15.2	25.9	2.4	18.9	15.2	15/01	3.2	29.1	16.4	24.0	1.4	21.4	16.9
19/11	55.8	28.3	18.1	20.6	2.6	17.5	15.0	16/01	0	31.3	17.8	26.7	1.2	23.2	19.3
20/11	0	30.8	16.8	25.7	3.4	19.5	16.0	17/01	38.4	29.6	17.3	21.5	1.1	23.8	20.7
21/11	0	29.5	18.7	14.8	3.6	20.0	16.1	18/01	19.8	27.1	17.0	18.3	1.5	22.4	20.0
22/11	2.8	22.6	14.9	14.1	1.6	15.6	10.1	19/01	3.8	22.9	17.0	10.9	2.6	20.6	17.6
23/11	0.2	23.0	13.7	14.4	1.7	19.0	13.4	20/01	0	20.3	16.0	6.3	1.1	22.1	18.7
24/11	1.2	19.9	16.1	6.8	2.5	18.3	15.7	21/01	0	27.2	15.9	21.6	0.9	23.2	20.0
25/11	0.6	22.8	14.4	15.7	2.0	18.3	16.0	22/01	0	29.4	14.4	31.3	1.4	24.6	20.3
26/11	0.6	28.1	13.4	26.6	2.0	19.7	16.0	23/01	0	31.2	16.3	28.9	1.6	23.0	19.9
27/11	9.4	26.5	14.0	22.9	1.8	18.2	15.9	24/01	0	30.5	19.9	24.5	1.5	23.1	20.0
28/11	0.6	25.9	12.0	22.1	2.8	14.4	15.8	25/01	20.6	28.4	18.3	18.1	1.3	23.8	19.7
29/11	4.6	28.5	13.4	23.3	2.3	18.3	13.8	26/01	0	26.0	17.6	15.0	1.2	23.1	19.5
30/11	0	25.1	4.5	32.5	1.9	21.1	16.3	27/01	0	30.2	15.8	26.8	1.1	23.0	19.1
01/12	0	28.0	7.3	32.4	1.6	21.9	18.0	28/01	0	30.6	16.7	26.1	2.0	22.9	19.8
02/12	0	25.0	13.2	18.5	2.7	22.2	18.6	29/01	0.2	29.1	20.0	24.2	2.0	23.8	19.2
03/12	6.3	26.1	12.3	22.9	1.9	24.1	18.8	30/01	0	28.9	17.5	19.4	1.6	22.1	18.1
04/12	2.8	30.9	12.7	26.3	2.6	22.1	18.4	31/01	0	27.7	18.6	17.1	1.4	23.1	19.0
05/12	0	21.4	15.7	9.4	2.1	20.0	18.1	01/02	0	31.8	16.6	30.3	1.7	23.5	19.1
06/12	18.4	16.0	13.7	4.5	2.5	14.8	14.7	02/02	0	29.8	17.0	19.8	1.6	23.9	18.1
07/12	0.2	24.8	14.4	22.9	1.7	20.7	17.9	03/02	0	31.6	14.9	28.7	1.9	23.7	19.5
08/12	3.6	28.5	14.6	23.0	1.4	19.2	17.6	04/02	2.8	28.9	18.6	16.0	1.3	24.7	20.3
09/12	4	29.8	16.2	26.2	1.7	19.8	17.3	05/02	0	29.5	18.1	22.2	1.1	23.4	18.7
10/12	0	32.2	15.6	27.8	1.6	19.7	17.0	06/02	0	31.2	15.2	28.3	1.3	23.7	18.7
11/12	0	31.2	16.8	30.1	1.4	19.3	16.8	07/02	0	32.8	13.6	27.5	1.9	23.8	19.1
12/12	0	29.9	14.2	31.8	1.7	19.3	17.1	08/02	0	32.9	17.3	28.9	2.1	23.8	20.0
13/12	31	26.5	12.7	24.8	1.4	-	-	09/02	0	33.4	13.1	31.4	2.4	22.4	18.8
14/12	0	28.6	14.7	24.2	1.4	22.3	18.8	10/02	0	32.1	15.5	29.0	2.5	21.8	18.5
15/12	2.2	28.5	14.7	23.6	1.6	-	-	11/02	0	31.1	18.3	22.9	1.5	22.0	18.6
16/12	24	25.2	15.4	20.3	-	-	-	12/02	0	33.0	15.7	27.5	1.7	22.2	19.8
17/12	26	27.1	13.5	26.3	1.6	-	-	13/02	0	33.0	14.6	26.1	2.6	22.2	19.8
18/12	58.4	29.1	14.3	31.8	2.3	23.1	18.7	14/02	0	32.6	14.8	24.0	2.0	-	-
19/12	17.9	27.5	14.8	9.7	1.7	21.7	18.7	15/02	0.2	32.4	17.0	26.3	1.3	22.9	19.8
20/12	0	23.9	14.8	13.1	2.5	19.1	16.4	16/02	0	28.6	18.3	21.3	1.3	21.0	17.9
21/12	0	28.5	16.1	20.1	1.4	18.6	16.2	17/02	0	28.3	17.4	25.1	1.3	21.6	18.1
22/12	0	20.4	15.9	8.7	1.3	21.1	17.8	18/02	0.2	30.1	14.9	24.2	1.3	22.8	19.1
23/12	1.7	28.9	15.7	12.5	2.8	22.3	18.1	19/02	7.6	30.1	16.7	17.4	1.6	23.4	19.0
24/12	0	22.6	14.8	12.6	1.2	20.5	18.2	20/02	15	28.7	18.0	22.0	1.2	24.7	19.2
25/12	6.4	30.6	15.6	31.0	0.8	20.9	18.5	21/02	0	27.8	17.5	21.2	1.5	24.2	19.2
26/12	5.2	28.6	16.4	25.6	1.5	24.0	19.5	22/02	1.4	28.4	17.4	18.6	1.1	24.4	19.6
27/12	6.4	25.0	12.6	19.4	1.5	24.5	19.8	23/02	0	28.5	16.5	20.5	2.2	24.5	19.4
28/12	0	25.8	14.9	20.6	1.4	22.8	18.8	24/02	0	31.6	14.0	25.4	2.4	22.5	18.0
29/12	0	28.6	14.9	31.0	1.8	22.5	18.4	25/02	3.6	32.5	16.0	22.3	2.2	21.2	17.9
30/12	12.6	29.6	16.6	29.4	3.0	22.9	18.5	26/02	0	31.3	16.3	24.9	1.1	20.9	17.6
31/12	0	26.9	15.9	17.8	2.5	21.9	18.7	27/02	0	32.4	17.0	22.6	2.3	22.6	19.8
01/01	0	29.8	16.2	24.1	2.6	-	-	28/02	0	32.6	15.7	27.4	2.5	20.1	17.4
02/01	0	32.2	16.7	31.7	1.2	23.6	19.1	01/03	0	33.7	16.1	24.6	1.3	19.7	17.7
03/01	0	30.8	17.5	29.1	2.1	24.9	18.7	02/03	4.8	34.5	17.2	27.3	1.1	21.2	18.5
04/01	47.2	31.1	15.7	32.0	1.8	23.5	19.2	03/03	3.2	32.7	14.3	27.1	1.8	22.7	19.0
05/01	0	29.6	15.2	27.0	1.9	21.3	18.4	04/03	0	28.1	16.4	21.7	1.8	23.9	19.3

TABLE A2

FRACTIONAL INTERCEPTION OF PHOTOSYNTHETICALLY ACTIVE RADIATION (FI), LEAF AREA INDEX OF GREEN (LAI) AND SENESCED LEAVES (LAIs), LEAF DRY MATTER OF GREEN (LDM) AND YELLOW LEAVES (LDMs), FRESH YIELD (Y), HARVESTABLE DRY MATTER (HDM) AND STEM DRY MATTER (SDM) DURING THE 1996/97 SEASON AT ROODEPLAAT

Crop	Date	FI	LAI	LAIs	LDM ($Mg \cdot ha^{-1}$)	LDMs ($Mg \cdot ha^{-1}$)	Y ($Mg \cdot ha^{-1}$)	HDM ($Mg \cdot ha^{-1}$)	SDM ($Mg \cdot ha^{-1}$)
Bush beans (cv. Bronco)	17/12/1996	0.3	0.17	0	0.12	0	0	0	0.04
	27/12/1996	0.79	0.46	0.02	0.28	0.02	0	0	0.19
	01/01/1997	0.74	1.24	0.04	1.91	0.06	3.71	0.82	0.93
	20/01/1997	0.66	1.79	0.02	1.91	0.05	5.63	1.37	0.67
	27/01/1997	0.65	1.83	0.29	1.25	0.48	11.1	1.73	1.27
Bush beans (cv. Provider)	17/12/1996	0.44	0.68	0.02	0.44	0.03	0.18	0.02	0.27
	27/12/1996	0.91	1.07	0.02	0.66	0.01	1.55	0.37	0.78
	07/01/1997	0.7	1.48	0.02	0.67	0.03	8.73	1.17	0.70
	20/01/1997	0.53	1.09	0.05	0.79	0.09	13.66	2.1	0.83
Chilli pepper	27/12/1996	0.02	-	-	-	-	-	-	-
	07/01/1997	0.04	0.02	0	0.04	0	-	-	0.02
	20/01/1997	0.14	0.06	0	0.14	0	-	-	0.05
	27/01/1997	0.1	0.34	0	0.2	0	-	-	0.13
	05/02/1997	0.4	0.66	0	0.34	0	-	-	0.41
	12/02/1997	0.33	0.52	0	0.41	0	-	-	0.51
	20/02/1997	0.25	-	0	-	0	-	-	-
	04/03/1997	0.25	0.52	0	0.6	0	-	-	0.67
Eggplant	27/12/1996	0.02	-	-	-	-	-	-	-
	07/01/1997	0.1	0.14	0	0.05	0	-	-	0.02
	20/01/1997	0.2	0.09	0	0.12	0	-	-	0.05
	27/01/1997	0.33	0.44	0.02	0.27	0.03	-	-	0.16
	05/02/1997	0.46	0.46	0.01	0.27	0.02	-	-	0.28
	12/02/1997	0.5	0.45	0.02	0.42	0.03	-	-	0.41
	20/02/1997	0.46	0.63	0.02	0.48	0.03	-	-	0.49
	04/03/1997	0.45	0.45	0.02	0.38	0.03	-	-	0.53
Green pepper	27/12/1996	0	-	-	-	-	-	-	-
	07/01/1997	0	0.02	0	0.03	0	-	-	0.02
	20/01/1997	0.1	0.09	0	0.11	0	-	-	0.09
	27/01/1997	0.1	0.4	0	0.19	0	-	-	0.12
	05/02/1997	0.21	0.42	0	0.34	0	-	-	0.27
	12/02/1997	0.29	0.51	0	0.35	0	-	-	0.32
	20/02/1997	0.37	0.41	0	0.31	0	-	-	0.36
	04/03/1997	0.35	0.33	0.01	0.34	0	-	-	0.6
Marrow (cv. Long White Bush)	27/12/1996	0.36	0.94	0.01	0.71	0	-	-	0.32
	07/01/1997	0.85	2.28	0.04	0.71	0.27	-	-	0.55
	20/01/1997	0.73	0.74	0.24	0.65	0.59	-	-	1.03
	27/01/1997	0.74	1.05	0.77	0.8	0.98	-	-	1.47
	05/02/1997	0.64	0.64	0.51	0.49	1.08	-	-	1.01
Marrow (cv. President)	17/12/1997	0.23	0.24	0.01	0.22	0.02	-	-	0.11
	27/12/1996	0.49	0.8	0.02	0.66	0.05	-	-	0.33
	07/01/1997	0.63	1.8	0.24	1.33	0.44	-	-	1.01
	20/01/1997	0.56	1.51	0.34	1.48	0.92	-	-	1.42
	27/01/1997	0.7	0.53	0.62	0.49	1.22	-	-	1.37
	05/02/1997	0.23	0.72	0.35	0.61	0.84	-	-	0.82

Table A2 (Continued)									
Crop	Date	FI	LAI	LAIs	LDM (Mg·ha^{-1})	LDMs (Mg·ha^{-1})	Y (Mg·ha^{-1})	HDM (Mg·ha^{-1})	SDM (Mg·ha^{-1})
Pumpkin (cv. Minette)	27/12/1996	0.6	0.6	0.03	0.35	0.06	-	-	0.16
	07/01/1997	0.85	2.33	0.15	1.53	0.33	-	-	1.12
	20/01/1997	0.84	2.79	0.36	1.74	0.44	-	-	1.8
	27/01/1997	0.62	1.31	0.26	1.04	0.72	-	-	1.83
	05/02/1997	0.44	0.48	0.26	0.26	0.35	-	-	0.5
Pumpkin (cv. Miniboer)	27/12/1996	0.47	0.74	0.02	0.58	0.04	-	-	0.19
	07/01/1997	0.94	2.52	0.2	0.77	0.38	-	-	0.71
	20/01/1997	0.73	0.67	0.15	0.5	0.41	-	-	0.64
	27/01/1997	0.74	0.77	0.77	0.58	0.99	-	-	1.12
	05/02/1997	0.91	0.77	0.39	0.5	0.42	-	-	0.64
Runner beans	17/12/1996	0.35	0.33	0	0.2	0	0	0	0.08
	27/12/1996	0.69	0.83	0.05	0.38	0.01	0	0	0.27
	07/01/1997	0.82	2	0.07	1.32	0.11	0	0	0.75
	20/01/1997	0.8	4.91	0.14	1.9	0.11	0.68	0.08	1.37
	27/01/1997	0.92	5	0.08	1.89	0.14	7.45	0.98	1.85
	05/02/1997	0.9	3.52	0.22	1.22	0.2	9.82	2.01	1.95
	12/02/1997	0.62	1.18	0.13	0.45	0.14	12.39	2.2	1.09
Squash (cv. Table Queen)	27/12/1996	0.39	0.12	0	0.09	0	-	-	0.04
	07/01/1997	0.49	0.44	0.01	0.28	0.01	-	-	0.15
	20/01/1997	0.5	0.26	0	0.86	0.05	-	-	0.74
	27/01/1997	0.51	0.56	0.41	0.8	0.8	-	-	1.18
	05/02/1997	0.52	1.06	0.17	0.22	0.3	-	-	0.54
Squash (cv. Waltham)	27/12/1996	0.3	0.09	0	0.07	0	-	-	0.03
	07/01/1997	0.72	1.12	0.04	0.37	0.24	-	-	0.24
	20/01/1997	0.3	0.53	0.02	0.64	0.05	-	-	0.51
	27/01/1997	0.67	0.61	0.12	0.68	0.22	-	-	0.59
	05/02/1997	0.72	0.8	0.08	0.72	0.19	-	-	0.78
	12/02/1997	0.5	0.38	0.02	0.49	0.11	-	-	0.78
Sweet-corn (cv. Cabaret)	27/12/1996	0.01	0.05	0	0.02	0	0	0	0.01
	07/01/1997	0.39	0.64	0	0.47	0.01	0	0	0.88
	20/01/1997	0.82	3.83	0.01	1.8	0.06	0	0	3.72
	27/01/1997	0.84	4.74	0.07	2.57	0.06	0.89	0.1	4.24
	05/02/1997	0.9	2.32	0.14	3.21	0.22	10.02	1.61	6.89
	12/02/1997	0.92	1.79	0.34	2.11	0.49	11.93	2.44	7.9
Sweet-corn (cv. Dorado)	27/12/1996	0.11	0.22	0	0.07	0	0	0	0.03
	07/01/1997	0.45	1.4	0.06	0.94	0	0	0	0.97
	20/01/1997	0.63	5.44	0	2.4	0	0	0	2.93
	27/01/1997	0.7	4.71	0.33	2.22	0.05	4.55	0.88	3.27
	05/02/1997	0.69	1.61	0.16	2.57	0.28	11	1.69	3.77
	12/02/1997	0.54	1.42	0.51	1.53	0.86	12.44	2.7	3.5
Sweet-corn (cv. Jubilee)	17/12/1996	0.35	1.33	0	0.9	0	0	0	1.19
	27/12/1996	0.58	1.11	0.03	0.82	0	0	0	0.57
	07/01/1997	0.87	3.54	0.09	2.52	0.07	5.22	4.59	3.13
	20/01/1997	0.89	-	0	-	0	14.76	-	3.88
	27/01/1997	0.86	5.01	0.05	3.08	0.07	-	-	4.76
	05/02/1997	0.78	1.57	0.76	2.24	1.34	20.96	6.2	5.81

TABLE A2 (CONTINUED)									
Crop	**Date**	**FI**	**LAI**	**LAIs**	**LDM ($Mg \cdot ha^{-1}$)**	**LDMs ($Mg \cdot ha^{-1}$)**	**Y ($Mg \cdot ha^{-1}$)**	**HDM ($Mg \cdot ha^{-1}$)**	**SDM ($Mg \cdot ha^{-1}$)**
Sweet-corn (cv. Paradise)	17/12/1996	0.12	0.64	0	0.3	0	0	0	0.25
	27/12/1996	0.49	1.54	0.01	0.96	0.01	0	0	0.58
	07/01/1997	0.83	2.29	0.03	1.45	0	0	1.97	2.89
	20/01/1997	0.85	2.39	0	1.51	0	10.68	-	3.48
	27/01/1997	0.75	3.69	0.17	1.87	0.13	20.03	4.73	2.29
	05/02/1997	0.56	1.44	0.14	1.67	0.29	20.74	5.45	4
Tomato (cv. HTX14)	27/12/1996	0.04	0.16	0	0.17	0	-	-	0.18
	07/01/1997	0.19	0.4	0	0.75	0	-	-	0.4
	20/01/1997	0.48	1.95	0.04	2.12	0.12	-	-	1.19
	27/01/1997	0.72	2.5	0.28	1.73	0.57	-	-	1.44
	05/02/1997	0.7	1.45	0.23	1.38	0.48	-	-	1.37
	12/02/1997	0.57	0.81	0.24	0.88	0.73	-	-	2.07
	20/02/1997	0.43	0.44	0.12	0.69	0.31	-	-	1.46
Tomato (cv. P747)	27/12/1996	0.04	0.22	0	0.2	0	-	-	0.17
	07/01/1997	0.39	0.3	0	0.66	0	-	-	0.76
	20/01/1997	0.53	1.63	0.13	1.16	0.25	-	-	1.35
	27/01/1997	0.56	3.06	0.23	1.46	0.42	-	-	1.58
	05/02/1997	0.83	0.63	0.39	0.43	0.7	-	-	1.39
	12/02/1997	0.63	0.69	0.29	0.74	0.77	-	-	1.55
	20/02/1997	0.81	0.34	0.32	0.35	0.76	-	-	1.68
Tomato (cv. Zeal)	27/12/1996	0.07	0.24	0	0.23	0	-	-	0.25
	07/01/1997	0.19	0.8	0	0.6	0	-	-	0.95
	20/01/1997	0.36	1.35	0.1	0.85	0	-	-	1.56
	27/01/1997	0.53	3.06	0.11	0.75	0.26	-	-	1.12
	05/02/1997	0.57	0.27	0.16	0.24	0.39	-	-	1.02
	12/02/1997	0.49	0.25	0.2	0.32	0.63	-	-	1.58
	20/02/1997	0.41	0.14	0.1	0.16	0.28	-	-	0.87