GROWTH ANALYSES AND SOIL WATER BALANCE OF SELECTED VEGETABLE CROPS

by

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Submitted in partial fulfilment of the requirements for the degree
Magister Institutionis Agrariae : Horticultural Science
in the Faculty of Natural and Agricultural Sciences
University of Pretoria
PRETORIA

JUNE 2000

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ACKNOWLEDGEMENTS

I am greatly indebted to my supervisors, Dr. N. Z. Jovanovic, Prof. J. G. Annandale and Prof. D. I. Ferreira for their guidance and support, Mr W. van Wyk (Department of Agriculture) who made available his field trial at Roodeplaat, and was responsible for crop management, to the Water Research Commission for funding the project, and to all who have contributed in many ways to this work and to the compilation of this manuscript. My appreciation also goes to Dr. J. M. Steyn of the Agricultural Research Council – Vegetable and Ornamental Crop Institute, Roodeplaat, for providing the weather data.

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DEGREE	:	**M.Inst.Agrar. (Horticultural Science)**

ABSTRACT

Two trials were set up at Roodeplaat (Gauteng Province, South Africa) on a clay loam soil, during the 1996 and 1996/97 growing seasons. The 1996 dry winter trial involved six winter vegetable species (*Allium cepa, Brassica oleracea, Beta vulgaris, Daucus carota, Beta vulgaris spp. cicia,* and *Lactuca sativa*), whilst the 1996/97 summer trial involved 19 cultivars covering 9 crop species (*Lycopersicon esculentum, Zea mays saccharata, Cucurbita pepo, Cucurbita maxima, Cucurbita moschata, Phaseolus vulgaris, Phaseolus multiflorus, Solanum melongena,* and *Capsicum annuum*). The objective was to determine crop water requirements and create a database of specific crop growth coefficients to be included in the Soil Water Balance (SWB) generic crop, irrigation scheduling model. The crops were irrigated with overhead sprinklers and irrigations were scheduled with a neutron probe. Soil water depletion was measured weekly with a neutron water meter, whilst growth analyses were carried out fortnightly. Fractional interception of photosynthetically active radiation was measured weekly with a sunfleck ceptometer. Weather data were recorded with an automatic weather station located close to the experimental site. Seasonal crop water requirements of these vegetables grown in Gauteng were successfully estimated. Crop water use of winter vegetables varied from around 280 mm for lettuce to 390 mm for carrots and swisschard. Seasonal crop water use of summer vegetables was estimated to be around 200 mm for both peppers, and between 350 and 400 mm for cucurbits. The following crop specific coefficients were determined: dry matter-transpiration ratio corrected for vapour pressure deficit, radiation

conversion efficiency, specific leaf area, and dry matter partitioning parameters. Simulated values obtained with the SWB model were compared to measured data. The model provided good predictions of crop water use and harvestable dry matter under well-watered conditions. The application of the SWB model for irrigation scheduling of vegetables is recommended.

CHAPTER 1

INTRODUCTION

Irrigation is essential for food production to overcome deficiencies in rainfall and to stabilise agricultural production especially in arid and semi-arid areas. The increasing scarcity of water and growing competition for water of good quality calls for effective and sustainable management of water for agriculture in seeking to satisfy future demand for food. Low efficiency of water use in agriculture, with poor management and inadequate designs are the main causes of high water losses resulting in low yields, reduced irrigated areas and environmental problems (Smith, 1995). A co-ordinated approach is required to improve water use efficiency; at the water source, at the conveyance system and at farm and field level. Irrigation scheduling is the technique to timely and accurately apply water to the crop and is the key to conserving water, and improving irrigation performance and sustainability of irrigated agriculture.

Research has made considerable advances over the last decades and a large number of techniques and methodologies have been made available for direct use in irrigation scheduling (Smith, 1995). This concerns in particular:

- Crop water requirement methodologies, such as introduced by FAO (Food and Agriculture Organization of the United Nations, Rome, Italy), make it possible to routinely estimate actual evapotranspiration from climatic data, using a crop coefficient combined with the reference evapotanspiration, ET_o.
- The soil water balance and related concepts and measurement techniques are essential for the application of irrigation scheduling.
- Water stress indicators which help to identify and quantify plant water stress. They include canopy temperature, the leaf elongation rate, the leaf water potential, the variations in stem diameter or the sap flow fluxes.
- Water yield functions which reproduce the effects of limited water availability on crop yields, including the variable sensitivity to water stress at different crop growth stages.
- Simulation models with different degrees of sophistication, which can reproduce the complexity of processes and may include decision support tools. They help in the real-time planning and management of both farm and system levels and are useful for irrigation scheduling.

In this study, a mechanistic modelling approach was followed because the empirical methods (reference evaporation and empirical crop coefficient) of scheduling irrigations have several inaccuracies (Annandale, Campbell, Olivier & Jovanovic, 2000). In particular, the Soil Water Balance (SWB) irrigation scheduling model was chosen because it describes the mechanisms of plant growth and water use and is suitable for any environmental conditions (Annandale, Benade, Jovanovic, Steyn & Du Sautoy, 1999). The mechanistic approach used in SWB to estimate crop water use has several advantages over the more empirical methods often used, for example, using thermal time to describe crop development removes the need to use different crop coefficients for different planting dates and regions. It splits evaporation and transpiration so that the problem of taking irrigation frequency into account is solved (Jovanovic & Annandale, 2000).

The SWB model gives a detailed description of the soil-plant-atmosphere continuum, making use of weather, soil and crop databases. It is a generic model and parameters specific for each crop have to be experimentally determined. The crop database includes several crop-specific growth parameters: dry matter-transpiration ratio corrected for vapour pressure deficit, radiation conversion efficiency, specific leaf area, stem-leaf dry matter partitioning parameter, canopy extinction coefficient for solar radiation, maximum rooting depth, maximum crop height, cardinal temperatures and growing day degrees for the completion of crop phenological stages (Annandale *et al.* 1999).

There is limited data on crop specific parameters of vegetables and two field trials were, therefore, set up at Roodeplaat (Gauteng Province, South Africa) during 1996 and 1996/97 cropping seasons. The objectives of the study were as follows:

1) To determine seasonal water requirements because little is known about crop water use of vegetables in Gauteng.
2) To determine the rooting depth of the different vegetable species because rooting depth is an important factor in crop-water relations, and
3) To determine specific crop growth parameters from weather and growth analysis data, and include them in the crop parameter database of the SWB model. The model will then be used as a tool to improve efficiency of irrigation.

CHAPTER 2

LITERATURE REVIEW

2.1 THE FIELD WATER BALANCE

Hillel (1990) reported that any attempt to control the supply of water to crops must be based on a thorough understanding of the variable state of water in the soil and of its cyclic movement into, within, and out of the root zone. The cycle of water in the field consists of sequential or concurrent dynamic processes, beginning with the entry of water into the soil (infiltration), continuing with its redistribution and downward drainage within the soil, and culminating with its uptake by plants and its return to the atmosphere in the twin processes of transpiration and evaporation.

The rate of infiltration can be governed by the rate at which water is applied to the surface, as long as the application rate does not exceed the maximum rate at which the soil can absorb water through its surface. That limiting rate, called the soil's infiltrability, is highest for initially dry sandy soils and lowest for wet clayey soils, especially if the soil surface has been compacted by traffic or by the beating action of raindrops. An important design criterion for a sprinkle or drip irrigation system is to deliver water only at the rate that the soil surface can absorb, since an excessive rate of application can induce ponding, restriction of aeration, runoff, erosion, and inter-row weed infestation (Hillel, 1990).

The water that has entered the soil during infiltration does not remain immobile after the infiltration event has ended. Because of gravity and tension gradients in the soil, this water generally continues to move downward, albeit at a diminishing rate, in a process called redistribution. In the course of this process, the relatively dry deeper zone of the soil profile absorbs the water draining from the infiltration-wetted upper part. Within a few days, however, the rate of flow can become so low as to be considered negligible. At this time, the remaining water content in the initially wetted zone is termed '*field capacity*' and is often taken to represent the upper limit of the soil's capacity to store water. The redistribution process depends on the antecedent (pre-infiltration) soil water content, the amount of water infiltrated, and primarily, the composition and structure of the soil profile. Field capacity tends to be higher in clayey than in sandy soils. Moreover, it is generally greater in layered than in uniform soil profiles of similar texture, as layering inhibits the internal drainage of water (Hillel, 1990).

The pattern and rate of evaporation from bare soil surfaces depend on the external climate as well as on the internal movement of soil water and heat. Soon after an infiltration event, while the soil surface is still wet, it is primarily the climate that dictates the rate of evaporation. As the surface zone desiccates (generally within a few days after the onset of evaporation), the evaporation rate necessarily diminishes to become very slow. Soils that crack as they desiccate may, however, continue to lose water at an appreciable rate for many days. Soils with a high water table can sustain a high evaporation rate still longer. Such soils generally become saline as the evaporating groundwater deposits its salts at the soil surface (Hillel, 1980).

Transpiration from plant canopies, rather than direct evaporation of soil water, becomes predominant when a crop shades the greater part of the surface. In an arid environment, situations may develop in which the plants cannot draw water fast enough to satisfy the climatically imposed demand. Under such conditions, plants experience stress and must limit transpiration if they are to avoid dehydration. They can do this, to a limited degree and for a limited time, by closing their stomates (Kramer, 1983). The inevitable price of this limitation is a reduction of growth, as the same stomatal openings, which transpire water, also serve for the uptake of CO_2 needed in photosynthesis. While the relative effects of stomatal closure on transpiration and on photosynthesis for different types of crops are still topics for research (Hanks and Hill, 1980), it is clear that conditions of stress limit yield in any case and should be avoided, to the extent possible, in irrigation management (Rawlins and Raats, 1975).

The field water balance is an account of all quantities of water added to, subtracted from, and stored within the root zone during a given period of time. The difference between the total amount added and that withdrawn must equal the change in storage. When gains exceed losses, storage increases: conversely, when losses exceed gains, storage decreases. Thus:

$$(\text{Storage}) = (\text{Gains}) - (\text{Losses})$$

This general statement can be amplified as follows:

$$(S + V) = (P + I + U) - (R + D + E + T)$$

(Hillel, 1990)

where S is accretion of water in the root zone, V the increment of water incorporated in the vegetation, P the precipitation, I irrigation, U the upward capillary flow into the root zone from below, R runoff, D downward drainage out of the root zone, E direct evaporation from the soil surface, and T transpiration by plants. The last two variables are difficult to separate and are therefore lumped together and termed

evapotranspiration. All quantities included in the field water balance are expressed in terms of volume of water per unit area (equivalent depth units) during the period considered.

Simple and readily understandable though the field water balance may seem in principle, it is still rather difficult to measure in practice. Often the largest component on the "losses" side of the ledger, and the one most difficult to measure directly, is evapotranspiration (ET). To obtain ET from the water balance we must have accurate measurements of all other terms of the equation. It might seem relatively easy to measure the amount of water added to the field by rain and irrigation (P + I), but this is seldom done on a field-by-field basis, either because of a lack of equipment or trained personnel, or simply through inattention. Even where the input is measured, there remains the problem of how to account for non-uniformities in aerial distribution. The amount of runoff generally is (or at least should be) small in agricultural fields, particularly in irrigated fields, so that, justifiably or not, it is most often ignored. The same goes for the change in water content of the vegetation (Hillel, 1990)

2.2 IRRIGATION AND VEGETABLE CROP PRODUCTION

For the most part, vegetables are high-value crops that are grown intensively. Management, labour, and capital investments are high; accordingly, the ability to irrigate vegetable crops is necessary and commonplace. In any case, the ability to properly irrigate vegetable crops is mandatory for successful commercial production.

2.2.1 Vegetable crop growth and development

Growth is considered to be the accumulation of biomass and influences the water budget through changes in leaf area index, which change interception, transpiration, and evaporation. Development is the orderly progress of the plant through its life cycle from germination to emergence, to flowering and maturity. Development influences the water budget by determining when the plant will transpire and cover the soil (Campbell & Stockle, 1993). The relationship between irrigation and vegetable crop growth and development can be affected by several factors. These include the economically important portion of the vegetable crop and the stage of growth at which it is harvested. The harvested plant part can include immature flowers, stems, leaves, tubers, roots, seeds, or fruits. With most annual vegetable crops,

irrigation is used only until the condition of market maturity is reached. It is the goal of irrigation to avoid water stress, especially during the formation of the harvested plant part.

The rooting characteristic of a vegetable crop is another growth factor that can affect irrigation practices. Rooting depth information for crops grown on specific soils is important for irrigation scheduling decisions. For example, a shallow-rooted crop would normally be irrigated more frequently with lesser amounts of water than a deep-rooted crop. Vegetable crops can be especially susceptible to water stress because of the shallow rooting characteristics, which many of them exhibit. Efficient use of water to avoid stress thus requires irrigation scheduling to take into account crop water needs, critical growth stages, rooting characteristics, soil water holding and transmitting characteristics, and proper selection of an irrigation system (Hiler & Howell, 1983)

2.2.2 Irrigation management for specific vegetable crops

Irrigation management of vegetable crops can vary dramatically with respect to plant species, cultural methods, location, and climate.

2.2.2.1 Greens

Several vegetables are classed as greens including swiss chard, kale and collard, mustard and others of less economic importance. Although diverse botanically, they are all short-season annuals with shallow root systems which are adapted to cool weather where evapotranspiration is low. Little is known about the water requirements of these crops. Where irrigation is used, overhead sprinkler is usually the method of choice (Stanley & Maynard 1990).

2.2.2.2 Salad crops

Celery and lettuce are the principal salad crops. Numerous other salad vegetables are of less economic importance. All are shallow-rooted and most, with the exception of celery, require a relatively short time to reach marketable size. Moore (1970) demonstrated the inefficiencies of furrow irrigation for lettuce. Surface drainage losses averaged 20% and percolation below the root zone accounted for 50% of the water applied. Leaching of NO_3-N averaged 100 kg ha^{-1}. Two-thirds of the water loss and three-fourths of the N loss occurred prior to thinning. Robinson & McCoy (1965) compared furrow and sprinkler irrigation for lettuce grown in the Imperial Valley of California. Sprinkler irrigation reduced

water use by 50% up to thinning. More uniform seedling growth resulted and this uniformity continued to harvest so that the number of harvests was less for sprinkler-irrigated plots. The two authors maintain, however, that the expansion of sprinkler use to entire season production of lettuce is limited by capital and operating costs, and by the likelihood of increased foliar-disease problems with frequent leaf wetting.

2.2.2.3 Crucifers

Cabbage, broccoli and cauliflower are the economically most important vegetables in the Cruciferae family. Evapotranspiration is lower than for many other vegetables because of the thick, waxy leaf covering common to *Brassica* and the cool weather in which most of these crops are grown. Vittum and Flocker (1967) stressed the importance of maintaining adequate, uniform soil water throughout the crop cycle. The same authors reported that water deficits, particularly in the 3 to 4 week period prior to harvest, lower crop yields and quality. On the other hand, excess water during this period may contribute to cabbage head bursting. Cabbage water requirements vary from 380 to 500 mm per season depending on climate, cultivar and growing season (Stanley & Maynard, 1990). Water and N management are often inseparable and together exert a critical influence on crop performance. Kolota (1979) cited by Nortje (1988), reported that irrigation should commence during the early growth stages at 65% of available water and at 75% of available water during the later growth stages. Tyurina (1977) stated that best yields were obtained irrigating when 80% of available water was reached. These recommendations imply that irrigation should be applied every second day during the South African summer season. Work done by Nortje (1988) over a five year period confirms that an average of 430 mm of water per season should be applied for optimum yields of cabbage grown in Roodeplaat (Pretoria, South Africa).

2.2.2.4 Root crops

Carrot is amongst the most important root crops economically. Of significant, but lesser value, are radish and beet. Carrot is grown in deep sandy or sandy loam mineral soils because impediments to storage root elongation cause forked or misshapen roots. In commercial practice, carrots are irrigated at the rate equivalent to 25 mm per week, which amounts to a seasonal total of up to 360 mm of water (Vittum & Flocker, 1967). Bradley, Smittle & Sistrunk (1967) studied the effect of supplemental irrigation on carrot yield and quality in Arkansas. Application of 38 mm of water at 7-, 10-, or 14-day intervals was compared with no irrigation. Irrigation, regardless of frequency, increased carrot yields. A 7-

day irrigation interval was superior to the longer intervals when harvest was delayed. Irrigation did not affect carotene content of the carrots, but solids content decreased with irrigation.

2.2.2.5 Bulbous crops

Onions and garlic are the principal bulb crops. Onion has a shallow root system that is concentrated in the surface 0.3 m. Frequent irrigation is practised to prevent soil water from being depleted below 25% of available water (Stanley & Maynard, 1990). Doorenbos and Kassam (1979) reported that onion is most sensitive to water deficit during the bulb-enlargement period, which occurs 50 to 80 days after transplanting. Water deficits may result in increased pungency of onion (Voss, 1979). Total water application for an onion crop varies from 450 to 1800 mm of water, depending upon method of application, soil type, rainfall, and growing season temperatures. Irrigation ordinarily is terminated as the onion begins to mature to allow drying to proceed (Stanley & Maynard, 1990).

2.2.2.6 Sweet-corn

Water use by sweet-corn changes with the age of the crop. Under irrigated conditions, these changes become important in maintaining soil water levels adequate for maximum production of grain or forage. Sweet-corn can extract about 80% of the available water in a deep soil before stomatal regulation begins. However, most irrigation scheduling programmes use 50% of soil water depletion as the point at which water is added to the field. Adding water at 50% depletion allows for maximum efficiency of irrigation plus a safe margin of water to cover periods of high water demand and mechanical failure in the irrigation system which could delay the application of water for a few days (Waldren, 1983).

Peak water use by sweet-corn is at about the time of silking or shortly thereafter. Much research has shown that water deficits at the time of tasseling and silking also cause the greatest reduction in yield. Water stress can reduce grain yield by 25% when prior to silking, by 50% when occuring at silking, and by 21% after silking (Rhoads & Bennette, 1990). Length of stress period is also important. Soil water depletion to the wilting percentage for 2 days during the tasseling or pollination period can result in as much as a 22% decrease in yield, while a 6-8 day period of depletion can cause a yield reduction of about 50% (Waldren, 1983).

Studies with sweet-corn have shown that 85% of available soil water depletion during silking results in 40% yield loss, reduced plant height, and increased incidence of stalk rot (Rhoads & Bennette, 1990). Sweet-corn grown under limited irrigation benefits most from water applied just prior to tasseling.

Water applied before planting, either in the fall or spring, appears to have little effect on yields except when an occasional very dry spring occurs. Although corn has a high water requirement, it is one of the most efficient crops in producing dry matter with the water it uses. Sweet-corn requires about 372 unit mass of water per unit mass of dry matter produced, compared with 271 for sorghum, 505 for wheat, 562 for cotton, and 858 for alfafa (Waldren, 1983).

2.2.2.7 Beans

Beans are moderately deep- rooted, with a strong tap-root and extensive lateral root system. Although the tap-root may extend to a depth of 1.5m, the main root zone of water extraction is to a depth of 0.5-0.7 m. The most critical plant growth stages with respect to water deficit are the flowering and pod-production periods. General water requirements for maximum production are in the range of 300 to 500 mm (Doorenbos & Kassam, 1979). The bean is a rapidly growing crop, and, for some snap bean cultivars, the time from planting to harvest may be as little as 45 days. Adequate soil water must be available constantly to ensure optimum growth and yield (Halterlein, 1983).

Many have demonstrated the importance of irrigation at blossom time. Vittum and Flocker (1967) have shown that a single irrigation applied at flowering may result in substantially improved yields. Higher yields resulted largely from an increased number of pods per plant, but pod size also increased. Halterlein (1983) reported that the method of irrigation might also be important. Yields were reportedly higher from strip irrigated beans than from those watered by overhead irrigation and water use was from 12 to 50% less. Drake and Silbernagel (1982) reported that irrigation method may also influence snap bean quality. Sprinkler irrigated bean in Washington was higher in $C_6H_8O_6$ (carbohydrate) content than furrow irrigated bean. On the other hand, furrow irrigated bean had better colour and was more tender than those that were sprinkler irrigated.

2.2.2.8 Solanaceous crops

Tomato and peppers- both sweet and pungent- are amongst the principal vegetables in this group. Tomato is a deep-rooted plant wherever soil physical and water conditions permit full root extension. The plant extracts most of the water from the top 0.5-0.7 m, and growth is restricted when available water falls below 60% in this zone. Water stress most seriously affects yields during the plant establishment, flowering, and fruit enlargement periods. Total water requirements are in the range of 400 to 600 mm (Doorenbos & Kassam, 1979). For direct-seeded crops, the requirements would be substantially greater.

Microirrigation is becoming increasingly important where water is scarce or expensive, or where there is concern about groundwater quality (Stanley & Maynard, 1990). Furrow, sprinkler, and micro- irrigation was used to maintain available water at 50% or higher for the surface 60 cm of soil in Alabama experiments (Dos, Turner & Evans, 1980). Tomato yields from irrigated plots were higher than those from non-irrigated plots but there were no significant yield differences among application methods in this three-year study.

Green pepper has a tap-root that may extend to 1.5 m when the crop is direct-seeded if soil physical and water conditions permit. The crop is frequently transplanted, which can lead to injury to the tap-root and a predominance of lateral roots. Water uptake is from the top 1.5 m in the former situation, but only 0.3 to 0.5 m depth in the latter case. Green pepper is sensitive to water stress throughout the crop season, but particularly during flowering and fruiting. Commercial green pepper crops are currently irrigated by sprinkler or micro systems depending on existent production systems.

CHAPTER 3

OVERVIEW OF THE SWB MODEL

There is increasing interest in scheduling irrigation with crop growth computer models since PC's have become accessible to crop producers (Bennie, Coetzee, Van Antwerpen & Van Rensburg, 1988). The Soil water Balance (SWB) model was developed as a real time, irrigation scheduling tool (Benade', Annandale & Van Zijl, 1997). It is based on the improved generic crop version of NEWSWB (Campbell & 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 the remaining water is passed on to the layer below. Water which passes below 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 standardized FAO (Food and Agriculture Organization of the United Nations, Rome, Italy) Penman-Monteith methodology (Allen, Pereira, Raes & Smith, 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 point. Thereafter, it is equal to the sum of potential evaporation and the square of the remaining evaporable water down to the air-dry soil water content (Campbell & Diaz, 1988).

Actual transpiration is determined on a daily basis as either supply or demand limited (Campbell & Norman, 1988). The daily dry matter increment is taken as the minimum of transpiration-limited (Tanner & Sinclair, 1983) and radiation-limited (Monteith, 1977) dry matter production, with water stress affecting the partitioning of assimilates to the different plant organs.

The SWB model gives a detailed description of the soil-pant- atmosphere continuum, making use of weather, soil and crop databases (Jovanovic & Annandale, 2000). The crop database includes several crop-specific growth parameters: dry matter-transpiration ratio corrected for vapour pressure deficit, radiation conversion efficiency, specific leaf area, stem-leaf partitioning parameter, canopy extinction coefficient for total solar radiation, maximum root depth, maximum crop height, cardinal temperatures

and growing day degrees for the completion of phenological stages. A detailed description of the SWB model is presented in the following sections.

3.1 MODEL DESCRIPTION

The SWB model includes three units, namely weather, soil and crop unit, which are discussed in the following sections (Annandale *et al.* 1999).

3.1.1 The weather unit

The weather unit calculates potential evapotranspiration (PET) from available meteorological input data (Smith, 1992). Daily Penman-Monteith grass reference evapotranspiration ET_o and PET are calculated in the Weather unit and used in the Soil unit to compute actual transpiration (T) and evaporation (E).

The Weather unit includes the procedure for initializing weather parameters and five functions where the following parameters are calculated:

1) R_a - Extraterrestrial radiation (MJ m^{-2} day^{-1}) ;
2) VPD - Vapour pressure deficit (kPa) ;
3) R_n - Net radiation (MJ m^{-2} day^{-1}) ;
4) ET_o - FAO reference evapotranspiration (mm day^{-1}) ; and
5) PET - Potential evapotranspiration (mm day^{-1}).

3.1.1.1 Extraterrestrial radiation

Potential solar radiation is calculated as a function of latitude (Lat) and day of year (DOY), as follows:

$$R_a = 118.08\, D_{rel} / \pi \, [\, \omega_s \sin(Lat) \sin(Dec) + \sin(\omega_s) \cos(Lat) \cos(Dec) \,] \qquad (1)$$

R_a is in MJ m^{-2} day^{-1}, whilst the constant 118.08 represents the solar constant in MJ m^{-2} day^{-1} . D_{rel} is the relative distance of the earth from the sun, a function of DOY :

$$D_{rel} = 1 + 0.033 \cos (2\pi \, DOY / 365) \quad (2)$$

ω_s is sunset hour angle (rad) , a function of latitude and solar declination (Dec) .

$$\omega_s = \text{arccoss} [- \tan (Lat) \ \tan (Dec)] \quad (3)$$

For the Southern Hemisphere, solar declination is calculated as follows:

$$Dec = - 0.409 \sin (2\pi / 365 \, DOY - 1.39) \quad (4)$$

(Duffie & Beckman, 1980)

whilst for the Northern hemisphere the sign of the equation is changed.

3.1.1.2 Vapour pressure deficit

Vapour pressure deficit is calculated using the following equation;

$$VPD = [e_s \ (T_{max}) + e_s (T_{min})] / 2 - e_a \quad (5)$$

where e_s is saturated vapour pressure (kPa) , a function of maximum (T_{max}) and minimum air temperature (T_{min}) , and e_a is the actual vapour pressure (kPa) .

Saturated vapour pressure is estimated from air temperature (T_a), as follows:

$$e_s = 0.611 \exp [17.27 \, T_a / (T_a + 237.3)] \quad (6)$$

(Tetens , 1930)

Actual vapour pressure is an input variable. If not available, it is calculated from measured minimum (RH_{min}) and maximum relative humidity (RH_{max}), and if that is not available, from measured wet bulb (T_w) and dry bulb temperature (T_d) .

Vapour pressure can be calculated as a function of percent relative humidity as follows:

$$e_a = [e_s (T_{min}) \ RH_{max} / 100 + e_s (T_{max}) \ RH_{min} / 100] / 2 \quad (7)$$

and from psychrometer readings as:

$$e_a = e_s\ (T_w) - 0.0008\ (T_d - T_w)\ P_a \qquad (8)$$

(Bosen, 1958)

P_a is atmospheric pressure.

If not available for use in Kc_{max} (FAO maximum crop coefficient) , RH_{min} is calculated as a function of T_{max} and T_{min} for use in the weather modified PET calculation :

$$RH_{min} = e_s\ (T_{min}) / e_s\ (T_{max}) \qquad (9)$$

If no atmospheric vapour measurements are available, SWB assumes T_{min} reaches dew point, and e_a is set to $e_s\ (T_{min})$.

VPD is used in the calculation of ET_o and water-limited dry matter production.

3.1.1.3 Net radiation

In this section, the R_n value is calculated to be used for computing the Penman-Monteith reference evapotranspiration as follows:

$$R_n = R_{ns} - R_{nl} \qquad (10)$$

R_{ns} - Short-wave net radiation (MJ m^{-2} day^{-1})

R_{nl} - Long-wave net radiation (MJ m^{-2} day^{-1})

Assuming the albedo of the reference crop is 0.23, R_{ns} is :

$$R_{ns} = 0.77\ R_s \qquad (11)$$

R_s - Solar radiation (MJ m^{-2} day^{-1})

R_s is an input value in MJ m^{-2} day^{-1}. In the absence of measured data, SWB calculates R_s after Allen (1995) as follows:

$$R_s = 0.17\, P_a / P_o\, (T_{max} - T_{min})^{0.5}\, R_a \qquad (12)$$

P_o is atmospheric pressure at sea level. T_{max} and T_{min} are in °C and they represent the minimum required input data for calculating R_s. Kelvin air temperatures are used to calculate net terrestrial radiation:

$$R_{nl} = f_c \in \sigma\, (T_{max}^4 + T_{min}^4) / 2 \qquad (13)$$

with f_c, the cloudiness factor

$$f_c = 1.35\, R_s / R_{so} - 0.35 \qquad (14)$$

(Doorenbos & Pruitt, 1976)

R_{so} is the short-wave radiation during bright sunshine ($MJ\ m^{-2}\ day^{-1}$):

$$R_{so} = 0.75\, R_a \qquad (15)$$

The factor " 0.75 " represents the maximum clear sky transmissivity of the atmosphere.

$\in$ is the clear sky emissivity of the earth's surface:

$$\in = 0.34 - 0.14\, e_a^{0.5} \qquad (16)$$

(Doorenbos & Pruitt, 1976)

and σ is the Stefan - Boltzman constant (4.9×10^{-9} $MJ\ m^{-2}\ K^{-4}$)

3.1.1.4 FAO reference evapotranspiration

The Penman-Monteith ET_o is calculated according to the FAO procedure, as recommended by Smith, Allen & Pereira (1996). The following equation is adopted:

$$ET_o = [\, 0.408\, \Delta\, (R_n - G) + \gamma\, 900 / (T_{avg} + 273)\, U_2\, VPD\,] / [\, \Delta + \gamma\, (1 + 0.34 U_2)\,] \qquad (17)$$

with Δ the slope of the saturation vapour pressure curve in kPa °C^{-1}

$$\Delta = 4098\ e_s / (T_a + 237.3)^2 \quad (18)$$

and G the soil heat flux (MJ m^{-2} day^{-1}) calculated from today's (DOY) and the previous day's (DOY-1) average air temperature (T_{avg})

$$G = 0.38\ [\ T_{avg}\ (DOY)\ -\ T_{avg}\ (DOY\text{-}1)\ ] \quad (19)$$

(Wright & Jensen, 1972)

where

$$T_{avg} = (T_{max} + T_{min}) / 2 \quad (20)$$

γ is the psychrometer constant (kPa $^{\circ}C^{-1}$) calculated as

$$\gamma = 0.00163\ P_a / \lambda \quad (21)$$

with λ the latent heat of vaporization (MJ kg^{-1})

$$\lambda = 2.501\ -\ 2.361 \times 10^{-3}\ T_{avg} \quad (22)$$

U_2 is wind speed measured at 2 m height (m s^{-1}). U_2 is a weather data input value. If it is not available, SWB assumes an average U_2 of 2 m s^{-1}. Smith *et al.* (1996) recommended an average U_2 of 3 m s^{-1} for windy, and 1 m s^{-1} for low wind conditions. If wind speed (U) is not measured at 2 m height, the logarithmic wind speed profile function is applied to calculate U_2 as follows:

$$U_2 = U\ 4.87 /\ \ln (67.8\ H_U - 5.42) \quad (23)$$

(Allen *et al.*, 1989)

H_U - Height at which speed is measured (cm)

3.1.1.5 Potential evapotranspiration

Potential evapotranspiration is used to determine actual transpiration and evaporation in the Soil unit. Crop PET is calculated as a function of the reference evapotranspiration and Kc_{max} , as follows:

$$PET = ET_o \, Kc_{max} \tag{24}$$

Kc_{max} represents the maximum value for the FAO crop coefficient (Kc) following rain or irrigation. It is calculated using the procedure recommended by Allen *et al.* (1996), and identified as the maximum of the following two equations:

$$Kc_{max} = 1.2 + [\, 0.04 \, (U_2 - 2) \, - \, 0.004 \, (RH_{min} \, - \, 45) \,] \, (H_c / 3)^{0.3} \tag{25}$$

$$Kc_{max} = K_{cb} + 0.05 \tag{26}$$

H_c - Crop height (m)

K_{cb} - FAO basal crop coefficient

The upper limit of Kc_{max} is set at 1.45. The calculation of H_c and K_{cb} is shown in the Crop unit.

3.1.1.6 Weather day step

The Weather day step procedure is executed on a daily basis until the present day or else until maturity. This function identifies the day of year and reads rainfall (R) and irrigation (I) input data.
The Weather day step procedure remembers the average air temperature of the previous day which is used to estimate soil heat flux in the section FAO reference evapotranspiration.
The Weather day step procedure uses the following variables:

- FAO basal crop coefficient, K_{cb};
- Crop height, H_c;
- Maximum daily temperature, T_{max} ;
- Minimum daily temperature, T_{min} ;

- Incoming solar radiation, R_s ;
- Actual vapour pressure, e_a ;
- Wind speed measured at 2 m height, U_2 ;
- Height at which wind speed is measured, H_U ;
- Daily minimum relative humidity, RH_{min} ;
- Daily maximum relative humidity, RH_{max} ;
- Dry bulb temperature, T_d ; and
- Wet bulb temperature, T_w .

K_{cb} and H_c are calculated in the Crop unit. T_{max} and T_{min} are essential input values. The H_U input value is needed if U is not measured at 2 m height. If measured input data are not available, SWB estimates R_s, e_a, U_2 and RH_{min} as described in the previous sections.

3.1.2 The soil unit

The aim of the Soil unit is to simulate the dynamics of water movement in the soil profile in order to determine soil water availability to the crop. Water movement is simulated with a cascading model. This divides the soil profile into a number of layers. Each layer has its own physical properties:

- Soil matric potential, ψ_m ($J\ kg^{-1}$)
- Volumetric soil water content, θ ;
- Volumetric soil water content at field capacity, θ_{fc} ;
- Volumetric soil water content at permanent wilting point, θ_{pwp} , and
- Campbell's "a" and "b" parameters of the log-log water retention function.

Soil water movement is calculated in the Soil unit and includes three procedures:

i) Calculation of soil layer thickness (dz);

ii) Soil parameters initialization; and

iii) Soil day step calculation.

In addition, two separate functions are used to calculate:

i) Soil water storage, and

ii) Allowable depletion.

SWB firstly calculates the thickness of each soil layer (i), using the following equation:

$$dz_i = z_i - z_{i-1} \quad (27)$$

z - Layer depth (m)

Layer depth (distance between the lower boundary of the layer and the soil surface) is an input value. In the procedure that initializes soil water parameters, SWB reads input values of initial θ, θ_{fc}, and θ_{pwp} for each of the layers. For uniform profiles only one set of layer values needs to be entered.

Campbell's "a" and "b" coefficients of the water retention function are calculated for each layer as follows (Campbell, 1985):

$$b = \ln (\psi_{pwp} / \psi_{fc}) / \ln (\theta_{fc} / \theta_{pwp}) \quad (28)$$

$$a = \exp (\ln (-\psi_{pwp}) + b \ln (\theta_{pwp}) \quad (29)$$

ψ_{pwp} - Soil matric potential at permanent wilting point (J kg^{-1})

ψ_{fc} - Soil matric potential at field capacity (J kg^{-1})

Hillel (1982) recommended values of -1500 J kg^{-1} for ψ_{pwp} and -10 J kg^{-1} for ψ_{fc}.

Volumetric water content at permanent wilting point is then recalculated as the lower limit of crop water uptake for a specific plant:

$$\theta_{pwp} = \exp (-\ln (-3 \psi_{lm} / 2 a) / b) \quad (30)$$

ψ_{lm} - Leaf water potential at maximum transpiration rate (J kg^{-1}).

ψ_{lm} is a crop specific parameter.

Air dry volumetric soil water content (θ_{ad}) is calculated as follows (Campbell & Stockle, 1993):

$$\theta_{ad} = 0.3\ \theta_{pwp} \tag{31}$$

θ_{ad} is used to set the lower limit of water loss through evaporation from the soil surface. As SWB assumes evaporation occurs from the top soil layer, θ_{ad} is only calculated for this layer.

The soil day step procedure is performed on a daily basis. It includes five more procedures which are performed in the following order:

i) Amount of precipitation intercepted by the canopy, I_c;
ii) Runoff, R_o;
iii) Infiltration and redistribution;
iv) Evaporation; and
v) Transpiration.

3.1.2.1 Interception

The amount of rainfall and irrigation are two of the required inputs of SWB. Interception of precipitation and irrigation (P + I) by the crop canopy is calculated only on days when rainfall and / or sprinkler irrigation occur. The amount of water intercepted by the canopy is assumed to be equal to the fractional interception of radiation by the canopy, including both photosynthetically active and senesced leaves (FI_{evap}), multiplied by a canopy storage parameter. The FI_{evap} calculation is shown in the Crop unit section whilst canopy storage is a crop specific parameter. The amount of precipitation penetrating the canopy and reaching the soil surface is reduced by the amount of water intercepted by the canopy. If the amount of precipitation is lower than potential interception, it is assumed that all precipitation is intercepted by the canopy and no rainfall and / or sprinkler irrigation water reaches the soil surface.

3.1.2.2 Runoff

Runoff is calculated on days when rainfall and / or sprinkler / flood irrigation occur. R_o is calculated adopting a semi-empirical algorithm based on the assumption that once precipitation is greater than, or equal to a value representing initial infiltration and surface storage, R_o increases with increasing precipitation.

Runoff is assumed to be zero if:

$$P + I \leq 0.2\ S \tag{32}$$

S - Runoff curve number (mm)

S is an input parameter giving an indication of the storage of surface. If rain plus irrigation exceeds 20% of S, runoff is calculated according to the following relation:

$$R_o = (P + I - 0.2\ S)^2 / (P + I + 0.8\ S) \tag{33}$$

(Stewart *et al.*,1976)

Surface runoff is then subtracted from the rainfall and / or irrigation water allowing the remainder to infiltrate the soil.

3.1.2.3 Infiltration and redistribution

Infiltration and redistribution of water in the soil profile are calculated on days when rainfall and / or irrigation occur. The model distributes water from rainfall and irrigation by filling soil layers to field capacity, starting from the top layer of the profile and moving downwards. SWB updates soil layer water content on a daily basis. Layer soil water deficit (SWD) is calculated as a function of θ using the following expression:

$$SWD = (\theta_{fc} - \theta)\ \rho_w\ dz \tag{34}$$

ρ_w - Density of water (1000 kg m^{-3})

If the amount of water penetrating a soil layer is larger than SWD for that layer, θ is set to θ_{fc}. The amount of water penetrating the deeper layer (P + I) is then reduced by SWD. If the amount of water penetrating a soil layer is lower than SWD for that layer, θ is increased by " (P + I) / ρ_w dz " . No more water is then available to infiltrate to deeper layers.

Drainage (D) is calculated when the sum of R and I exceeds the water deficit of the soil profile. If rainfall and / or irrigation water is still available after the last soil layer has been filled to field capacity, D is set to be equal to the remaining water. Drainage is assumed to be instantaneous.

3.1.2.4 Evaporation

The actual partitioning between evaporation and transpiration depends on the available energy reaching the crop canopy and soil surface and resistances to water flow (Ritchie, 1972 ; Norman & Campbell, 1983). Water loss by evaporation is assumed to occur only from the top soil layer. The potential evaporation (PE) is expressed as follows:

$$PE = (1 - Fl_{evap})\ PET \tag{35}$$

PET is calculated in the Weather unit and Fl_{evap} in the Crop unit. Evaporation proceeds at the potential rate until θ_{pwp} is reached (atmospheric evaporative demand limited). If the water content in the top soil layer decreases below θ_{pwp}, then evaporation becomes supply limited (Campbell, 1985)

$$E = PE\ ((\theta - \theta_{ad}) / (\theta_{pwp} - \theta_{ad}))^2 \tag{36}$$

According to this equation, actual evaporation decreases by reducing the layer's water content. Water content in the top soil layer is reduced by the amount of water evaporated from the soil surface, on a daily basis. If the calculated θ is below θ_{ad}, θ is assumed to be equal to θ_{ad}. E is then calculated as follows:

$$E = (\theta - \theta_{ad})\ \rho_w\ dz \tag{37}$$

3.1.2.5 Transpiration

Water loss by transpiration is calculated on days when root depth (RD) and fractional interception of radiation by photosynthetically active leaves (FI_{transp}) are greater than 0. SWB assumes that layer water uptake is weighted by root density when soil water potential is uniform. No root water uptake is calculated for the uppermost soil layer, which is reserved for evaporation. Soil matric potential is calculated daily as a function of the actual soil water content using the following equation (Campbell, 1985):

$$\psi_m = a \ln \theta^{-b} \quad (38)$$

By plotting ψ_m and θ on a log-log scale and fitting a straight line to the data, it is possible to derive Campbell's " a " and " b " values from the intercept and the slope of the relationship (Eqs. 28 & 29). Reduction in ψ_m closes stomata and decreases transpiration and dry matter production. Transpiration is therefore computed as a function of ψ_m. The following equation is applied to each layer in the soil profile, in order to calculate water loss by transpiration as a function of soil water potential:

$$\text{Loss} = FI_{transp} \ Tr_{max} \ f \ (\psi_x - \psi_m) \ / \ (0.67 \ \psi_{lm}) \ / \ (\rho_w \ dz) \quad (39)$$

Tr_{max} - Maximum transpiration rate (mm day^{-1})

f - Layer root fraction

ψ_x - Xylem water potential (J kg^{-1})

Tr_{max} is a crop specific parameter. The factor " f " is computed for each soil layer, according to the following expression:

$$f = dz \ (2 \ (RD - z) + dz) \ / \ RD^2 \quad (40)$$

(Campbell & Diaz, 1988)

In the layer where z is larger than RD, the factor " f " is calculated as follows:

$$f = ((RD - z + dz) / RD)^2 \quad (41)$$

ψ_x is calculated using the expression:

$$\psi_x = \psi_{lm} (\psi_{avg}^* + 0.67\ T^*) \quad (42)$$

where

$$\psi_{avg}^* = \psi_{avg} / \psi_{lm} \quad (43)$$

ψ_{avg} - Root weighted average soil matric potential (J kg^{-1})

$$\psi_{avg} = \Sigma\ f_i\ \psi_{lm} \quad (44)$$

The subscript " i " indicates the soil layer. T^* is the dimensionless actual water uptake. T^* is chosen as the minimum between the dimensionless root uptake rate (U^*) and the maximum dimensionless loss rate (E^*):

$$U^* = 1 - 0.67\ \psi_{avg}^* \quad (45)$$

$$E^* = PET / Tr_{max} \quad (46)$$

The factor " 0.67 " takes into account the resistances which water flow encounters in the path from the soil toward the leaf. The major resistances are in the endodermis, where water enters the root steele and in the leaf, at the bundle sheath. For typical plants growing in moist soil, the potential drop across the endodermis is 60 - 70% of the total (Campbell, 1985). In this model, root resistance is assumed to be two thirds of total plant resistance, with leaf resistance the remaining third. Xylem resistance is assumed to be negligible as water flows in cell walls and xylem vessels without crossing membranes. Soil resistance is also considered negligible. Water uptake is calculated only when: $\psi_{avg}^* < 1.5$.

If the ratio between root weighted average soil matric potential and leaf water potential at maximum transpiration rate exceeds 1.5, actual crop transpiration is assumed to be 0. Under this condition, the xylem water potential is equal to the root weighted average soil matric potential ($\psi_x = \psi_{avg}$) and no water flow through the plant occurs.

Actual water content is reduced in each soil layer by the amount of water absorbed by the roots. The lower limit of θ is θ_{pwp}. If the difference between actual water content and water loss by transpiration is smaller than the water content at permanent wilting point (θ - Loss < θ_{pwp}), θ is set equal to θ_{pwp} and the water taken by the roots is:

$$\text{Loss} = \theta - \theta_{pwp} \tag{47}$$

Finally, water losses by transpiration are converted into mm units and cumulated for each soil layer to determine daily T in mm.

A dimensionless water stress index (SI) is caculated as follows:

$$SI = T / (FI_{transp}\ PET) \tag{48}$$

PET is calculated in the Weather unit, whilst FI_{transp} in the Crop unit. SI is used to simulate partitioning of daily dry matter production to different plant organs (Crop unit).

3.1.2.6 Soil water storage

Soil water storage is calculated on a daily basis as the sum of the water content in mm in each soil layer. This is subtracted from profile water content at field capacity to determine profile deficit.

3.1.2.7 Allowable depletion

Allowable depletion level (ADL) in the root zone is calculated on a daily basis. ADL is calculated in mm for each soil layer where the root system is present, as follows:

$$ADL = (\theta_{fc} - \theta_{pwp})\ \rho_w\ dz \tag{49}$$

Soil layer ADL values are added to calculate ADL in the root zone. For the layer not completely explored by the roots, ADL is calculated as follows:

$$ADL = -(z - RD)\ (\theta_{fc} - \theta_{pwp})\ \rho_w \tag{50}$$

In this way, ADL is reduced by the amount of available water ($(\theta_{fc} - \theta_{pwp})\ \rho_w\ dz$) below the root zone. SWB uses allowable depletion to guide irrigation timing.

3.1.3 The crop unit

The aim of the Crop unit section is to simulate crop growth. The Crop unit involves three procedures:

i) Initialization;
ii) Planting; and
iii) Day step calculation.

Crop initialization sets initial values of several crop parameters to zero. Crop height requires a starting value greater than zero. It is set to 0.001m.

The procedure for crop planting is initiated once a valid planting date has been identified. Top dry matter (TDM) is set to TDM at emergence (crop specific parameter). For most crops, TDM at emergence is estimated to be equivalent to seed mass per square metre. Initial root dry matter (RDM) is calculated as:

$$RDM = f_r\ TDM / (1 - f_r) \tag{51}$$

f_r - Fraction of dry matter partitioned to roots (crop specific parameter).

Initial leaf area index (LAI) is calculated as follows:

$$LAI = SLA\ TDM \tag{52}$$

SLA - Specific leaf area ($m^2 kg^{-1}$)

SLA is a crop parameter that describes the leaf morphology of a specific crop.

The crop day step procedure is performed on a daily basis and includes the following calculations:

- Growing day degrees (GDD);
- Fractional interception of radiation (FI);
- Crop height (H_c);
- Dry matter production increment (DM_i);
- Harvestable dry matter increment (HDM_i);
- Partitioning of DM_i into plant organs;
- Partitioning of DM_i under conditions of water stress;
- Leaf area index (LAI); and
- Rooting depth (RD).

The simulation of crop growth and development is discussed in the following sections.

3.1.3.1 Growing day degrees

Crop development is simulated using thermal time, an approach suggested by Monteith (1977). The calculation of growing day degrees starts after crop planting. GDD are accumulated daily using the following expression:

$$GDD := GDD + GDD_i \tag{53}$$

GDD_i - Growing day degrees increment

Growing day degrees increment is calculated as follows:

$$GDD_i = T_{avg} - T_b \tag{54}$$

T_b - Base temperature (°C)

T_b is a crop specific parameter. When the average daily temperature is below the base temperature, GDD_i is set to 0. If the average temperature is greater than the cutoff temperature, then:

$$GDD_i = T_{cutoff} - T_b \quad (55)$$

where T_{cutoff} is an optimal temperature for crop development in ^0C (crop specific parameter).

The succession of phenological stages is simulated using day degree requirement parameters for emergence (EMDD), completion of vegetative growth (FLDD) , transition period between vegetative and reproductive growth (TransDD) , and maturity (MTDD).

3.1.3.2 Fractional interception of radiation

Fractional interception of radiation is used to determine the portion of radiation available for crop transpiration and evaporation from the soil surface. The two parameters calculated in this section are:

$$FI_{transp} = 1 - e^{(-K\,LAI)} \quad (56)$$

and:

$$FI_{evap} = 1 - e^{(-K\,(LAI + yLAI))} \quad (57)$$

K - Canopy radiation extinction coefficient (crop specific parameter)

yLAI - Leaf area index of senesced (yellowed) leaves

FI_{transp} is the amount of radiation intercepted by the canopy and used for photosynthesis and transpiration. The amount of radiation penetrating the canopy and used for evaporation from the soil surface is given by " $1 - FI_{evap}$ ".

3.1.3.3 Crop height

Crop height is used in the calculation of potential evapotranspiration in the Weather unit. H_c is assumed to be 0.001 m until emergence. After emergence, it increases linearly until the end of the transition period between vegetative and reproductive growth, when it reaches its maximum (Hc_{max}, crop specific parameter). SWB calculates H_c daily, using the following equation:

$$Hc = 0.001 + (GDD - EMDD)\,(Hc_{max} - 0.001) / (FLDD + TransDD - EMDD) \quad (58)$$

After the transition period between vegetative and reproductive stage has been completed, crop height remains equal to Hc_{max}.

3.1.3.4 Daily dry matter production increment (DM_i)

After crop emergence, SWB calculates DM_i on a daily basis until the crop reaches maturity. DM_i is calculated as either water supply or radiation limited.

Water supply limited DM_i (kg m^{-2}) is predicted using the relationship between dry matter accumulation and transpiration (Tanner & Sinclair, 1983):

$$DM_i = DWR\ (T/VPD) \tag{59}$$

DWR - Dry matter water ratio (Pa)

VPD is in Pascals (Pa) and T in millimetres (mm).

Under conditions of radiation limited crop growth, DM_i is calculated using the equation recommended by Monteith (1977):

$$DM_i = E_c\ T_f\ FI_{transp}\ R_s \tag{60}$$

E_c - Radiation conversion efficiency (kg MJ^{-1})

T_f - Temperature factor for radiation-limited crop growth

where

$$T_f = (T_{avg} - T_b) / (T_{lo} - T_b) \tag{61}$$

T_{lo} - Temperature for optimum light-limited growth (^0C)

The upper limit of T_f is set to 1 when $T_{avg} > T_{lo}$. Daily dry matter increment is chosen as the minimum of the water supply and radiation limited DM_i.

3.1.3.5 Daily harvestable dry matter increment

SWB assumes that, after flowering, DM_i is firstly partitioned to reproductive sinks, then to the other plant organs. The calculation of the daily harvestable dry matter increment is therefore the first in the series of calculations carried out to determine dry matter partitioning to plant organs.

On the day when the flowering stage commences, initial harvestable dry matter (HDM) of the crop is calculated as follows:

$$HDM = Transl\ SDM \tag{62}$$

Transl - Factor determining translocation of dry matter from stem to storage organs (crop specific parameter)

SDM - Stem dry matter (kg m^{-2})

During the flowering stage, the following equation is used to calculate the daily harvestable dry matter increment:

$$HDM_i = rpf\ DM_i \tag{63}$$

rpf - Reproductive partitioning fraction

where

$$rpf = (GDD - FLDD) / TransDD \tag{64}$$

FLDD and TransDD are crop specific parameters. The upper limit of rpf is set to 1 (all dry matter produced is partitioned to the reproductive portion). If the crop has not flowered, rpf is set to 0 . Once the HDM calculation has been completed, SWB subtracts HDM_i from DM_i.

3.1.3.6 Partitioning of dry matter into other plant organs

SWB assumes that DM_i is firstly partitioned into roots, then into leaves and finally into the stem. Daily dry matter increment for roots (RDM_i) is calculated as follows:

$$RDM_i = f_r\ DM_i \tag{65}$$

f_r is set to 0 once root depth has reached a maximum value. Maximum rooting depth (RD_{max}) is a crop specific parameter.

Canopy dry matter daily increment (CDM_i) is then calculated:

$$CDM_i = (1 - f_r)\ DM_i \tag{66}$$

Daily increment of leaf dry matter (LDM_i) is calculated as follows:

$$LDM_i = f_l\ CDM_i \tag{67}$$

f_l - Fraction of top dry matter partitioned into leaves

f_l is calculated as a function of canopy dry matter (CDM):

$$f_l = 1 / (1 + PART\ CDM)^2 \tag{68}$$

PART is the stem-leaf paritioning factor.

The daily increment of stem dry matter (SDM_i) is then calculated as follows:

$$SDM_i = CDM_i - LDM_i \tag{69}$$

HDM_i is finally added to CDM_i in order to include grain dry matter into TDM.

3.1.3.7 Partitioning of dry matter under conditions of water stress

Assimilate partitioning is affected by water stress. Water stress conditions are simulated when the calculated daily water stress index is lower than the threshold (crop specific parameter) . SI is calculated in the Soil unit as the ratio of actual and potential transpiration.

Under conditions of water stress, a half of the daily leaf dry matter increment is partitioned into roots, and the other half into the stem:

$$RDM_i = RDM_i + LDM_i / 2 \tag{70}$$

$$SDM_i = SDM_i + LDM_i / 2 \quad (71)$$

$$CDM_i = CDM_i - LDM_i / 2 \quad (72)$$

If the root system has already reached the maximum depth ($f_r = 0$), the daily leaf dry matter increment is fully partitioned into the stem:

$$SDM_i = SDM_i + LDM_i \quad (73)$$

LDM_i becomes zero and one stress day is accumulated.

3.1.3.8 Leaf area index

Once emergence has taken place, LAI daily increments (LAI_i) are calculated using the following relationship:

$$LAI_i = LDM_i \; SLA \quad (74)$$

LAI is then calculated by cumulating LAI_i values. It represents the "green leaf" or photosynthetically active canopy, which contributes to transpiration and dry matter production. Leaf senescence is also accounted for in SWB. This is done by tracking each individual day's LAI age (LAI_{age}). The age (in d °C) of each day's leaf area increment is kept track of from the day it was generated. Once the LAI_i reaches a maximum age (crop specific parameter), it is classified as leaf area of "yellowed/dead leaves" ($yLAI_i$) as it stops contributing to photosynthesis and dry matter production. The green LAI value is then reduced by $yLAI_i$. Leaf area index of senesced leaves (yLAI) is increased by $yLAI_i$, so as to estimate shading of the soil for the evaporation calculation (Soil unit).

A water stress factor (wsf) is used to simulate premature leaf senescence under water stress conditions. When SI is lower than the threshold value, wsf is calculated as follows:

$$wsf = 1 / SI \quad (75)$$

Ageing of leaves is speeded up by multiplying the daily thermal time increment by wsf:

$$LAIage = wsf\, GDD_i \tag{76}$$

The upper limit of wsf is set to 2, indicating that the ageing of leaves under water stress conditions can be at most twice as fast as under well watered conditions.

3.1.3.9 Rooting depth

Rooting depth is calculated using the following equation

$$RD = RGR\ RDM^{0.5} \tag{77}$$

RGR - Root growth rate ($m^2\ kg^{-0.5}$)

RGR is a crop specific parameter. RD is used in the calculation of transpiration (Soil unit).

CHAPTER 4

MATERIALS AND METHODS

4.1 PURPOSE OF THE STUDY

The SWB irrigation scheduling model is a generic crop growth model. It requires parameters specific for each crop to be experimentally determined. Very little literature is available on growth parameters and crop water use of vegetables. Two field trials involving six winter vegetables and nineteen varieties of summer vegetables were, therefore, set up at Roodeplaat (Gauteng, South Africa). The objectives of the trials were: to determine specific crop growth coefficients for several irrigated vegetables; to determine the rooting depth of different vegetable crops; and to determine seasonal crop water use.

4.2 LOCATION AND ENVIRONMENTAL CHARACTERISTICS

The field trial was established at Roodeplaat (Lat. 25° 48' S, Long. 29° 05' E, Alt 1510 m), 30 km North East of Pretoria. The region is a summer rainfall area with an average rainfall of about 650 mm per annum (October-March). The highest average monthly maximum temperature is 30 °C (January), whilst the lowest average monthly minimum temperature is 1.5 °C (July). Frequent occurrence of frost is experienced during winter months. The soil is a deep clay loam Red Valsrivier (Soil Classification Working Group, 1991). Prior to establishment of the trials, soil samples were taken and analysed (Table 4.1) by the Dept of Agriculture (Gauteng).

4.3 EXPERIMENTAL SET UP

Six winter vegetables were grown during the 1996 season on 5 x 12 m plots. The experimental field was 30 x 12 m in size. During the 1996/97 summer season, nineteen cultivars covering nine crop species were grown on 4 x 5 m plots. Crops were irrigated with an overhead sprinkler system and irrigations were scheduled using neutron gauge measurements. Surrounding plots were also irrigated and advection was therefore limited. Data on crops, cultivars, planting and harvest dates, as well as row

spacings are summarised in Table 4.2. Agronomic practices commonly used in the area were adopted. The field was ploughed (0.3 m deep) and a rotavator was used to prepare 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 beetroot received a topdressing of 112 kg N 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, two days 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). Towards the end of December, four varieties of sweet-corn, two varieties of bush beans and the runner beans received a topdressing of 84 kg N ha^{-1} in the form of LAN (28). Before planting, all summer vegetables were sprayed with Dual at 2 ℓ ha^{-1} for weed control. The eggplant, green and chilli pepper, as well as three varieties of tomato were occasionally sprayed with lambda-cyhalothrin (Karate) plus dematon-s-methyl (Metasystox) for pest control.

Table 4.1 : Soil chemical and physical properties (Roodeplaat – Dept of Agriculture)

Property		Top soil 0 – 20 cm	Sub-soil 20 – 50 cm
P (Bray) (mg kg^{-1})		16.2	2.6
Ammonium acetate extractable (mg kg^{-1})	K	209	-
	Ca	912	-
	Mg	242	-
Resistance (Ohm)		1800	-
pH (H_2O)		7.26	7.11
Clay (%)		27	31

Table 4.2: Planting and harvest dates, and row spacings for six winter and nineteen summer vegetable cultivars (Roodepaat, 1996/97)

Crop	Planting date	Final harvest date	Row spacing (m)
Onions (*Allium cepa* cv. Mercedes)	2 May 1996*	20 Sept. 1996	0.15 x 0.2
Cabbage (*Brassica oleracea* cv. Grand Slam)	2 May 1996*	20 Sept. 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 Sept. 1996	0.4 x 0.5
Swiss Chard (*Beta vulgaris* cv. Ford Hook Giant)	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 Dec. 1996	5 Feb. 1997	1.0
Sweet-corn (*Zea mays Saccharata* cv. Paradise)	12 Dec. 1996	5 Feb. 1997	1.0
Sweet-corn (*Zea mays Saccharata* cv. Dorado)	9 Dec. 1996	12 Feb. 1997	1.0
Beans bush (*Phaseolus vulgaris* cv. Provider)	12 Nov. 1996	20 Jan. 1997	1.0
Beans bush (*Phaseolus vulgaris* cv. Bronco)	27 Nov. 1996	27 Jan. 1997	1.0
Beans runner (*Phaseolus multiflorus* cv.Lazy Housewife)	27 Nov. 1996	12 Feb. 1997	1.0
Pumpkin (*Cucurbita pepo* cv. Miniboer)	12 Nov. 1996*	5 Feb. 1997	1.0 x 0.5
Pumpkin (*Cucurbita pepo* cv. Minette)	12 Nov. 1996*	5 Feb. 1997	1.0 x 0.5
Marrow (*Cucurbita maxima* cv. Long White Bush)	12 Nov. 1996*	5 Feb. 1997	1.0 x 0.5
Marrow (*Cucurbita maxima* cv. President)	12 Nov. 1996*	5 Feb. 1997	1.0 x 0.5
Squash (*Cucurbita moschata* cv. Table Queen)	12 Nov. 1996*	5 Feb. 1997	1.0 x 0.5
Squash (*Cucurbita moschata* cv. Waltham)	12 Nov. 1996*	5 Feb. 1997	1.0 x 0.5
Tomato table (*Lycopersicon esculentum* cv. Zeal)	29 Nov. 1996*	20 Feb. 1997	1.0 x 0.5
Tomato process. (*Lycopersicon esculentum* cv. P747)	29 Nov. 1996*	20 Feb. 1997	1.0 x 0.5
Tomato process (*Lycopersicon esculentum* cv. HTX14)	29 Nov. 1996*	20 Feb. 1997	1.0 x 0.5
Eggplant (*Solanum melongena* cv. Black Beauty)	19 Dec. 1996*	4 Mar. 1997	1.0 x 0.5
Green pepper (*Capsicum annuum* cv. King Arthur)	19 Dec. 1996*	4 Mar. 1997	1.0 x 0.5
Chilli pepper (*Capsicum annuum* cv. Super Cayenne)	19 Dec. 1996*	4 Mar. 1997	1.0 x 0.5
* Transplanted			

4.4 FIELD MEASUREMENTS

Soil water content (WC) was measured with a neutron water meter, Model 503DR CPN Hydroprobe (Campbell Pacific Nuclear, California, USA). The neutron water meter was calibrated for the site and weekly readings were taken in the middle of each plot for 0.2 m soil layers down to 1.0 m. At the same positions, rain gauges were installed in order to measure amounts of irrigation water and rainfall. Neutron probe readings were used to schedule irrigations weekly. Irrigations were performed to refill the soil profile up to field capacity for the plot where the highest soil water deficit was measured. In this way, crop water stress was avoided, but drainage occurred for some plots.

Radiation fractional interception (FI) of photosynthetically active radiation (PAR) was measured weekly with a Decagon sunfleck ceptometer (Decagon, Pullman, Washington, USA), making one reference reading above the canopy and 10 readings beneath it. Growth analyses were carried out fortnightly, by sampling 1 m^2 of plant material at representative sites, with no replications due to small plot size. Harvestable fresh mass was measured directly after sampling, and dry matter of plant organs after drying in an oven at 60 ^{0}C for 4 to 5 days. Leaf area was measured with an LI 3100 leaf area meter (LiCor, Lincoln, Nebraska, USA) and leaf area index (LAI) calculated from the data. Root depth was estimated during the growing season from WC measurement. Phenological development was also monitored for each crop.

Weather data were recorded using an automatic weather station (Mike Cotton Systems, Cape Town, South Africa). The following weather data were collected:

- Solar radiation with an MCS 155-1 sensor (MC Systems, Cape Town, RSA);
- Rainfall with an Ota Keiki Deisakusho tipping bucket rain gauge; and
- Wet and dry bulb temperature with MCS 152 thermistors.

Hourly averages were stored with an MCS 120-02 EX data logger. The weather station was located a few hundred metres from the trial site.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 GROWTH ANALYSIS

The six winter vegetables grew well on the field except for lettuce which showed signs of soft rot and as a result periodic harvests had to be terminated earlier than in other crops. This can explain the importance of choice of irrigation system for a particular crop, as Robinson & McCoy (1965) also found that lettuce grown under sprinkler irrigation tends to have soft rot problems. The dry winter season presented favourable conditions for the other vegetable crops. In summer vegetables, the accumulated dry matter of different plant components showed an overall tendency to increase with age of the stand until the stage of dry matter partitioning to fruits when mostly fruit dry matter increased. It was, however, difficult to accurately measure fruit dry mass for some of the Cucurbitae and Solanaceous vegetables as fruits were harvested by intruders during the growing season, and due to spatial variability. For these crops, only data until the reproductive stage commenced were used to determine specific crop growth parameters. The leaf dry matter in almost all summer crops increased dramatically until the third month (depending on thermal time requirements for each crop), when it started to drop because of senescence. The harvestable dry matter, on the other hand, increased until harvest indicating that most of the dry matter was being partitioned to the harvestable portion.

Generally, the fractional interception of PAR increased in proportion to leaf area until the reproductive stage, when PAR started to be reflected by dead leaves. Dry matter production pattern and partitioning into plant organs followed a similar pattern in crops that have a similar growth habit and canopy structure, e.g. in cabbage and lettuce, or in carrots and beetroot. There were differences in sweet-corn varieties in terms of height and yields. The runner beans grew very tall, reaching a height of about 2 metres. This can be attributed to the type of cultivar and the stand. Spatial variability in fruit production might have resulted in sampling errors in cucurbits and tomatoes. The yields of the vegetables, when converted to fresh yield using percentage of water in harvestable part, were good and consistent with commercial production.

5.2 CROP GROWTH PARAMETERS

One aim of this study was to determine crop specific growth parameters for SWB and this section outlines how the following parameters were determined. Table 5.1 reviews values of crop parameters suggested as model inputs.

5.2.1 Canopy radiation extinction coefficient

Canopy radiation extinction coefficients have been calculated using field measurements of LAI and FI. They were calculated adopting this formula (Annandale, *et al.*, 1999):

$$FI = 1 - e^{-K\,LAI} \tag{78}$$

The canopy radiation extinction coefficient calculated from FI measurements with the ceptometer refers to the range of photosynthetically active radiation (PAR: 0.4 - 0.7 µm). The canopy radiation extinction coefficient for PAR (K_{PAR}) can be used to calculate photosynthesis as a function of intercepted PAR. A canopy extinction coefficient for total solar radiation (K_{solar}) is, however, required for predicting radiation-limited dry matter production (Monteith, 1977), and for partitioning of evapotranspiration (ET) into evaporation (E) and transpiration (T) in the soil water balance (Ritchie, 1972; Campbell & Diaz, 1988). The procedure suggested by Campbell & van Evert (1994) was used to convert K_{PAR} into K_{solar}:

$$K_{bd} = K_{PAR} / a_p^{\,0.5} \tag{79}$$

$$K_{solar} = K_{bd}\,((a_n \cdot a_p)^{0.5})^{0.5} \tag{80}$$

where : K_{bd} - Canopy radiation extinction coefficient for " black " leaves ($_b$), and for diffuse ($_d$) radiation.

a_p - Leaf absorptance in the PAR spectrum.

a_n - Leaf absorptance in the near infrared spectrum (NIR : 0.7 - 3 µm).

The value of a_p was assumed to be 0.8, whilst a_n was assumed to be 0.2 (Goudriaan, 1977)

Table 5.1: Specific crop growth parameters included in the SWB database

Crop parameters	Crop			
	Onions (cv. Mercedes)	Cabbage (cv.Grand Slam)	Carrots (cv. Kuroda)	Beetroot (cv.Crimson Globe)
Canopy radiation extinction coefficient[1]	0.75	0.83	1.31	0.93
Corrected dry matter-water ratio (Pa)[1]	7	9	7	9
Radiation conversion efficiency (kg MJ^{-1})[1]	0.0015	0.0016	0.0008	0.0016
Base temperature (°C)[2]	7.2	4.4	7.2	4.4
Temperature for optimum growth (°C)[3]	20	15	15	15
Cutoff temperature (°C)[2]	29.4	23.9	23.9	23.9
Emergence day degrees (d °C)[1]	0	0	100	100
Day degrees at end of vegetative growth (d °C)[1]	450	600	600	800
Day degrees for maturity (d °C)[1]	837	1234	1067	1509
Transition period day degrees (d °C)[3]	10	10	10	10
Day degrees for leaf senescence (d°C)[3]	837	1234	1067	1509
Maximum crop height (m)[4]	0.5	0.3	0.3	0.4
Maximum root depth (m)[1]	0.8	0.8	0.8	0.8
Fraction of total dry matter translocated to harvestable portion[3]	0.5	0.5	0.5	0.5
Canopy storage (mm)[3]	1	1	1	1
Leaf water potential at maximum transpiration (kPa)[3]	-1500	-1500	-1500	-1500
Maximum transpiration (mm d^{-1})[3]	9	9	9	9
Specific leaf area (m^2 kg^{-1})[1]	8.11	6.93	15.27	10.09
Leaf-stem partition parameter (m^2 kg^{-1})[1]	1.12	0.44	0.45	1.44
Total dry matter at emergence (kg m^{-2})[3]	0.007	0.0019	0.0007	0.0019
Fraction of dry matter partitioned to roots[3]	0.2	0.2	0.2	0.2
Root growth rate (m^2 $kg^{0.5}$)[3]	7	3	4	5
Stress index[3]	0.95	0.95	0.95	0.95

1 - Calculated from field data
2 - Obtained from Knott (1988)
3 - Estimated
4 - Measured

Table 5.1: Specific crop growth parameters included in the SWB database

Crop parameters	Crop				
	Swiss chard (cv. Fort Hook Giant)	Chilli pepper (cv. Super Cayenne)	Eggplant (cv. Black Beauty)	Green pepper (cv. King Arthur)	Lettuce (cv. Great Lakes)
Canopy radiation extinction coefficient[1]	0.44	0.42	0.735	0.345	0.56
Corrected dry matter-water ratio (Pa)[1]	8	4.5	2.4	4.5	3.5
Radiation conversion efficiency (kg MJ^{-1})[1]	0.0002	0.00163	0.0009	0.0015	0.0014
Base temperature (°C)[2]	4.4	18.3	18.3	18.3	7.2
Temperature for optimum growth (°C)[3]	15	22.5	25.3	22.5	15
Cutoff temperature (°C)[2]	23.9	26.6	35	26.6	23.9
Emergence day degrees (d °C)[1]	50	0	0	0	0
Day degrees at end of vegetative growth (d °C)[1]	1509	150	150	150	300
Day degrees for maturity (d °C)[1]	1509	350	350	350	656
Transition period day degrees (d °C)[3]	10	200	200	200	10
Day degrees for leaf senescence (d °C)[3]	1509	150	200	150	656
Maximum crop height (m)[4]	0.3	0.6	0.6	0.5	0.4
Maximum root depth (m)[1]	0.8	0.6	0.6	0.6	0.6
Fraction of total dry matter translocated to harvestable portion[3]	0.5	0.05	0.05	0.05	0.5
Canopy storage (mm)[3]	1	1	1	1	1
Leaf water potential at maximum transpiration (kPa)[3]	-1500	-1500	-1500	-1500	-1500
Maximum transpiration (mm d^{-1})[3]	9	9	9	9	9
Specific leaf area (m^2 kg^{-1})[1]	12.64	11.2	15.4	12.2	20.27
Leaf-stem partition parameter (m^2 kg^{-1})[1]	1.46	1.04	0.981	1.07	8.28
Total dry matter at emergence (kg m^{-2})[3]	0.003	0.0019	0.0019	0.0019	0.001
Fraction of dry matter partitioned to roots[3]	0.2	0.2	0.2	0.2	0.2
Root growth rate (m^2 $kg^{0.5}$)[3]	3	6	6	6	5
Stress index[3]	0.95	0.95	0.95	0.95	0.95

1 - Calculated from field data
2 - Obtained from Knott (1988)
3 - Estimated
4 - Measure

Table 5.1: Specific crop growth parameters included in the SWB database

Crop parameters	Crop			
	Marrow (cv. Long White	Marrow (cv.President)	Pumpkin (cv. Minette)	Pumpkin (Miniboer)
Canopy radiation extinction coefficient[1]	0.5	0.58	0.52	0.7
Corrected dry matter-water ratio (Pa)[1]	3	3	5.5	5.5
Radiation conversion efficiency (kg MJ^{-1})[1]	0.0014	0.0014	0.001	0.0005
Base temperature (°C)[2]	10	10	10	10
Temperature for optimum growth (°C)[3]	21.1	21.1	21.1	21
Cutoff temperature (°C)[2]	32.2	32.2	32.2	32
Emergence day degrees (d °C)[1]	0	0	0	0
Day degrees at end of vegetative growth (d °C)[1]	250	400	400	200
Day degrees for maturity (d °C)[1]	1000	1000	1000	1000
Transition period day degrees (d °C)[3]	750	600	600	800
Day degrees for leaf senescence (d °C)[3]	300	400	300	400
Maximum crop height (m)[4]	0.65	0.6	0.7	0.6
Maximum root depth (m)[1]	0.8	1	0.8	0.8
Fraction of total dry matter translocated to harvestable portion[3]	0.05	0.05	0.05	0.1
Canopy storage (mm)[3]	1	1	1	1
Leaf water potential at maximum transpiration (kPa)[3]	-1500	-1500	-1500	-1500
Maximum transpiration (mm d^{-1})[3]	9	9	9	9
Specific leaf area (m^2 kg^{-1})[1]	16.6	11.6	16	18
Leaf-stem partition parameter (m^2 kg^{-1})[1]	1.3	1.18	1.1	1.1
Total dry matter at emergence (kg m^{-2})[3]	0.005	0.005	0.0019	0
Fraction of dry matter partitioned to roots[3]	0.2	0.2	0.2	0.2
Root growth rate (m^2 $kg^{0.5}$)[3]	4	4	5	5
Stress index[3]	0.95	0.95	0.95	1

1 - Calculated from field data
2 - Obtained from Knott (1988)
3 - Estimated
4 - measured

Table 5.1: Specific crop growth parameters included in the SWB database

Crop parameters	Crop				
	Runner beans (cv. Lazy Housewife)	Bush beans (cv.Bronco)	Bush beans (cv. Provider)	Squash (cv. Waltham)	Squash (cv.Table Queen)
Canopy radiation extinction coefficient[1]	0.329	0.792	0.792	0.946	0.706
Corrected dry matter-water ratio (Pa)[1]	6	6	2.5	3.5	3.5
Radiation conversion efficiency (kg MJ^{-1})[1]	0.00093	0.00122	0.00117	0.00036	0.00068
Base temperature (°C)[2]	10	10	10	10	10
Temperature for optimum growth (°C)[3]	18.3	18.3	18.3	21.1	21.1
Cutoff temperature (°C)[2]	26.6	26.2	26.6	32.2	32.2
Emergence day degrees (d °C)[1]	50	80	50	0	0
Day degrees at end of vegetative growth (d °C)[1]	600	300	400	400	400
Day degrees for maturity (d °C)[1]	950	700	800	1100	1000
Transition period day degrees (d °C)[3]	50	400	200	700	600
Day degrees for leaf senescence (d °C)[3]	450	250	300	500	400
Maximum crop height (m)[4]	2.3	0.5	0.5	0.3	0.4
Maximum root depth (m)[1]	0.6	0.6	0.4	0.8	0.8
Fraction of total dry matter translocated to harvestable portion[3]	0.05	0.05	0.05	0.05	0.05
Canopy storage (mm)[3]	1	1	1	1	1
Leaf water potential at maximum transpiration (kPa)[3]	-1500	-1500	-1500	-1500	-1500
Maximum transpiration (mm d^{-1})[3]	9	9	9	9	9
Specific leaf area (m^2 kg^{-1})[1]	23.1	12.2	16.8	9.9	9.7
Leaf-stem partition parameter (m^2 kg^{-1})[1]	0.8	0.57	1.01	1	1.2
Total dry matter at emergence (kg m^{-2})[3]	0.0019	0.0019	0.0019	0.005	0.005
Fraction of dry matter partitioned to roots[3]	0.2	0.2	0.2	0.2	0.2
Root growth rate (m^2 $kg^{0.5}$)[3]	4	4	4	5	4
Stress index[3]	0.95	0.95	0.95	0.95	0.95

1 - Calculated from field data
2 - Obtained from Knott (1988)
3 - Estimated
4 - Measured

Table 5.1: Specific crop growth parameters included in the SWB database

Crop parameters	Crop			
	Sweet corn (cv. Cabaret)	Sweet corn (cv.Dorado)	Sweet corn (cv. Jubilee)	Sweet corn (cv. Paradise)
Canopy radiation extinction coefficient[1]	0.5	0.4	0.36	0.3
Corrected dry matter-water ratio (Pa)[1]	9	8	9	9
Radiation conversion efficiency (kg MJ^{-1})[1]	0.0026	0.0027	0.0038	0.0022
Base temperature (°C)[2]	5	5	5	5
Temperature for optimum growth (°C)[3]	20	20	20	20
Cutoff temperature (°C)[2]	30	30	30	30
Emergence day degrees (d °C)[1]	50	50	50	50
Day degrees at end of vegetative growth (d °C)[1]	800	700	800	800
Day degrees for maturity (d °C)[1]	1100	1150	1400	1400
Transition period day degrees (d °C)[3]	200	200	200	200
Day degrees for leaf senescence (d °C)[3]	400	350	800	500
Maximum crop height (m)[4]	1.7	1.7	2.1	2.1
Maximum root depth (m)[1]	1	0.8	0.6	0.6
Fraction of total dry matter translocated to harvestable portion[3]	0.05	0.05	0.05	0.05
Canopy storage (mm)[3]	1	1	1	1
Leaf water potential at maximum transpiration (kPa)[3]	-1500	-1500	-1500	-1500
Maximum transpiration (mm d^{-1})[3]	9	9	9	9
Specific leaf area (m^2 kg^{-1})[1]	15.1	17.8	14.1	16.6
Leaf-stem partition parameter (m^2 kg^{-1})[1]	2	1.5	2	2
Total dry matter at emergence (kg m^{-2})[3]	0.0019	0.0019	0.0019	0.0019
Fraction of dry matter partitioned to roots[3]	0.2	0.2	0.2	0.2
Root growth rate (m^2 $kg^{0.5}$)[3]	4	4	4	4
Stress index[3]	0.95	0.95	0.95	0.95

1 - Calculated from field data
2 - Obtained from Knott (1988)
3 - Estimated
4 - Measured

Table 5.1: Specific crop growth parameters included in the SWB database

Crop parameters	Crop		
	Tomato (cv. HTX14)	Tomato (cv.P747)	Tomato (cv. Zeal)
Canopy radiation extinction coefficient[1]	0.32	0.32	0.26
Corrected dry matter-water ratio (Pa)[1]	7	7	7
Radiation conversion efficiency ($kgMJ^{-1}$)[1]	0.0022	0.0018	0.0016
Base temperature (°C)[2]	15.3	15.3	15.3
Temperature for optimum growth (°C)[3]	22.5	22.5	22.5
Cutoff temperature (°C)[2]	26.6	28.6	26.6
Emergence day degrees (d °C)[1]	0	0	0
Day degrees at end of vegetative growth (d °C)[1]	50	100	100
Day degrees for maturity (d °C)[1]	330	330	330
Transition perod day degrees (d °C)[3]	280	230	230
Day degrees for leaf senescence (d °C)[3]	130	100	100
Maximum crop height (m)[4]	0.45	0.65	0.6
Maximum root depth (m)[1]	0.8	0.8	0.6
Fraction of total dry matter translocated to harvestable portion[3]	0.05	0.05	0.05
Canopy storage (mm)[3]	1	1	1
Leaf water potential at maximum transpiration (kPa)[3]	-1500	-1500	-1500
Maximum transpiration (mm d^{-1})[3]	9	9	9
Specific leaf area ($m^2\ kg^{-1}$)[1]	14.3	12.1	15.5
Leaf-stem partition parameter ($m^2\ kg^{-1}$)[1]	2	2	2
Total dry matter at emergence ($kg\ m^{-2}$)[3]	0.005	0.005	0.005
Fraction of dry matter partitioned to roots[3]	0.2	0.2	0.2
Root growth rate ($m^2\ kg^{0.5}$)[3]	4	4	4
Stress index[3]	0.95	0.95	0.95

1 - Calculated from field data
2 - Obtained from Knott (1988)
3 - Estimated
4 - Measured

Measurements of LAI and FI have been used to calculate canopy radiation extinction coefficient. Only data until leaf senescence were considered in the calculation of K_{solar}. K_{solar} values for these vegetable crops are presented in Table 5.1. Figure 1 shows an example of LAI-FI function for swiss chard, for other crops refer to Appendix A. FI values measured with the ceptometer are highly dependent on solar orientation. It is important to note that slight differences in spacing between rows, and sampling during different periods of the day can cause variability in FI measured values. Ideally, measurements of FI should be made at the same sampling positions and at the same time of the day in order to avoid solar orientation effects (Barnard, *et al*, 1998). In practice, however, it is not always possible to achieve this due to logistical reasons. K values have been used in the model for predicting radiation-limited dry matter production, and for partitioning of E and T in the soil water balance. 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.

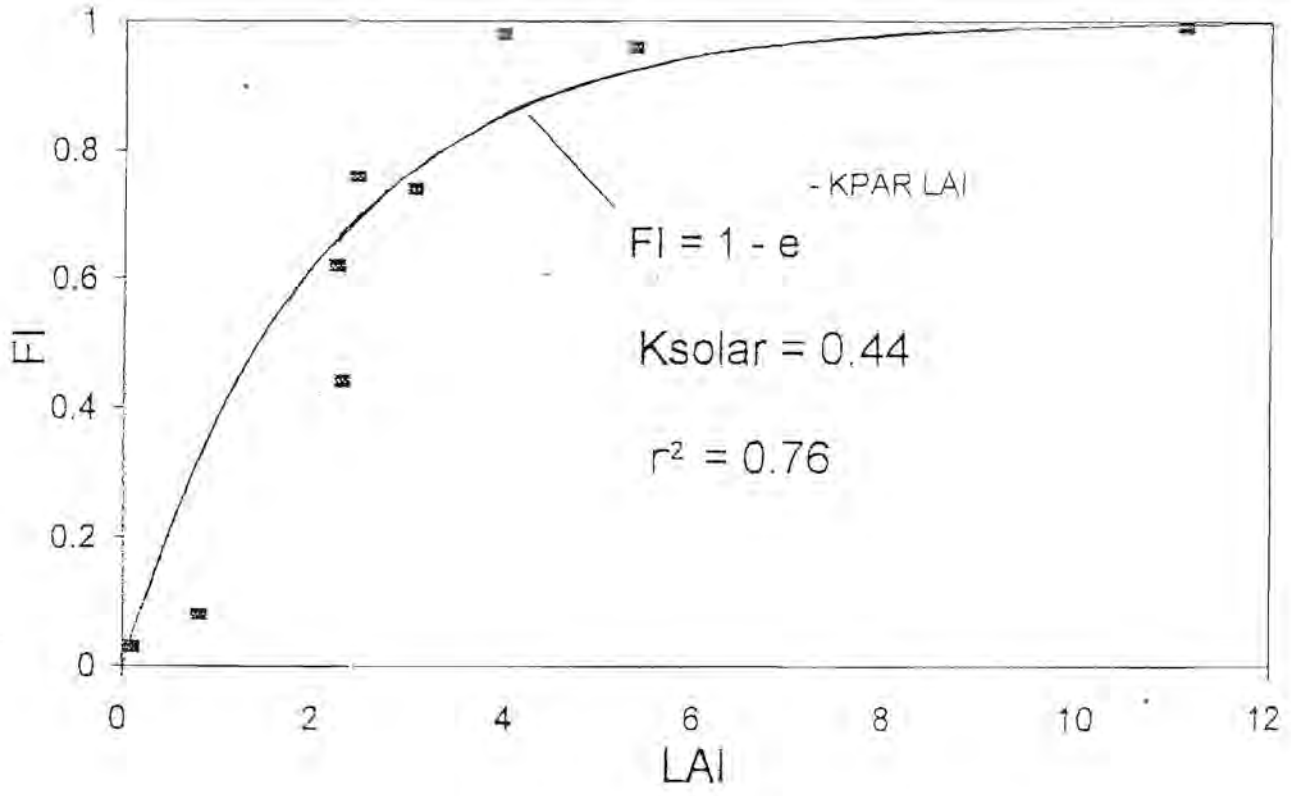

Figure 1 . Correlation between leaf area index (LAI) and radiation fractional interception (FI) for swiss chard ($FI = 1 - e^{-KPAR\ LAI}$). Canopy radiation extinction coefficient (K_{SOLAR}) and coefficient of determination of the exponential regression function (r^2) are shown.

5.2.2 Dry matter-transpiration ratio (DWR)

DWR is the crop specific parameter that determines the crop water use efficiency. Tanner & Sinclair (1983) recommended that the relation between dry matter production and crop transpiration should be corrected to account for atmospheric conditions, in particular for vapour pressure deficit (VPD). DWR was therefore calculated as follows:

$$DWR = (DM\ VPD) / ET \tag{81}$$

where : DM - dry matter production (kg m^{-2})

ET - evapotranspiration (mm)

Above ground DM was measured periodically during growth analyses. ET was calculated weekly as follows:

$$ET = P + I - R_o - D - \Delta Q \tag{82}$$

where : P - Precipitation (mm)

I - Irrigation (mm)

R_0 - Runoff (mm)

D - Drainage (mm)

ΔQ - Soil water storage (mm)

R_0 was assumed to be negligible as no high intensity rain occurred and the irrigation system application rate did not exceed the soil infiltration rate. SWB was used to estimate D. A positive sign for ΔQ indicates a gain in soil water storage. ΔQ was estimated from soil water content measurements with the neutron water meter.

VPD represents the seasonal average vapour pressure deficit in Pascals (Pa). Daily average VPD was calculated from measurements of T_w and T_d adopting a procedure recommended by the FAO (Smith, 1992):

$$VPD = [e_s T_{max} + e_s T_{min}] / 2 - e_a \quad (83)$$

where : e_s - Saturated vapour pressure (kPa)

T_{max} - Maximum daily temperature (^{0}C)

T_{min} - Minimum daily temperature (^{0}C)

e_a - Actual vapour pressure (kPa)

e_s at T_{max} and T_{min} was calculated by replacing air temperature (T_a) with T_{max} and T_{min} in the following equation (Tetens, 1930):

$$e_s = 0.611 \exp [17.27 T_a / (T_a + 237.3)] \quad (84)$$

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

$$e_a = e_s (T_w) - 0.0008 (T_d - T_w) P_a \quad (85)$$

where P_a is atmospheric pressure in kPa, and e_s at T_w was calculated using T_w (Eq. 84). P_a was calculated adopting the following formula (Burman, Jensen and Allen, 1987):

$$P_a = P_o [(T_o - \alpha \, Alt) / T_o]^{g/(\alpha Rg)} \quad (86)$$

where : P_o - Standard atmospheric pressure at sea level (101.3 kPa)

T_o - Standard temperature at sea level (293 K)

α - Adiabatic lapse rate (K m^{-1})

Alt - Altitude above sea level (m)

g - Gravitational acceleration (9.8m s^{-1})

Rg - Specific gas constant for dry air (286.9 J kg^{-1} K^{-1})

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

Evaporation from the soil surface should not be included in the calculation of DWR as it does not contribute to the building of dry material. The portion of soil water lost by evaporation can be substantial in vegetable crops particularly at the beginning of the growing season when canopy cover is sparse. DWR values had therefore to be corrected. Model simulations of crop growth have been used to separately calculate evaporation (E) and transpiration (T) and correct DWR values. Calculated values of DWR for all vegetables are presented in Table 5.1. The DWR values represent the lower limit because root growth was not measured and root dry matter was therefore not included in dry matter of plant organs except for the harvestable portion of root crops.

The water use efficiency of summer vegetables was generally high. Sweet-corn and tomato had substantially higher water-use efficiencies (DWR) compared to other summer vegetables. Amongst winter vegetables, cabbage and beetroot had the highest water use efficiency, followed in order by spinach, carrots, onions and lettuce.

5.2.3 Radiation conversion efficiency

Radiation conversion efficiency was calculated adopting the following formula (Monteith, 1977):

$$E_c = DM / \sum (T_f FI R_s) \quad (87)$$

where : T_f - Temperature factor for light-limited crop growth ; and,

R_s - Total solar radiation (MJ m^{-2} day^{-1})

DM, R_s and FI for solar radiation were measured. Root dry matter was not measured and therefore not included in the term DM. The harvestable portion of the root crops was, however, included in the term DM. T_f was calculated as follows:

$$T_f = (T_{avg} - T_b) / (T_{lo} - T_b) \quad (88)$$

where : T_b - Base temperature (°C)

T_{lo} - Temperature for optimum light-limited growth (°C)

T_b and T_{lo} are input parameters. T_{lo} was estimated.The upper limit of T_f was set to 1.

The model uses dry matter production as the minimum of water-supply or radiation-limited dry matter. Radiation conversion efficiency is a crop specific parameter, which is used in the model to calculate dry matter production under conditions of radiation-limited growth. Figure 2 shows an example of TDM (top dry matter production) values as a function of the term Σ (T_f FI R_s) for swiss chard. For other crops refer to Appendix B. The slope of the regression line represents the radiation conversion efficiency. The high squared correlation coefficients indicate that E_c is a relatively constant and predictable parameter under conditions of good water supply. Calculated E_c values for the vegetable crops are presented in Table 5.1. Only data until leaf senescence were used to calculate E_c. E_c values for onions, carrots and beetroot were generally in the range of those reported by Monteith (1988) for root crops. 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.

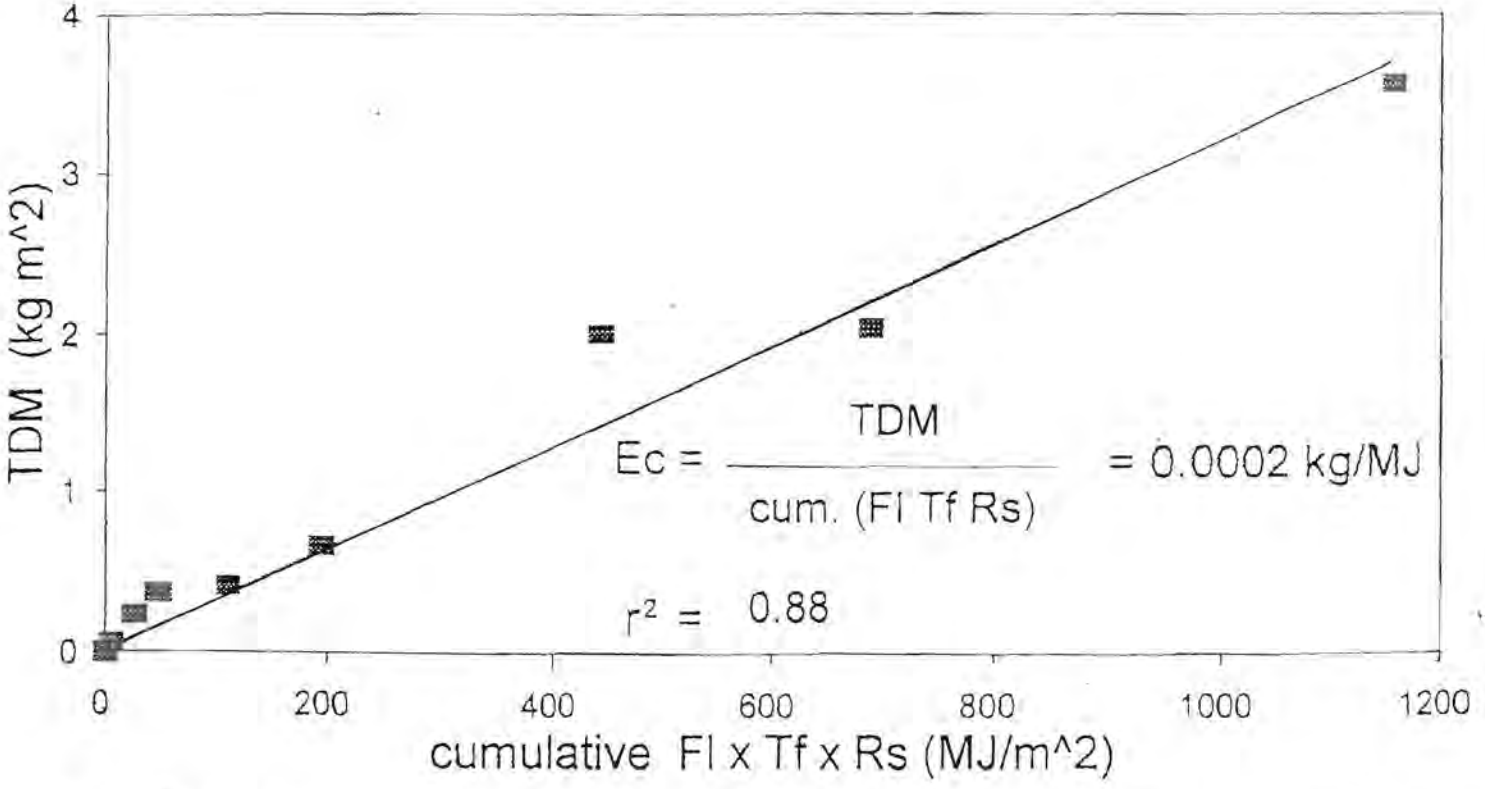

Figure 2: Dry matter production of swiss chard as a function of the cumulative product of temperature factor (T_f) for light-limited crop growth, solar radiation fractional interception (FI) and total incoming solar radiation (R_s). Radiation conversion efficiency (Ec) in kg/MJ and coefficient of determination of the linear function are shown.

5.2.4. Specific leaf area and stem-leaf partitioning parameter

DM is preferentially partitioned to reproductive sinks and roots. The remaining DM is partitioned to canopy dry matter (CDM - dry matter of leaves and stems). SWB calculates leaf dry matter (LDM) and stem dry matter (SDM) as follows:

$$LDM = CDM / (1 + p\ CDM) \text{ and} \quad (89)$$

$$SDM = CDM - LDM \quad (90)$$

LDM is used to calculate LAI as follows:

$$LAI = SLA\ LDM \quad (91)$$

where SLA is the specific leaf area in $m^2\ kg^{-1}$. SLA and p are parameters describing the morphology of a specific crop. SLA and 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 until leaf senescence. The partitioning parameter (p) was determined as a function of SLA, LAI and CDM. Caution should be exercised in the adoption of constant values for SLA and p in crop modelling, as these parameters may vary considerably during the growing season (Jovanovic *et al.*, 1999).

5.2.5 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 intervals. Maximum rooting depths (RD_{max}) for these vegetable crops are shown in Table 5.1. Values of RD_{max} were generally in the range of those reported by Green (1985). RD_{max} ranged from 40 cm for bush beans, 60 cm for chilli pepper, eggplant, green pepper, lettuce and runner beans, 80 cm for beetroot, cabbage, carrots, onions, pumpkin, squash, spinach and tomatoes, to 100 cm for marrows. In

sweet-corn, the rooting depth varied with cultivar from 60 cm for Paradise to 100 cm for Cabaret. These figures give an indication of the rooting depths for the various vegetables, but can differ from one soil and growing condition to another.

Growing day degrees (GDD) was determined from daily average temperature (T_{avg}), after Monteith (1977):

$$GDD = (T_{avg} - T_b)\,\Delta t \qquad (92)$$

where T_b is the base temperature in °C and Δt is one day. For some crops, values of T_b recommended by Knott (1988) were used. 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_{cutoff}). T_{cutoff} values recommended by Knott (1988) were used. GDD required for emergence was calculated for crops planted by direct seeding (carrots, beetroot, spinach, sweet-corn, beans etc.), whilst GDD until harvest was determined for all crops. Optimum and cut-off temperatures for sweet-corn were estimated by calibration against measurements of air temperature and phenology. GDD for the transition period between vegetative and reproductive growth as well as for leaf senescence were estimated by calibration against field measurements of crop growth, phenology and water use for all crops.

5.3 Yield and soil water balance

Harvestable dry matter as well as fresh yield at the end of the season are presented in Table 5.2. Root dry matter was not measured except in the case of root crops. HDM and fresh yield are not available for those crops that were harvested several times during the growing season by intruders. Yield variations were observed in different cultivars of sweet-corn and bush beans. The fresh yields of winter vegetables were consistent with those normally obtained in commercial production. Observed crop water use per crop is not shown in Table 5.2 because it was difficult to determine evaporation, transpiration and drainage from neutron probe measurements. Measurements of soil water deficit with the neutron probe were, however, used to calibrate the SWB model (Section 5.4) in order to estimate the soil water balance components. Seasonal soil evaporation, crop transpiration and drainage simulated with the SWB model,

Table 5.2. Yield and soil water balance for winter and summer vegetable crops (Roodeplaat, 1996/97)

Crop	Measured Harvestable dry matter ($kg.m^{-2}$)	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)
Onion	0.31	2.84	245	114	356	289	13
Cabbage	0.92	4.29	160	191	351	289	13
Carrots	0.76	5.76	204	179	383	348	30
Beetroot	0.76	4.97	285	77	362	348	30
Lettuce	0.2	1.85	212	80	292	241	30
Swisschard	0.56	6.14	205	172	377	348	30
Bushbean (cv. Bronco)	0.17	1.11	157	137	294	369	100
Bushbean (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. L. W. 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 (cv. HTX14)	-	-	207	112	319	390	113
Tomato (cv. P747)	-	-	213	70	283	390	133
Tomato (cv. Zeal)	-	-	212	75	287	390	132

as well as measured irrigation and rainfall are shown in Table 5.2. 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. Crop water use of winter vegetables varied from around 280 mm for lettuce to 390 mm for carrots and swisschard. Lettuce had the lowest water demand probably because it was harvested earlier in the growing season. Seasonal crop

water use of summer vegetables was estimated to vary from just less than 200 mm for green pepper to around 400 mm for pumpkin (cv. Miniboer). Water use was estimated to be around 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. The figures presented in Table 5.2 give an indication of seasonal crop water requirements that farmers could expect from these vegetable species in Gauteng. Localized irrigation (micro, or drip) could possibly reduce the soil evaporation component of the soil water balance, and improve water use efficiency.

5.4 Model simulations

Model simulations were tested against observed field measurements of rooting depth (RD), leaf area index (LAI), top dry matter (TDM), and harvestable dry matter (HDM) as well as soil water deficit. An example of model output for onion is shown in Figure 3 (for other crops, refer to Appendix C). The soil water balance graph (top graph) of SWB includes the following information:

- Irrigation and rainfall input data in the top part of the graph.
- Simulated soil water deficit to field capacity in the bottom part of the graph.
- The horizontal line on the graph represents the field capacity level.
- Simulated profile soil water deficit as well as root zone deficit to field capacity at the end of the simulation in the top right corner of the graph.
- The output summary below the graph shows: planting date, irrigation system, crop, irrigation timing and amount, type of model, seasonal rainfall, irrigation, transpiration, evaporation, drainage, canopy interception, runoff, saturated profile soil water content, soil water content at field capacity, allowable depletion at the end of the simulation, and mass balance error.
- The vertical bars in the top part of the graph represent the sum of rainfall and irrigation. For these simulations, the output parameter "Precip" shown in the summary below the soil water balance graphs represents the sum of seasonal rainfall and irrigation. Rainfall plus irrigation was measured with rain gauges read by operators weekly. It was, therefore, not possible to differentiate rainfall and irrigation amounts.

Measured values are represented with symbols whilst simulations are shown as solid lines. For all winter vegetables but swiss chard, much lower values of dry matter production were predicted with SWB

at the end of the growing season when compared to measured data (Figure 3 and Appendix C)). It is possible that plant samples were not properly dried in the oven and these data were omitted in the determination of crop growth parameters. For cucurbits and solanaceous vegetables, it was not possible to obtain a reliable simulation of dry matter production as fruits were stolen during the growing season. During the winter season, it is not clear why the model overestimated soil water deficit during the mid-season stage of some crops as fractional interception of radiation was simulated accurately by the model. A possible reason could have been capillary rise, which reduced the actual soil water deficit. Capillary rise cannot be accounted for in the cascading water movement of SWB. The crops did not show any visual symptoms of water stress during the mid-season stage. Generally a good fit between simulations and measured data was observed for all crops.

It is important for developers of growth simulation models to test models' accuracy. Model simulations were tested against observed field data of LAI, RD, HDM & TDM, and water deficit. The statistical parameters used were:

N - Number of observations

r^2 - Coefficient of determination

D - Index of agreement of Willmott (1981)

RMSE - Root of the mean square error

MAE - Mean absolute error expressed as a percentage of the observed values

These parameters were recommended by de Jager (1994) to assess model accuracy. He also recommended as model prediction reliability criteria that r^2 and D should be > 0.8 whilst MAE should be $< 20\%$. The parameters of the statistical analysis are shown in output graphs (Figure 3 and Appendix C). This allows quick, efficient and quantitative evaluation of model performance.

In this study, field data were used to calibrate the SWB model for 25 vegetable cultivars. The model should now be validated using independent data sets in order to test its applicability for different environmental conditions.

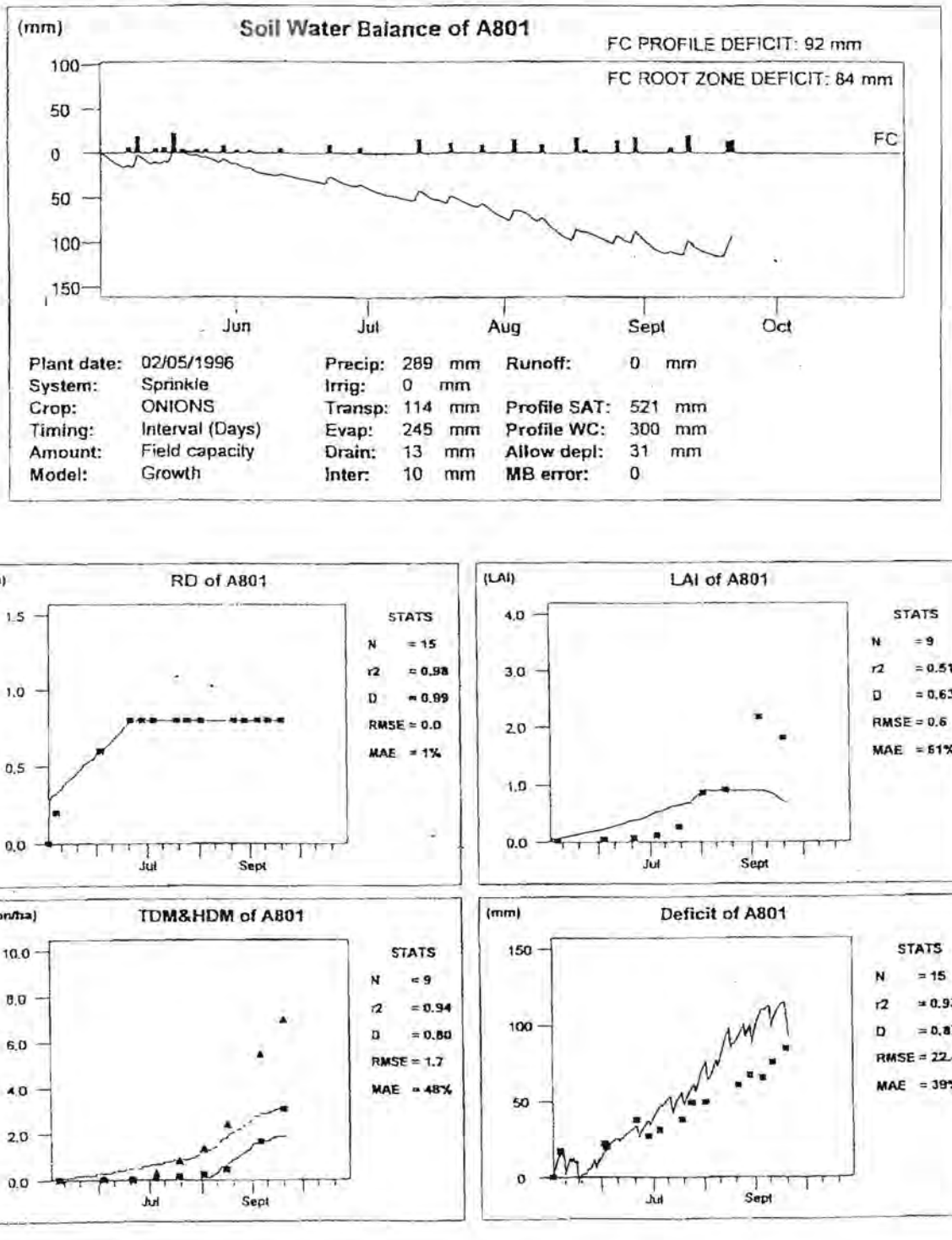

Figure 3 : Soil water balance output graph of SWB (top graph), simulated (solid line) and measured (symbols), root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit for onions.

CHAPTER 6

CONCLUSIONS

All over the world, effort is made to produce crops in the most economically profitable way. The same equally applies to vegetable crops. Vegetables are amongst the most economically important agricultural crops. The challenge is to manage inputs in a way that will give better returns to the farmer. One of the most important inputs in vegetable production is irrigation, particularly as it relates to yield and yield components. The objectives of this study centred on determining specific crop growth coefficients, the estimation of rooting depth, and determination of seasonal crop water use of different vegetable crops. Growth analysis and water balance data for the selected vegetable crops have been obtained, from which growth model parameters were determined. A database of specific crop growth parameters required by the SWB model has been generated. These crop parameters will now enable accurate model simulations, which will eventually increase water use efficiency and reduce water usage on farms. These parameters could also be used in other models. Some modelling approaches may, however, require the calculation of other parameters and, for this purpose, growth analysis, soil water and weather data are presented in Appendices D and E. Differences in cultivars could affect the crop growth parameters. High canopy extinction coefficients were calculated for horizontal leaf canopies (bush beans, eggplant, pumpkin and squash) due to their particular canopy structure, which reaches full canopy cover at low LAI. During the winter season, cabbage and beetroot had the highest water use efficiency (DWR) followed in order by spinach, carrots, onions and lettuce. Sweet-corn and tomato had substantially higher water use efficiencies compared to the other summer 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.

Maximum rooting depth of these vegetables was estimated from measurements of soil water content with the neutron meter. Values of maximum rooting depth were generally in the range of those reported by Green (1985), ranging from 40 cm for bush beans to 100 cm for sweet-corn.

The SWB model was successfully calibrated for six winter and nineteen summer vegetable cultivars, and used to estimate seasonal water requirements that farmers could expect from these vegetables grown in Gauteng. Crop water use of winter vegetables varied from around 280 mm for

lettuce to 390 mm for carrots and swisschard. Lettuce had the lowest water demand because it was harvested earlier in the growing season. Seasonal crop water use of summer vegetables was estimated to vary from just less than 200 mm for green pepper to around 400 mm for pumpkin (cv. Miniboer). Water use was estimated to be around 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. These cultivars are fairly new and they show some promise for commercial production. Due to the mechanistic, dynamic modelling approach followed, accurate estimates of irrigation requirements for these crops with SWB are expected under a wide range of soil and climatic conditions, but this needs to be tested using independent data sets.

In many developing countries and rural communities, crop yields per unit of irrigated land are low. The causes of low yields usually are complex and often are the results of both technical and non-technical factors. A major irrigation factor that adversely affects crop yields is the untimely delivery of irrigation water. Yields are reduced when the amount of water needed by the crop between irrigations is greater than that which can be extracted from the soil because of limited root systems or soil-water holding capacities. Substantial reductions in yield due to plant water stress at critical growth stages may occur even though the total amount of water delivered during the cropping season may be adequate. Basically, water must be made available to farms in proportion to the average rate of evapotranspiration (ET) expected from well-watered crops. The challenge in developing countries and rural communities is to gain a better understanding of crop growth and water use. Water is in high demand in South Africa, so it is imperative that the use of irrigation water be optimized. Further development of the SWB model is necessary in order to make it more user-friendly to also address the needs of small scale irrigation farmers. The valuable contribution arising from this study was the guidelines developed for farmers regarding the amount of irrigation water to apply to vegetable crops in Gauteng. The efficiency of irrigation water could thus be improved if these guidelines are followed, and a higher yield produced per unit of irrigation water applied.

It is predicted that irrigation farmers will have to pay a higher price for their water in the future and there will thus be a need to optimize the economics of irrigation (Backeberg, 1989). In 1987, two of the priorities that were classified as essential (KKBN, 1987) included the development of an irrigation scheduling strategy to minimise the negative effects of plant water stress during water deficit, and the development of crop growth simulation models for South African conditions with the emphasis on water-yield relationships. Of significance is that all this science must be related back to farmers, and so

technology transfer is of vital importance. The challenge is to improve communications between irrigation scientists, extension officers and farmers in implementing better irrigation systems and practices. Technology transfer is a slow process, but can be improved by modern communication and transportation systems.

CHAPTER 7

SUMMARY

A fundamental change has recently taken place in our conception of soil-plant-water relations, leading to a more dynamic and holistic approach. With the development of the Soil Water Balance (SWB) irrigation scheduling model in mind, two field experiments were set up at Roodeplaat (Gauteng Province, South Africa) during the 1996/97 growing seasons. The objectives of the study had three main focus areas:

(i) To determine specific crop growth coefficients for six winter and nineteen summer vegetable cultivars and include them in the crop growth parameter database of the SWB model. These coefficients are: dry-matter water ratio corrected for vapour pressure deficit, radiation conversion efficiency, canopy radiation extinction coefficient, specific leaf area and leaf-stem partition parameter.

(ii) To determine the rooting depth of different vegetable crops.

(iii) To determine seasonal crop water use of vegetables.

Crops were irrigated with overhead sprinklers and irrigations were scheduled using neutron gauge measurements. The following field measurements were taken:

(i) Soil water content was measured with a neutron water meter. Rain gauges were also installed to measure amounts of irrigation and rainfall.

(ii) Fractional interception (FI) of photosynthetically active radiation (PAR) was measured with a Decagon sunfleck ceptometer.

(iii) Growth analyses (dry matter of plant organs and leaf area index (LAI)) were carried out fortnightly by sampling 1 m^2 of plant material at representative sites.

(iv) Rooting depth was estimated during the growing season from soil water content measurements.

(v) Weather data were recorded using an automatic weather station.

One of the major achievements in this study was that several of the crop growth parameters required by SWB were successfully determined. Canopy radiation extinction coefficients have been calculated using field measurements of LAI and FI. Dry matter-water ratio (DWR) was calculated using

measured values of dry matter production and evapotranspiration. The calculated values of DWR were corrected to account for vapour pressure deficit. Radiation conversion efficiency (E_c) was calculated from solar radiation, dry matter production and canopy cover data. High squared correlation coefficients for E_c were calculated, indicating that E_c is a relatively constant and predictable parameter under conditions of good water supply. Values of maximum rooting depth ranged from 40 cm for bush beans to 100 cm for sweet-corn. Root depth was estimated from weekly measurements of soil water extraction with the neutron meter. Crop water use of winter vegetables varied from around 280 mm for lettuce to 390 mm for carrots and swisschard. Crop water use of summer vegetables was estimated to vary from 200 mm for green pepper to around 400 mm for cucurbits. Water use of beans, sweet-corn and tomato varied depending on cultivar.

Model simulations were tested against observed field measurements. Generally, a good fit between simulations and measured data was observed for all crops. A statistical analysis was used to test model accuracy and to calibrate the model. The model can now be tested and applied by commercial users and other agricultural scientists. Technology transfer will be central to the achievement of the latter.

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CHAPTER 9

APPENDICES

Appendix A : Canopy radiation extinction coefficient - Figures 1.1 to 1.5

Appendix B : Radiation conversion efficiency – Figures 2.1 to 2.5

Appendix C : Model simulations and statistical analysis – Figures 3.1 to 3.25

Appendix D : Weather data for the duration of the two trials

Appendix E : Growth analyses data

Appendix A : Canopy radiation extinction coefficient

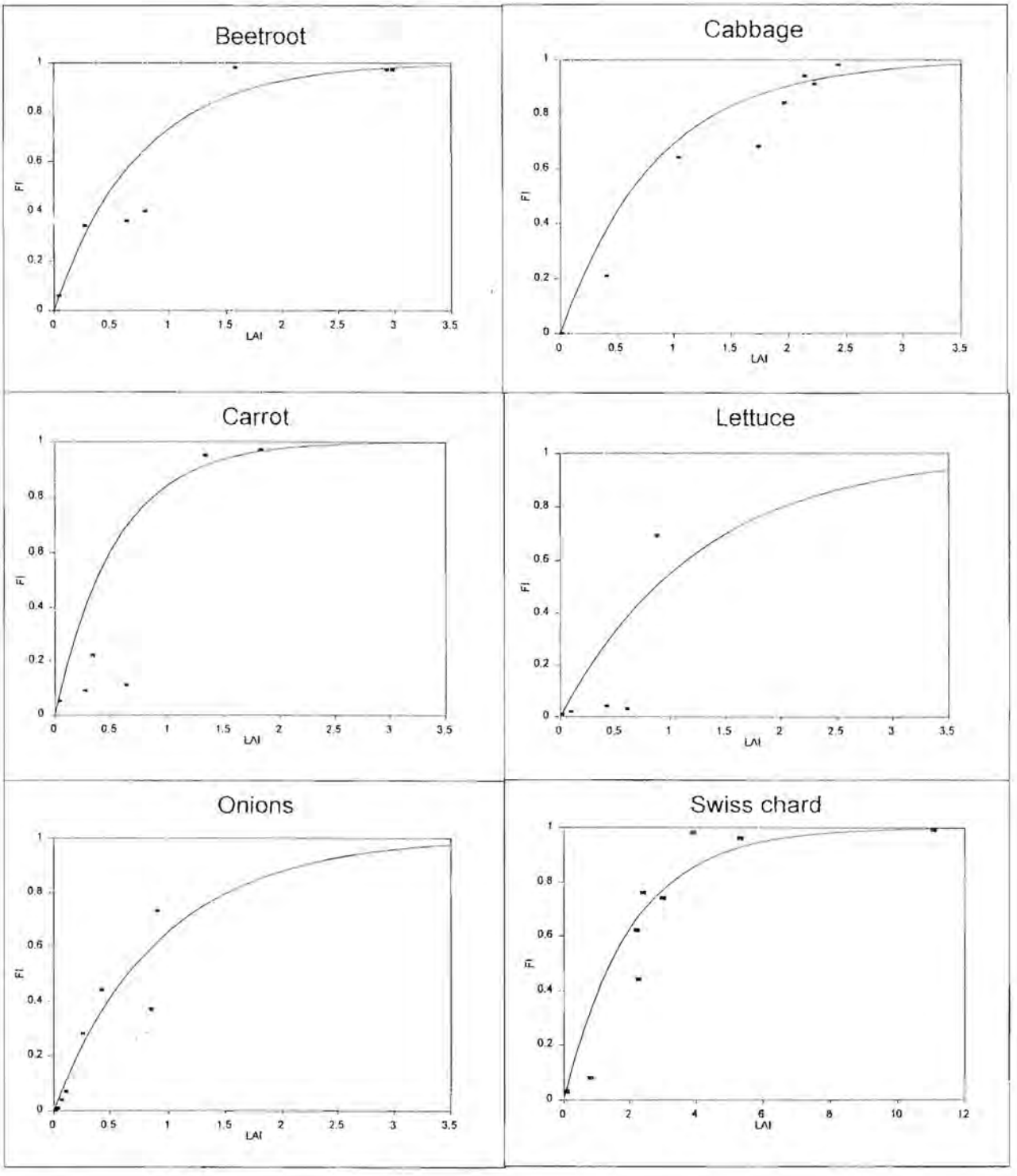


Figure 1.1 : Correlation between leaf area index (LAI) and radiation fractional interception (FI) for beetroot, cabbage, carrot, lettuce, onions and swiss chard.

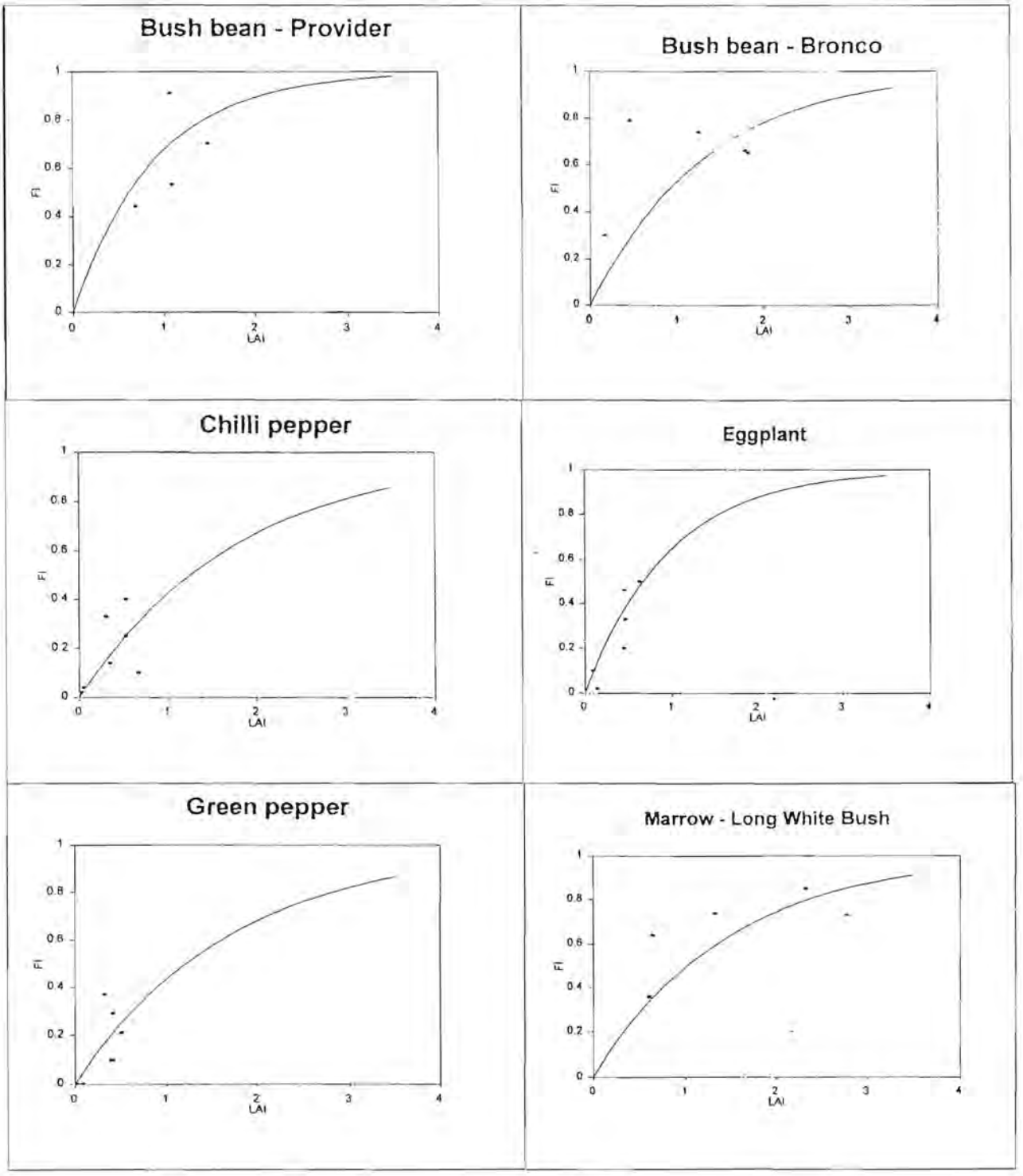


Figure 1.2 : Correlation between leaf area index,(LAI) and radiation fractional interception (FI) for bush beans (cv.'s Provider and Bronco), chilli pepper, eggplant, green pepper and marrow (cv. Long White Bush).

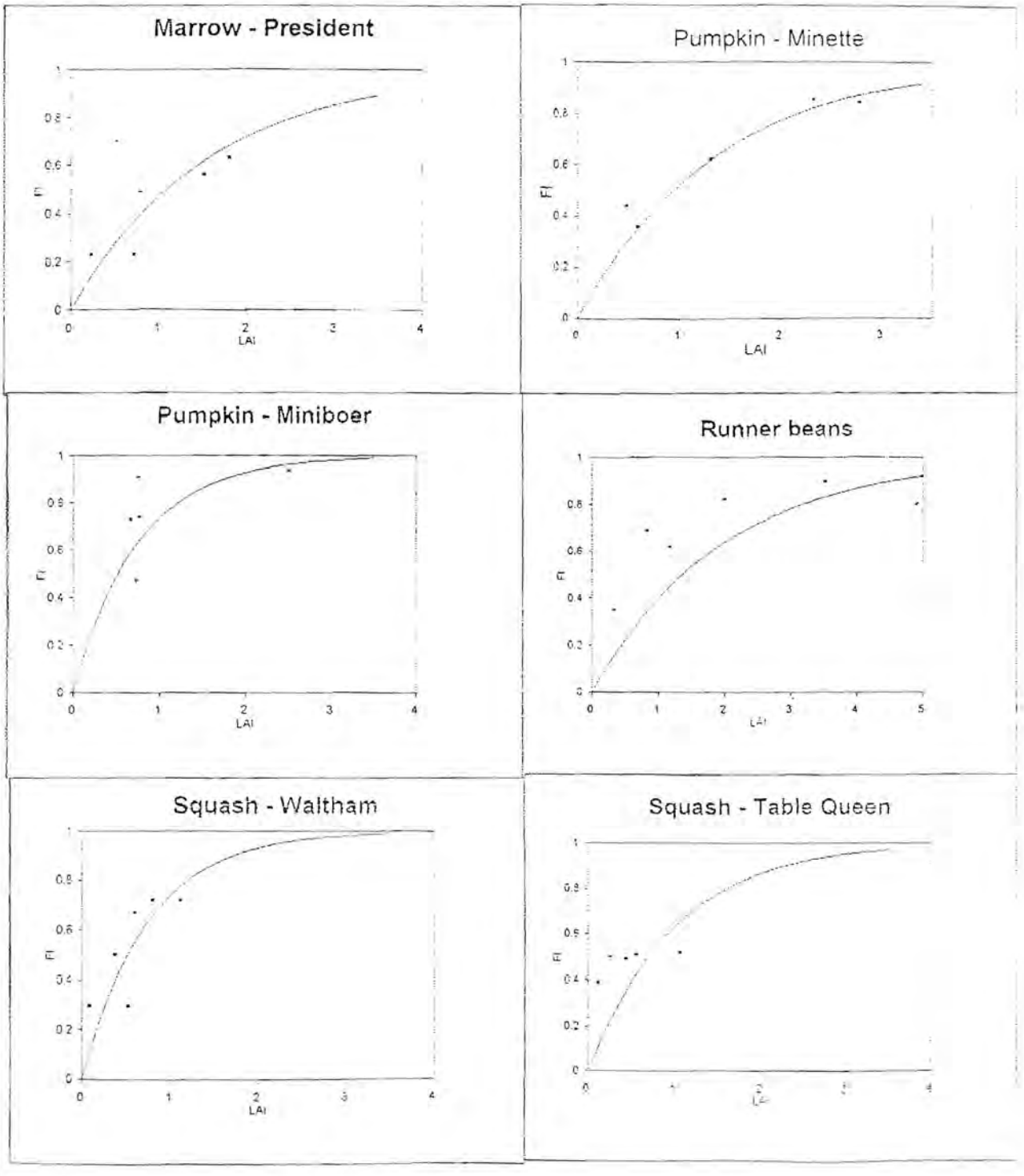


Figure 1.3 : Correlation between leaf area index (LAI) and radiation fractional interception (FI) for marrow (cv. President), pumpkin (cv.'s Minette and Miniboer), runner beans and squash (cv.'s Waltham and Table Queen).

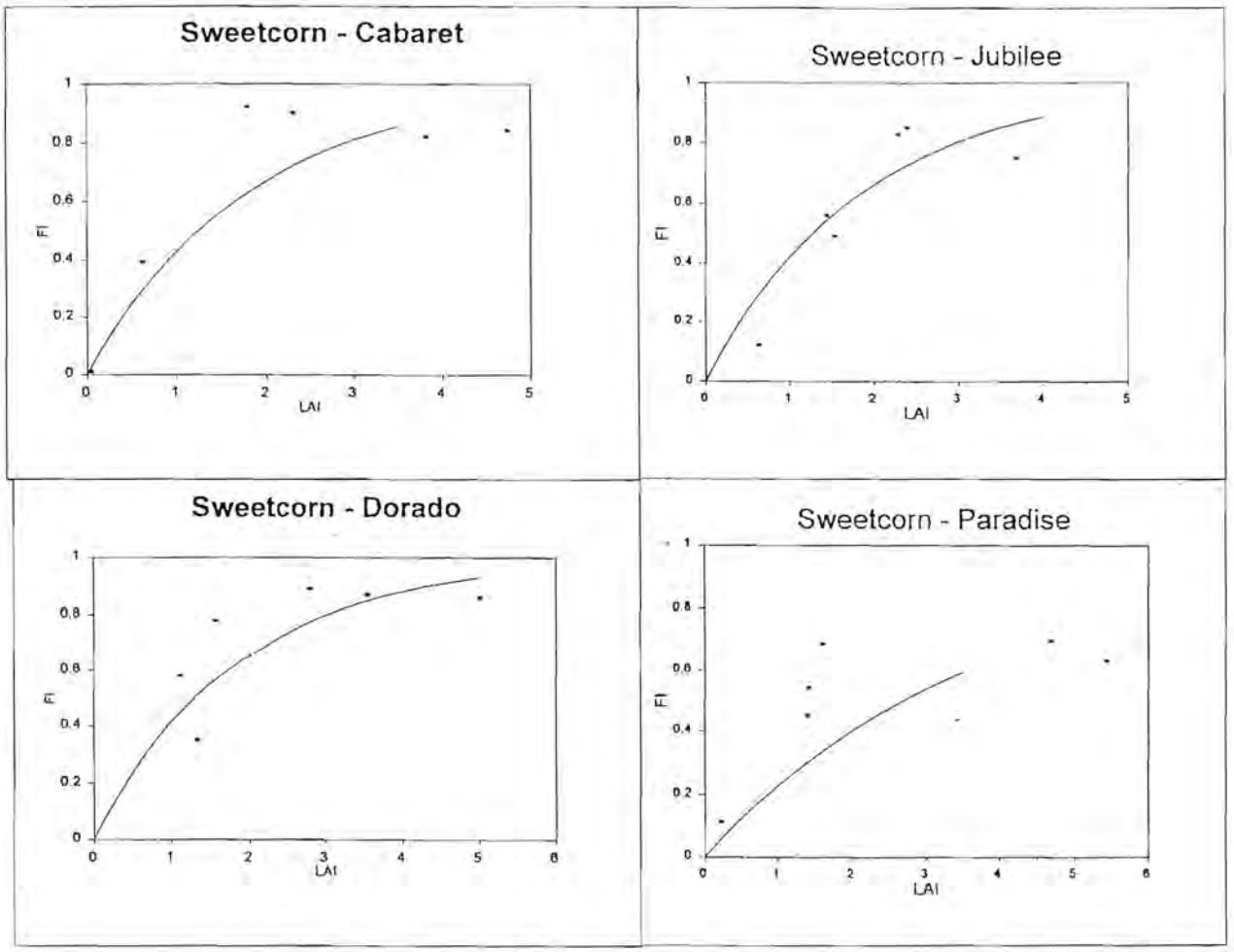


Figure 1.4 : Correlation between leaf area index (LAI) and radiation fractional interception (FI) for sweet-corn (cv.s Cabaret, Jubilee, Dorado and Paradise).

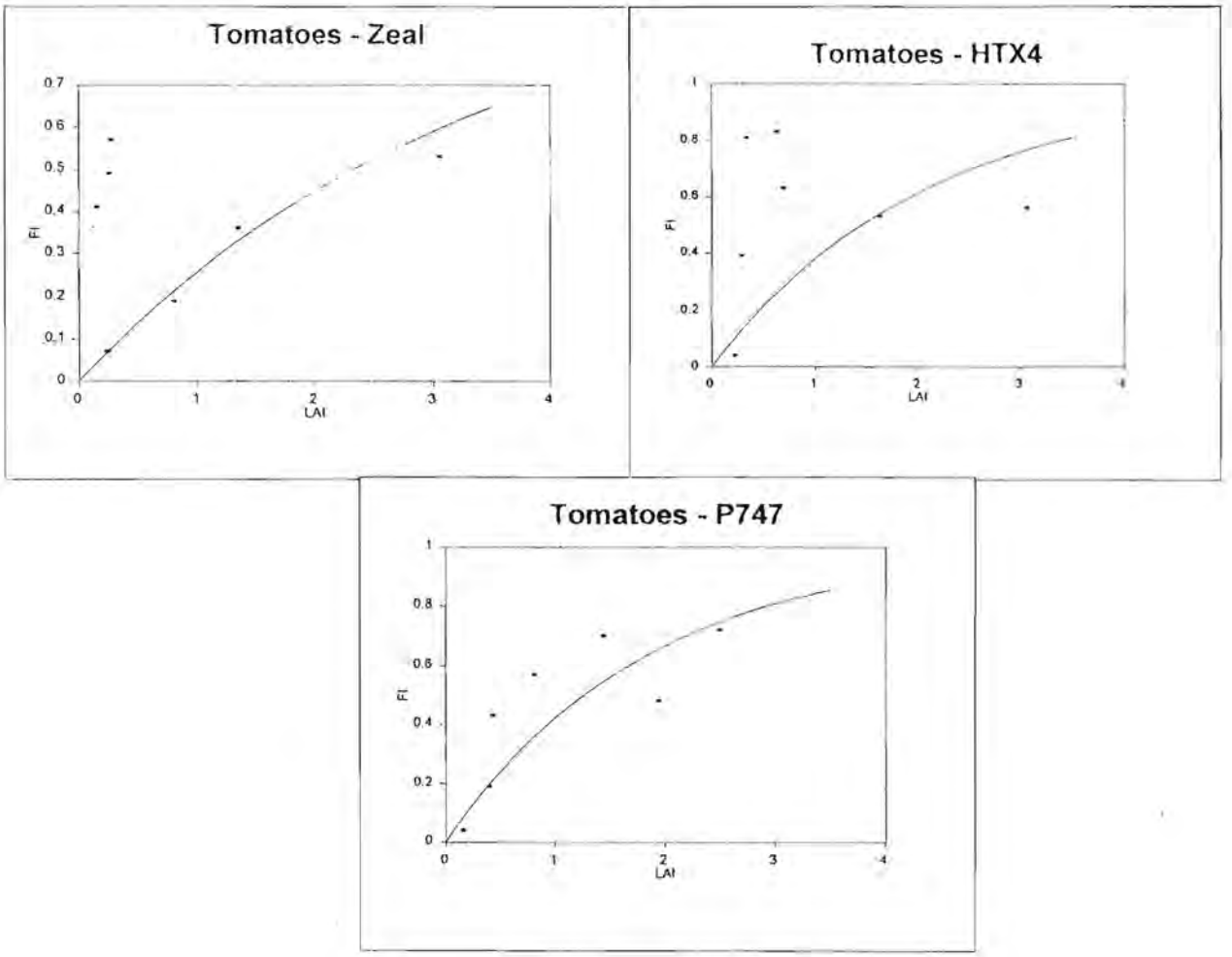


Figure 1.5 : Correlation between leaf area index (LAI) and radiation fractional interception (FI) for tomato (cv.s HTX14, P747 and Zeal).

Appendix B : Radiation conversion efficiency

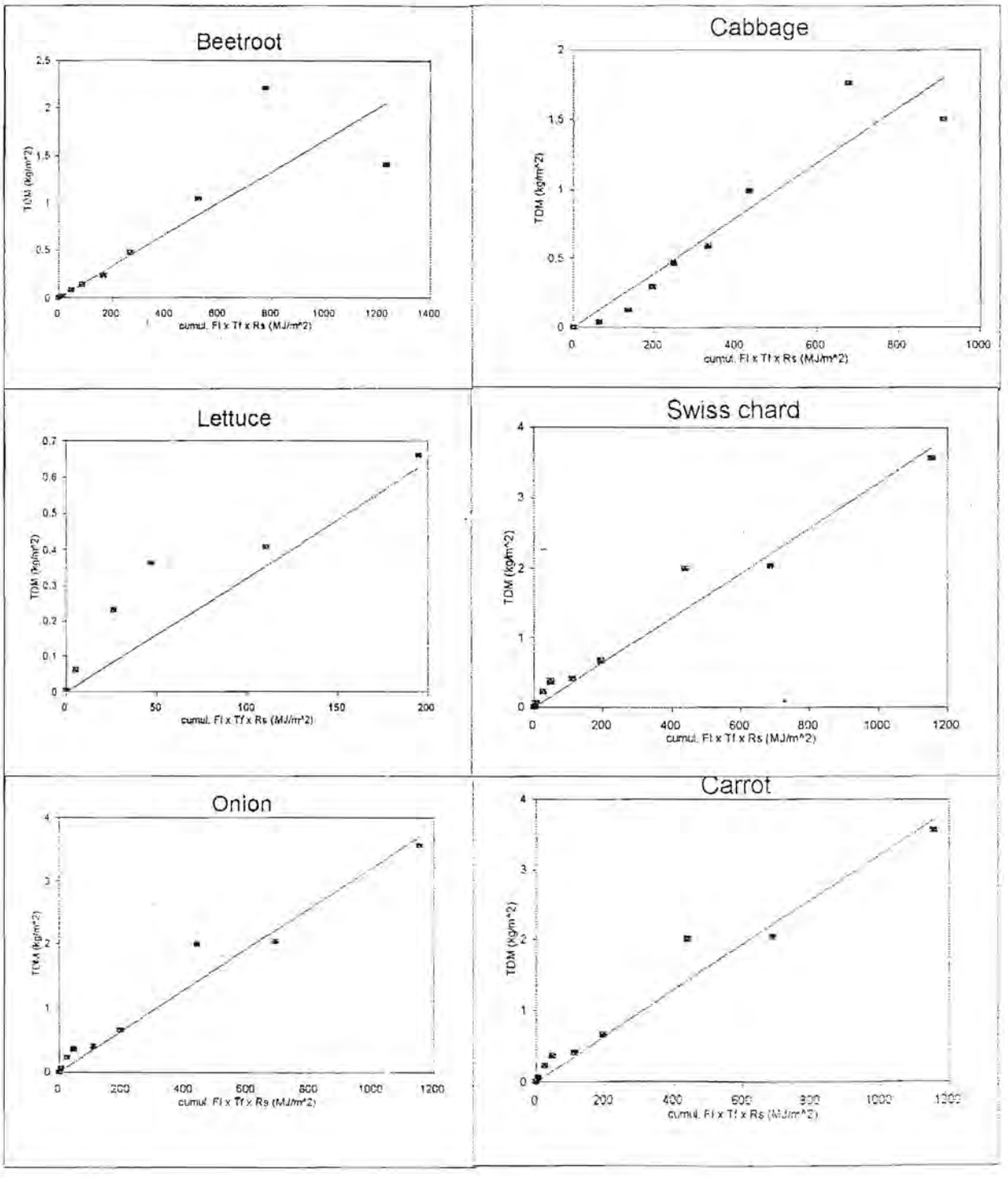


Figure 2.1 : Dry matter production as a function of the cumulative product of temperature factor (T_f) for light-limited crop growth, solar radiation fractional interception (FI) and total incoming solar radiation (R_s) for, clockwise from top left, beetroot, cabbage, spinach, carrot, onion, and lettuce.

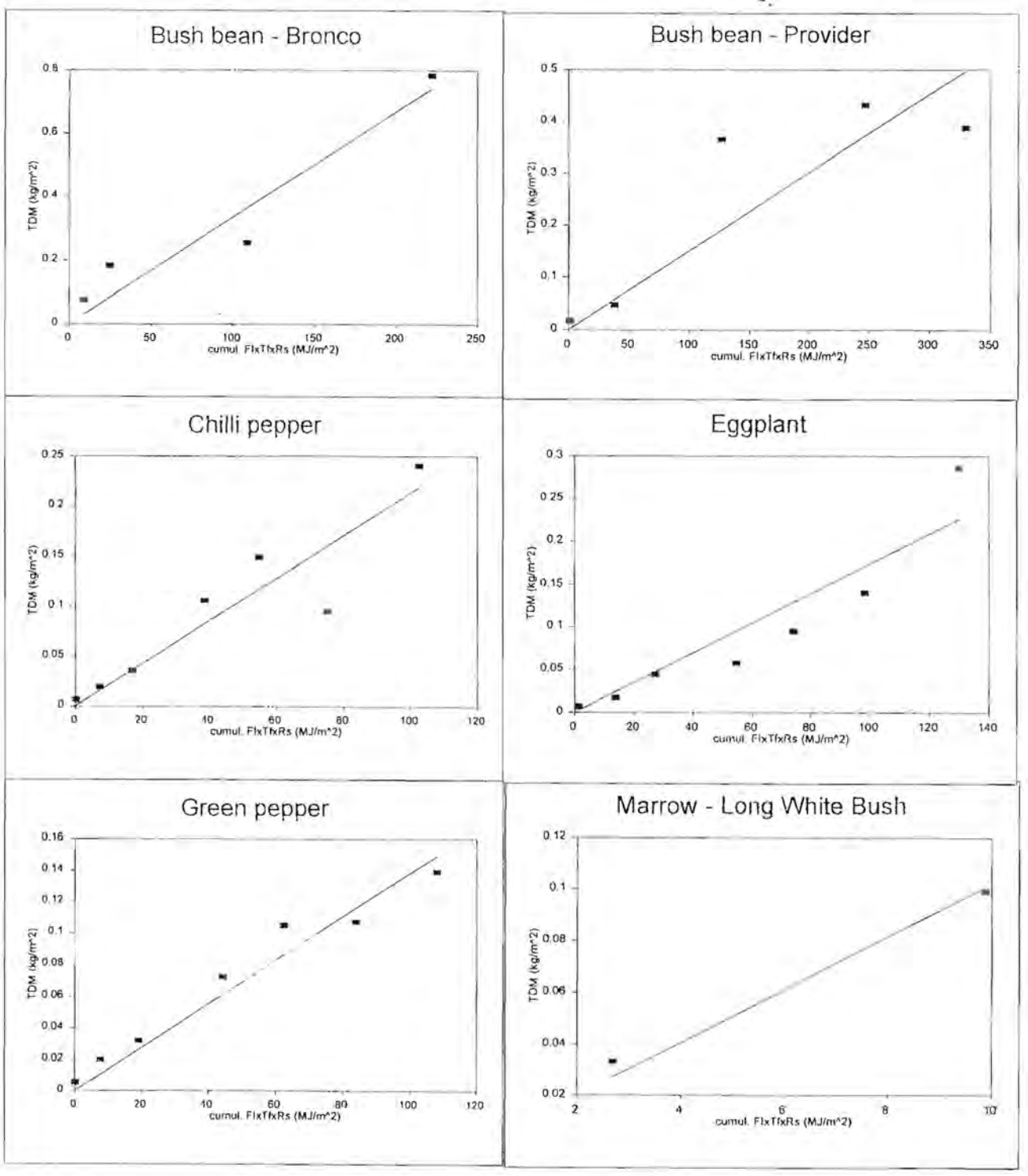


Figure 2.2 : Dry matter production as a function of the cumulative product of temperature factor (T_f) for light-limited crop growth, solar radiation fractional interception (FI) and total incoming solar radiation (R_s) for, clockwise from top left, bush bean (cv.'s Bronco and Provider), eggplant, marrow (cv. Long White Bush), green pepper, and chilli pepper.

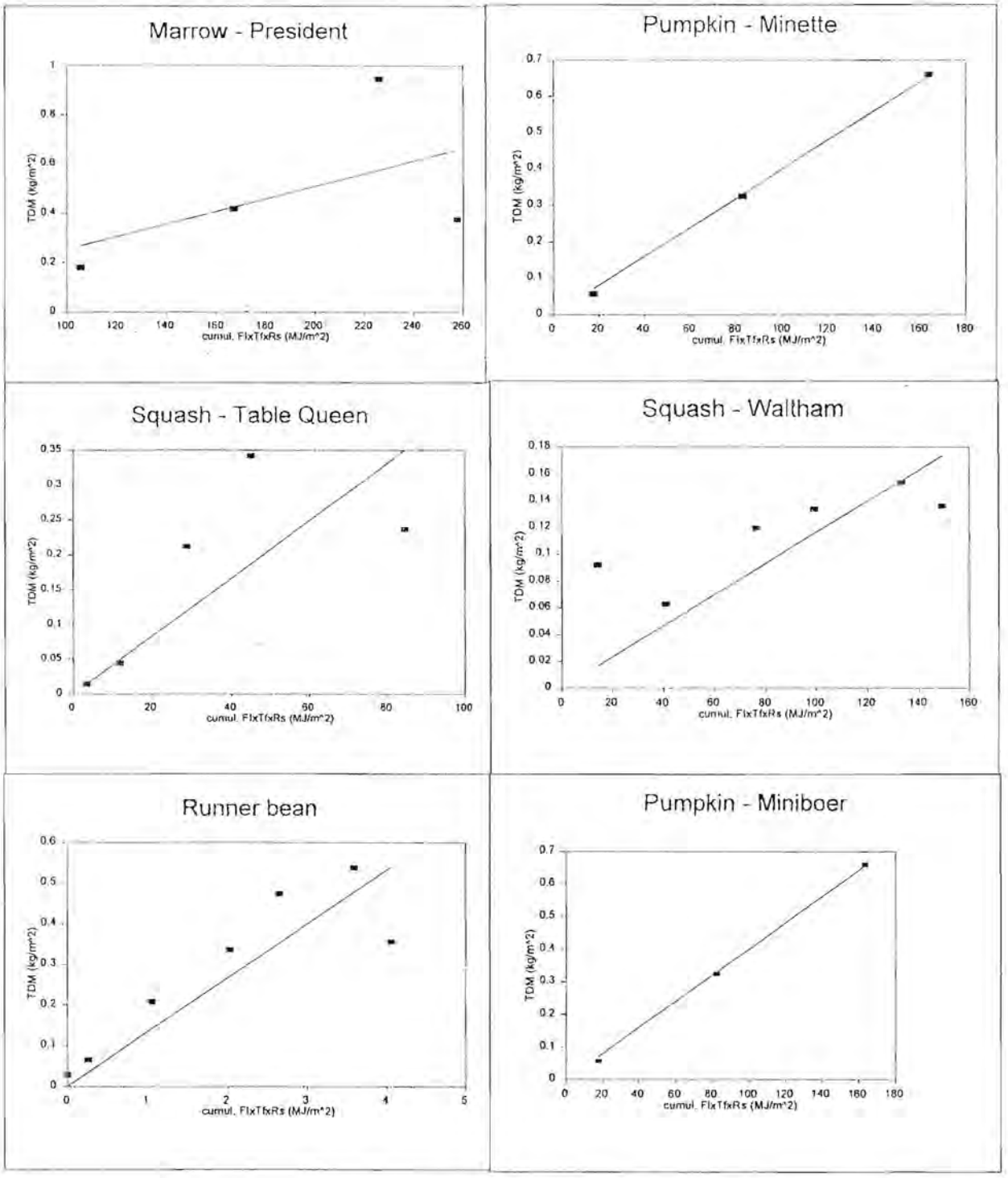


Figure 2.3 : Dry matter production as a function of the cumulative product of temperature factor (T_f) for light-limited crop growth, solar radiation fractional interception (FI) and total incoming solar radiation (R_s) for, clockwise from top left, marrow (cv. President), pumpkin (cv. Minette), squash (cv. Waltham) pumpkin (cv. Miniboer), runner bean, and squash (cv. Table Queen).

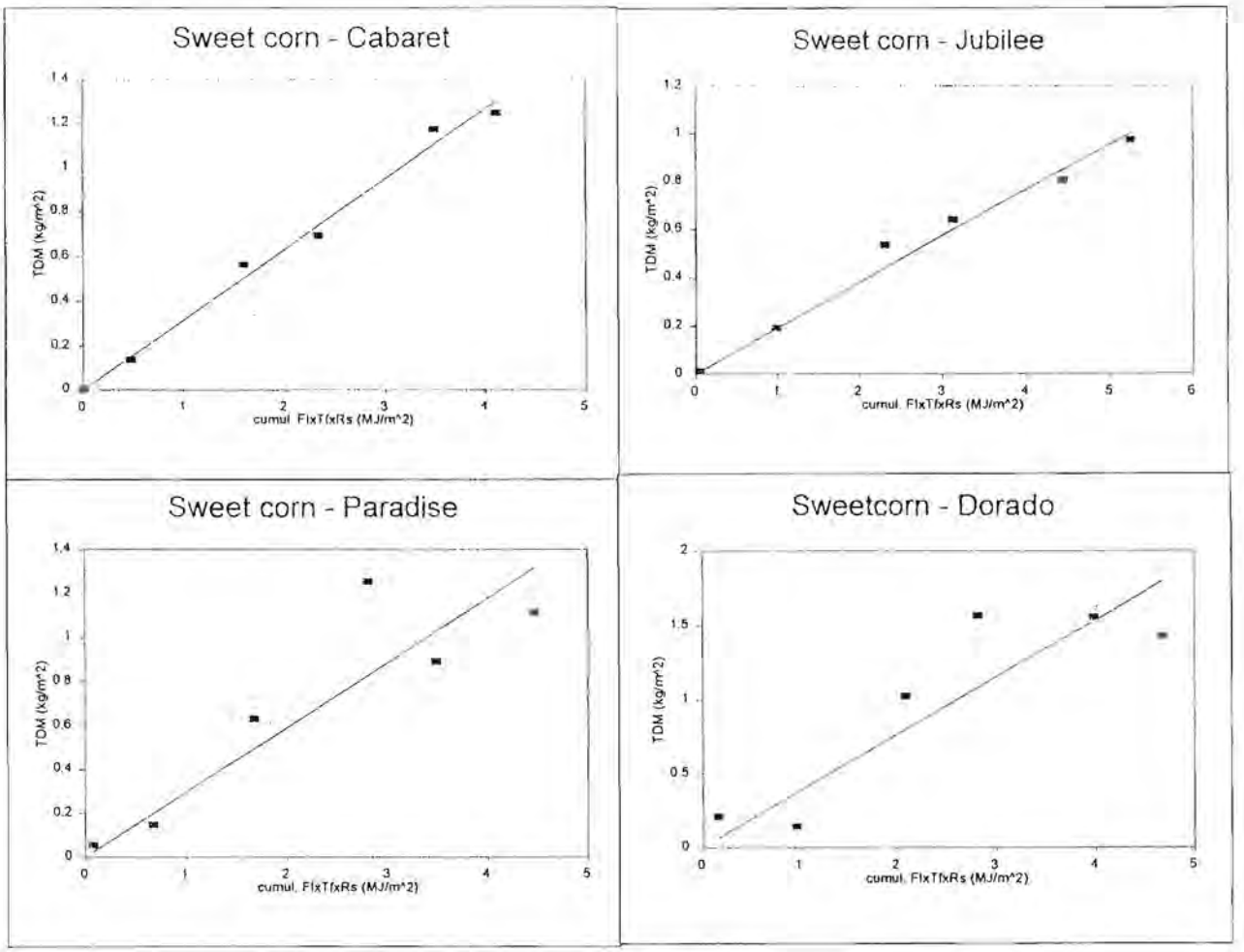


Figure 2.4 : Dry matter production as a function of the cumulative product of temperature factor (T_f) for light-limited crop growth, solar radiation fractional interception (FI) and total incoming solar radiation (R_s) for, clockwise from top left, sweet corn (cv's Dorado, Jubilee, Cabaret and Paradise).

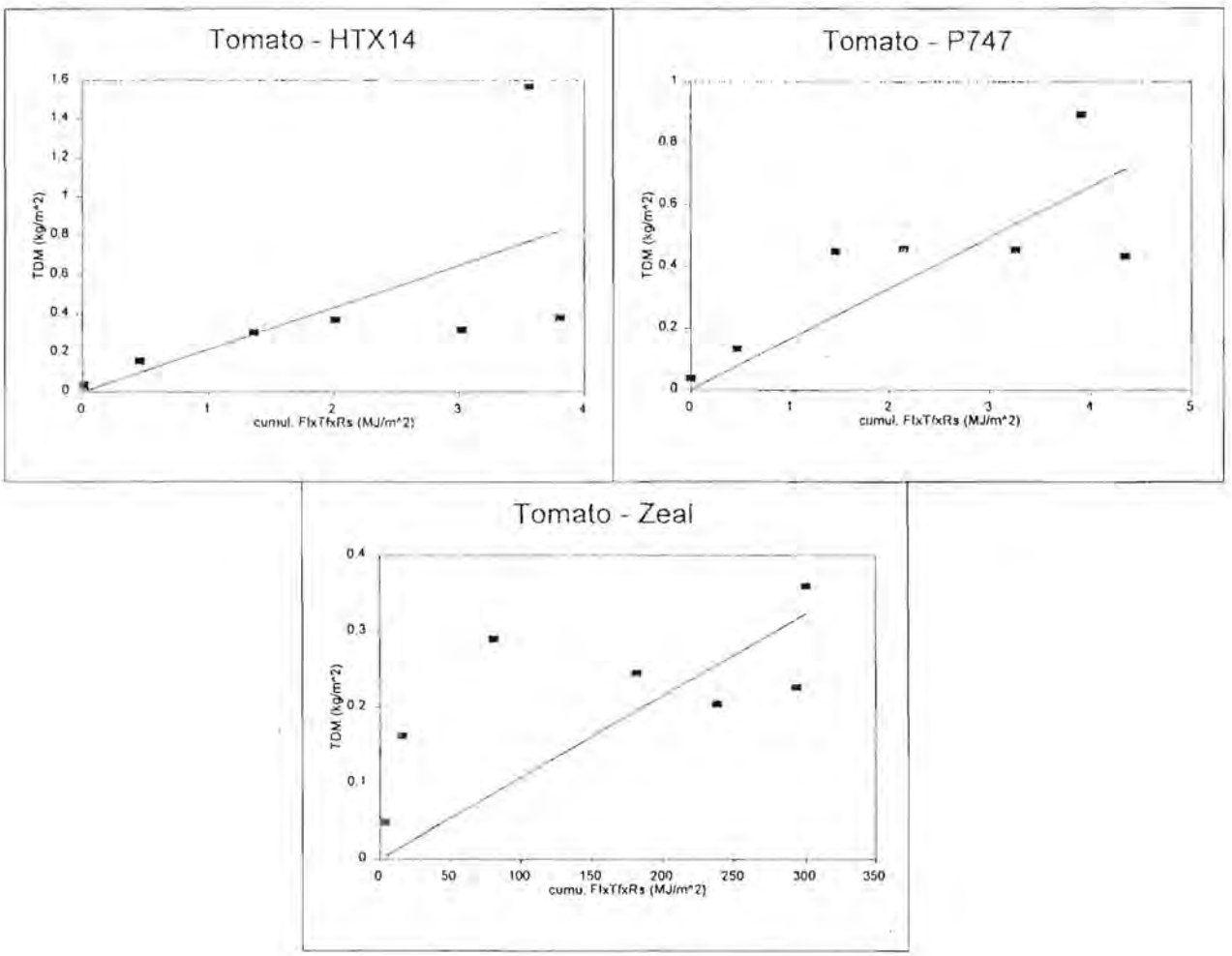
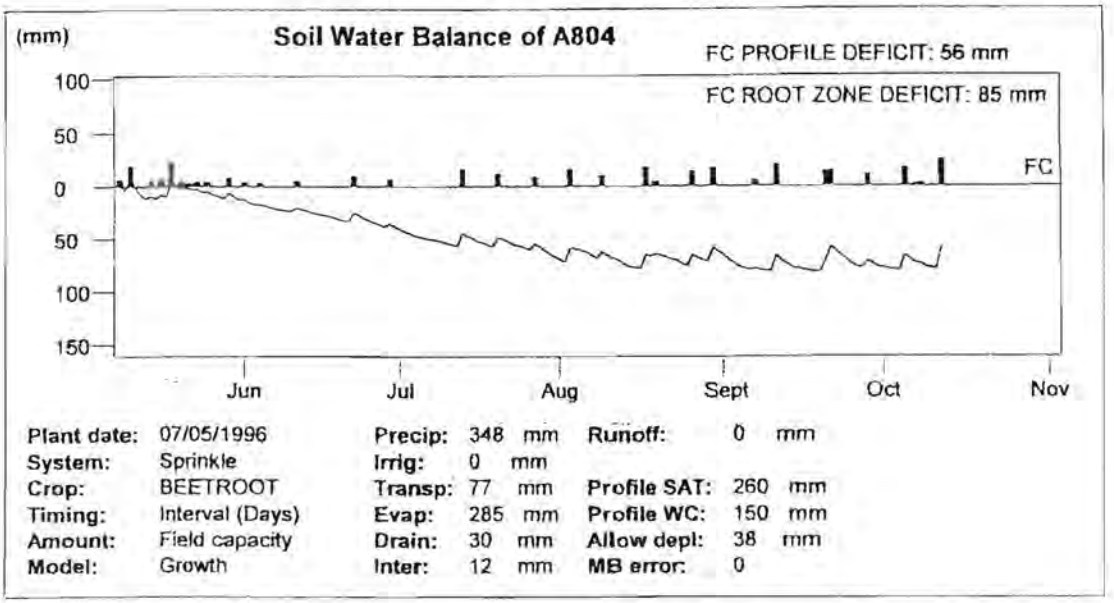


Figure 2.5 : Dry matter production as a function of the cumulative product of temperature factor (T_f) for light-limited crop growth, solar radiation fractional interception (FI) and total incoming solar radiation (R_s) for tomato (cv.'s Zeal, HTX4 and P747).

Appendix C : Model simulation and statistical analysis



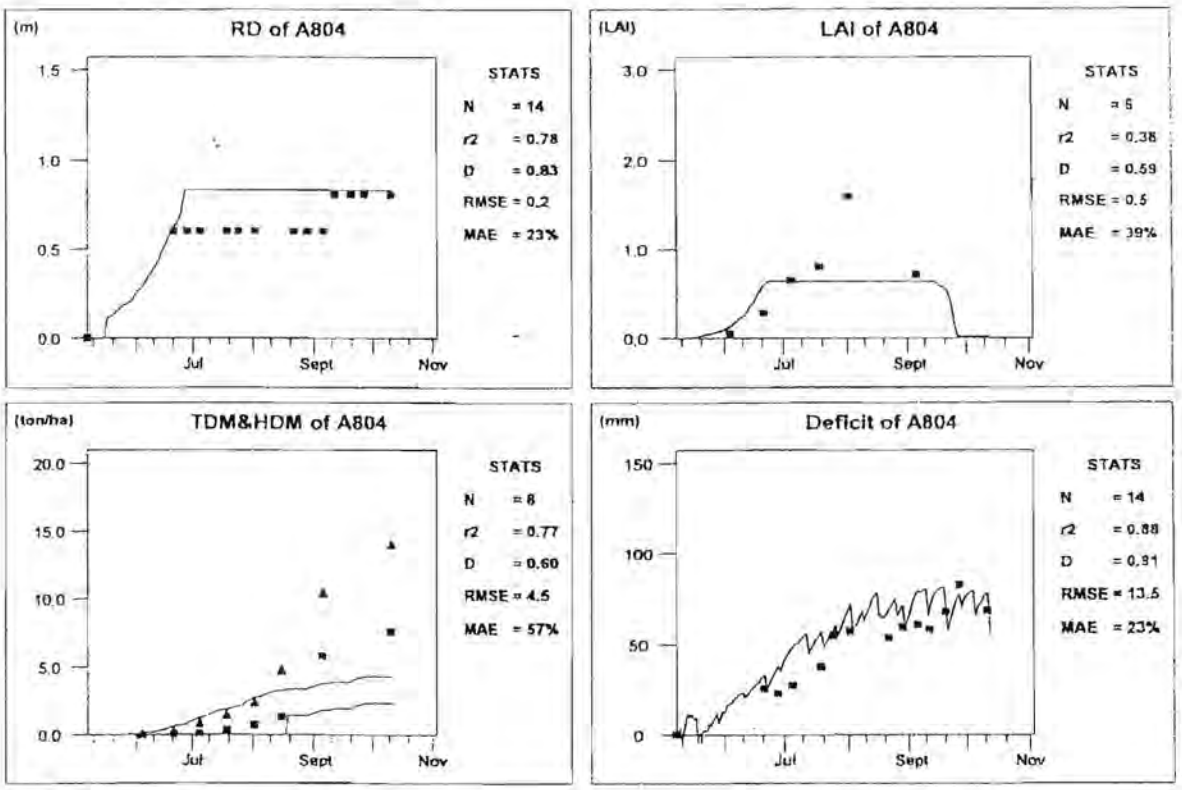
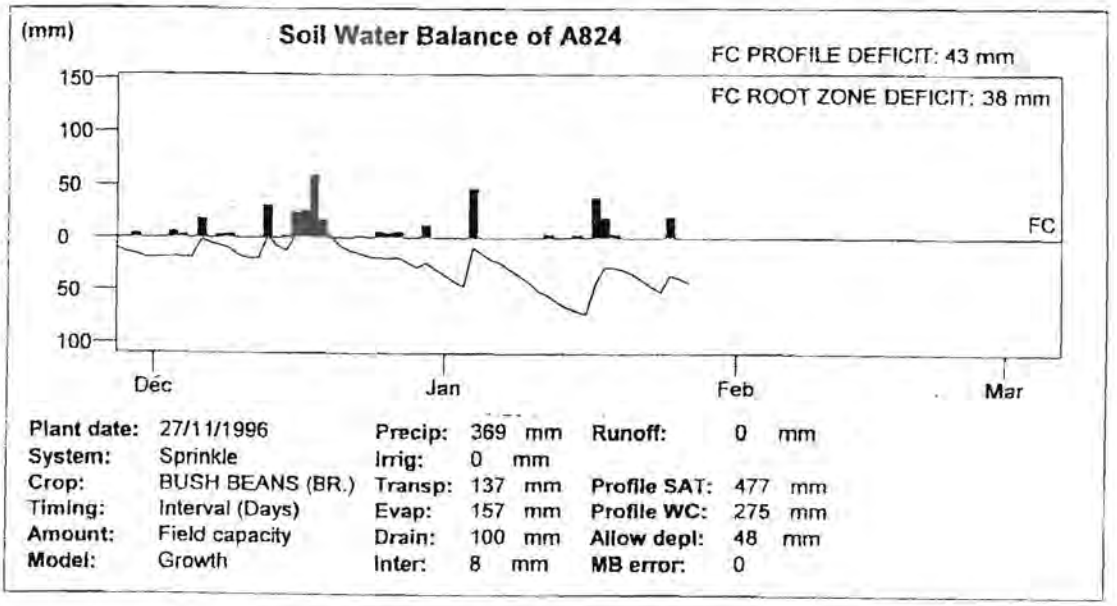


Figure 3.1 : Soil water balance output graph, simulated (solid line) and measured (symbols), root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM) as well as soil water deficit for beetroot



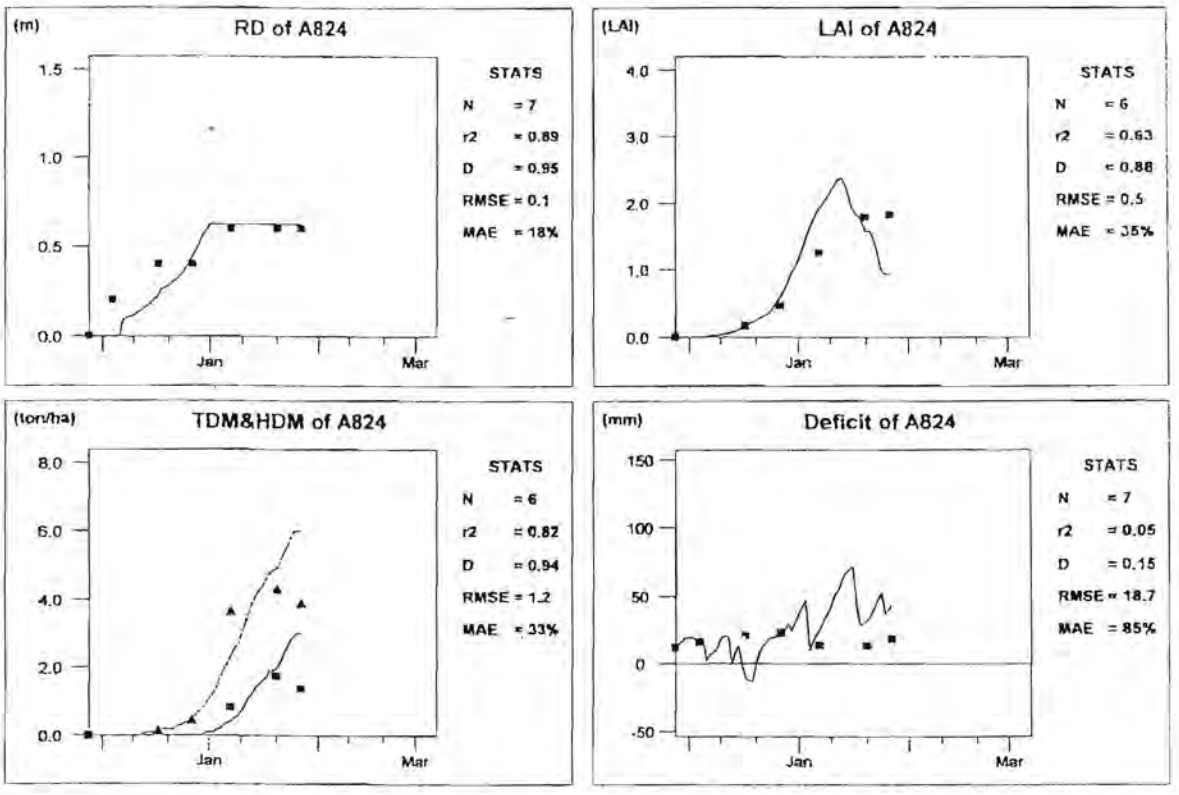
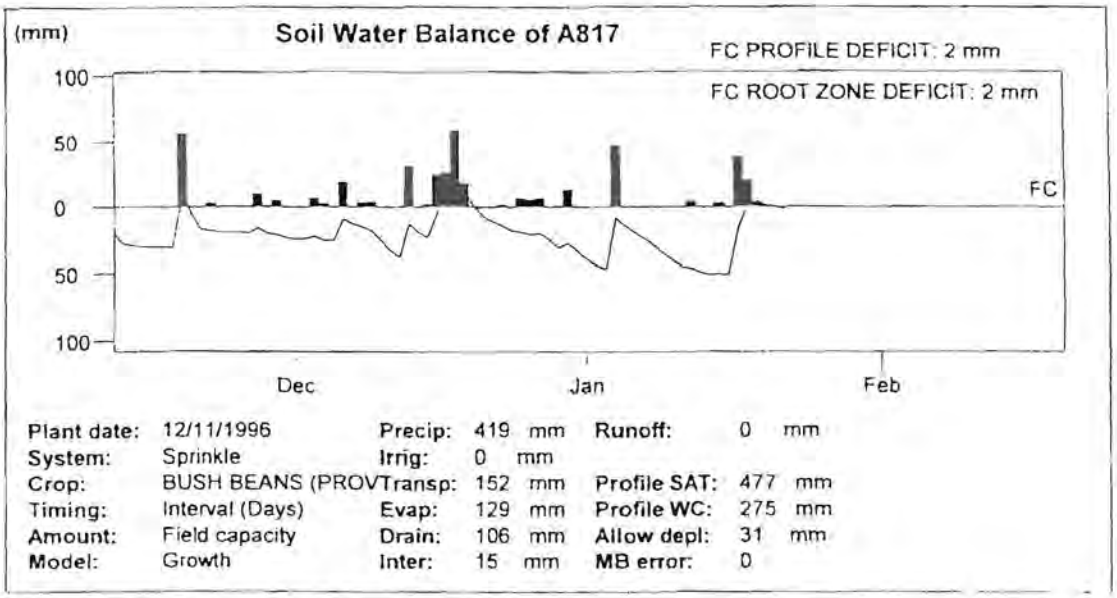


Figure 3.2 : Soil water balance output graph, simulated (solid lines) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit for bean (cv. Bronco)



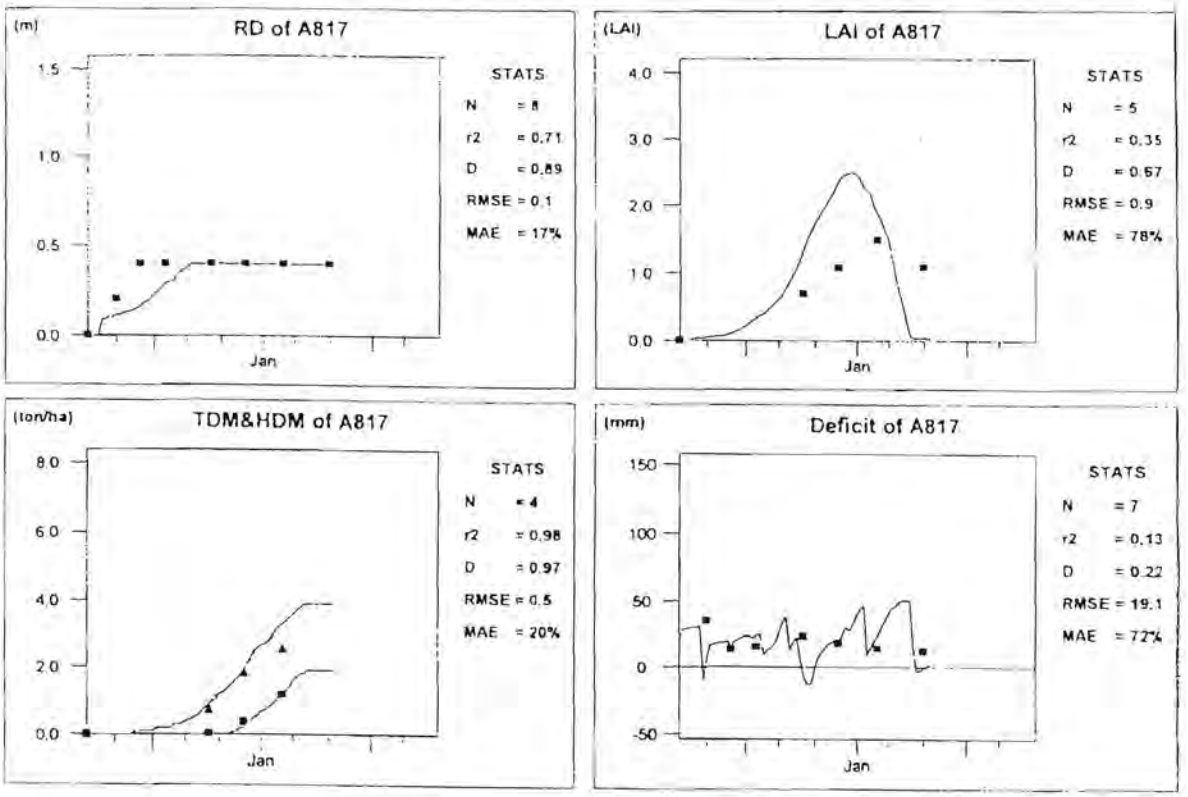
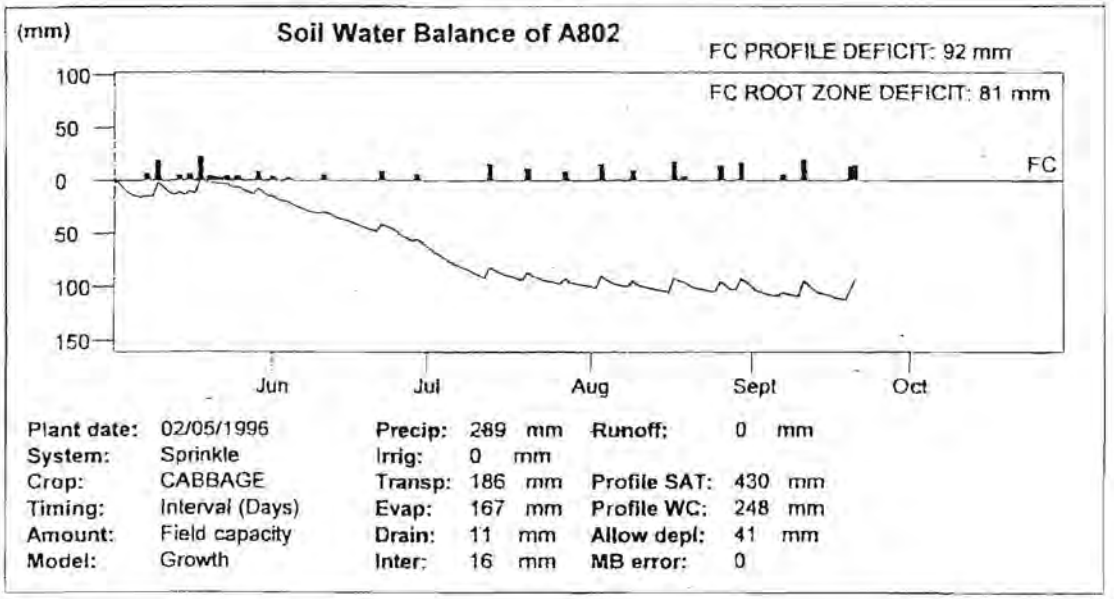


Figure 3.3 : Soil water balance output graph, simulated (solid lines) and measured (symbols0 root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit for bush bean (cv. Provider).



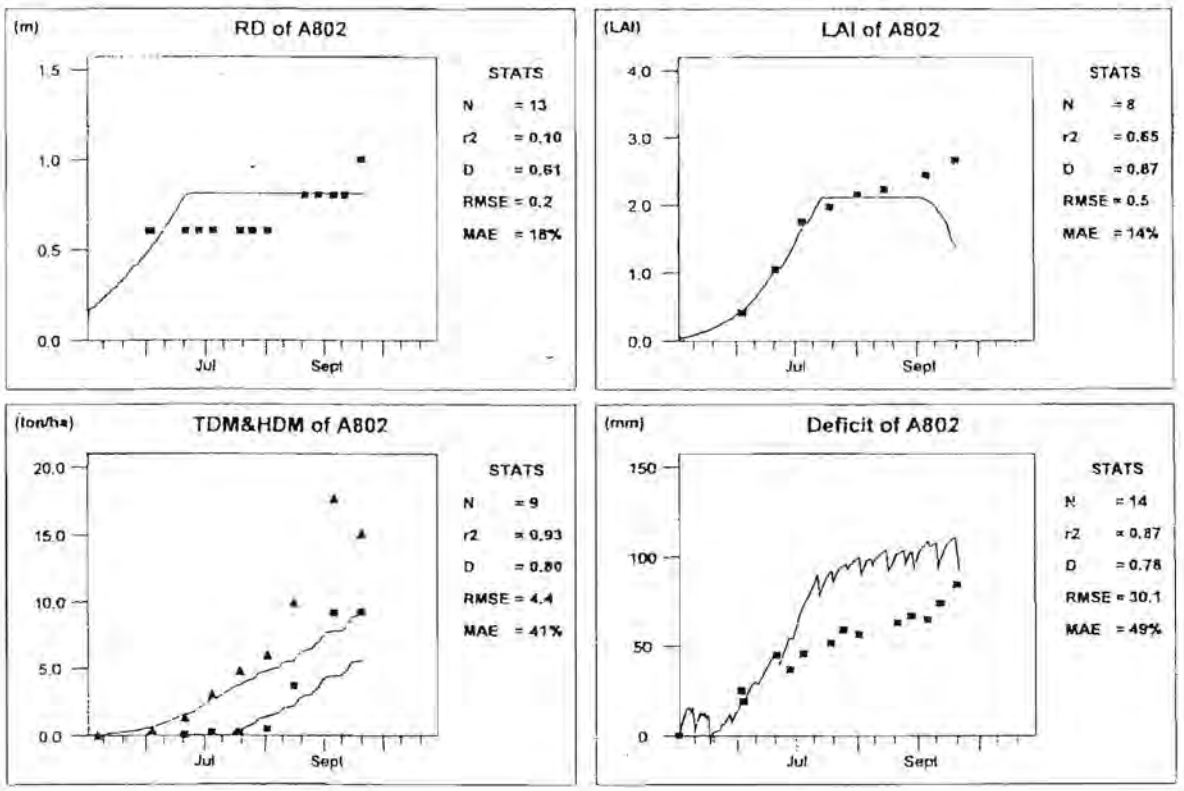


Figure 3.4 : Soil water balance output graph, simulated (solid lines) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit for cabbage.

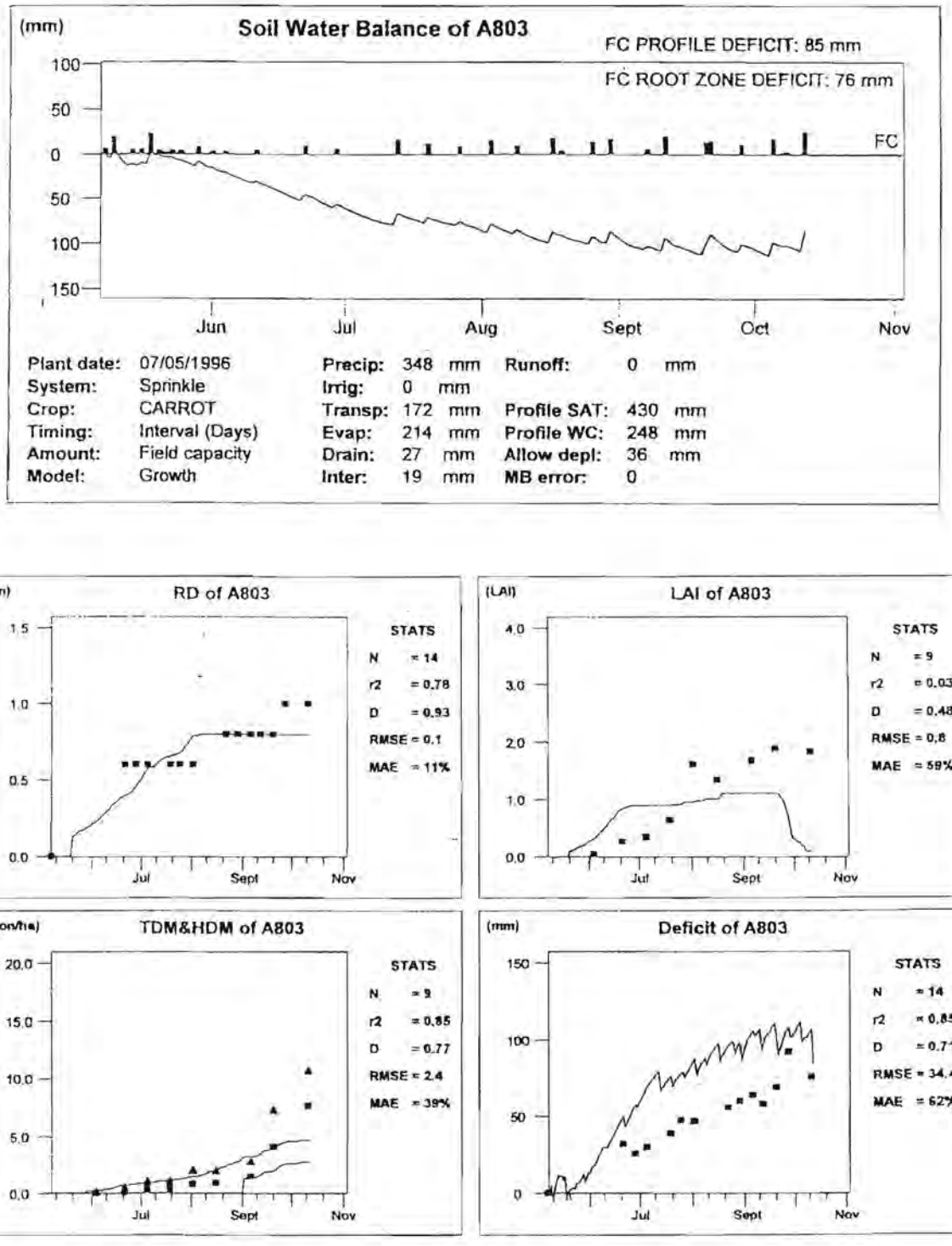
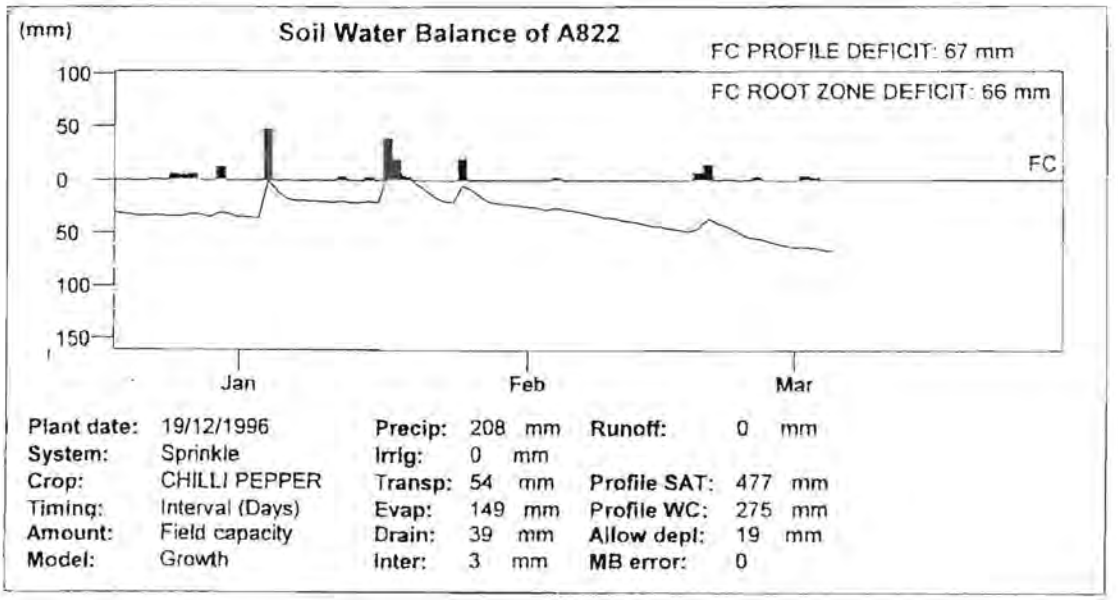


Figure 3.5 : Soil water balance output graph, simulated (solid lines) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit for carrot



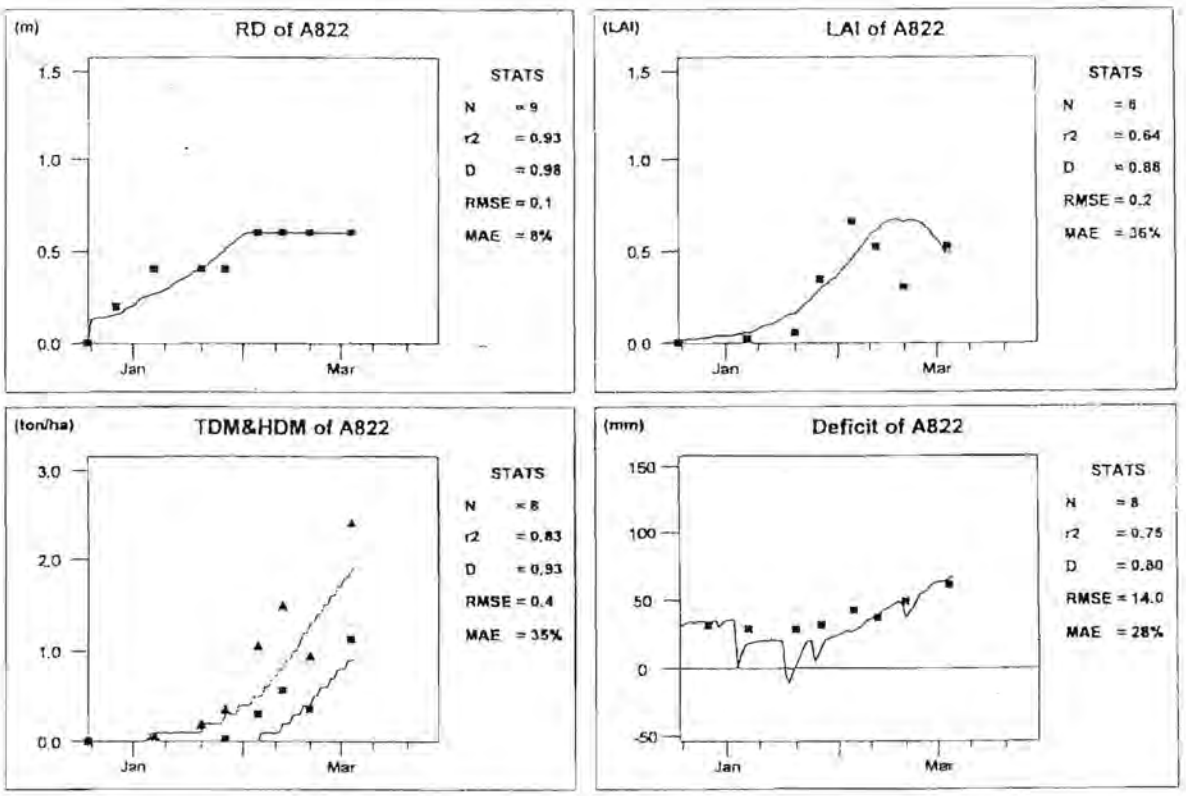
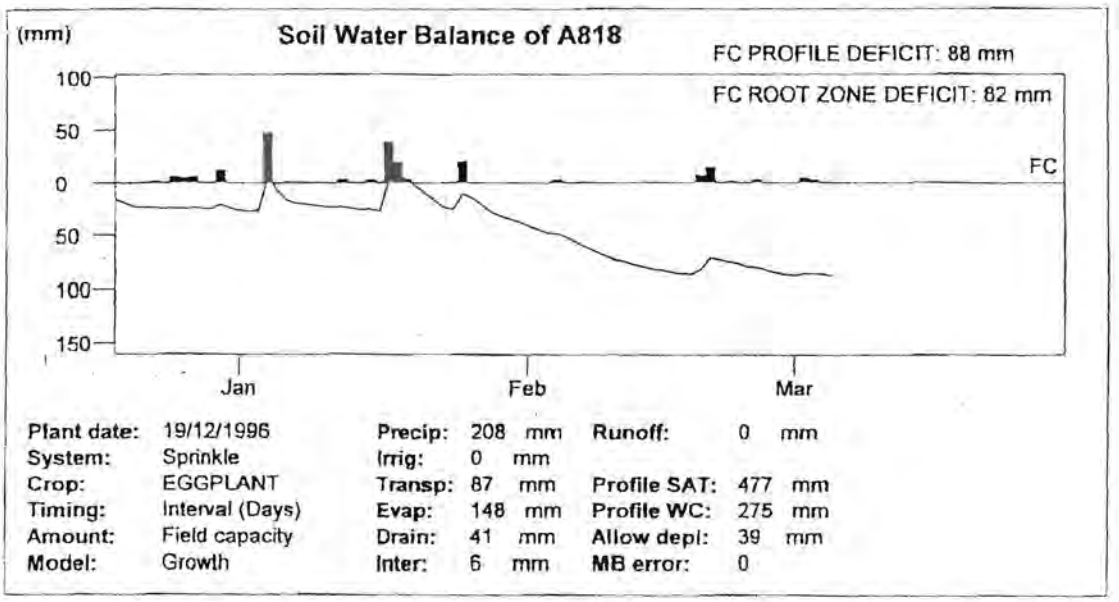


Figure 3.6 : Soil water balance output graph, simulated (solid lines) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit for chilli pepper.



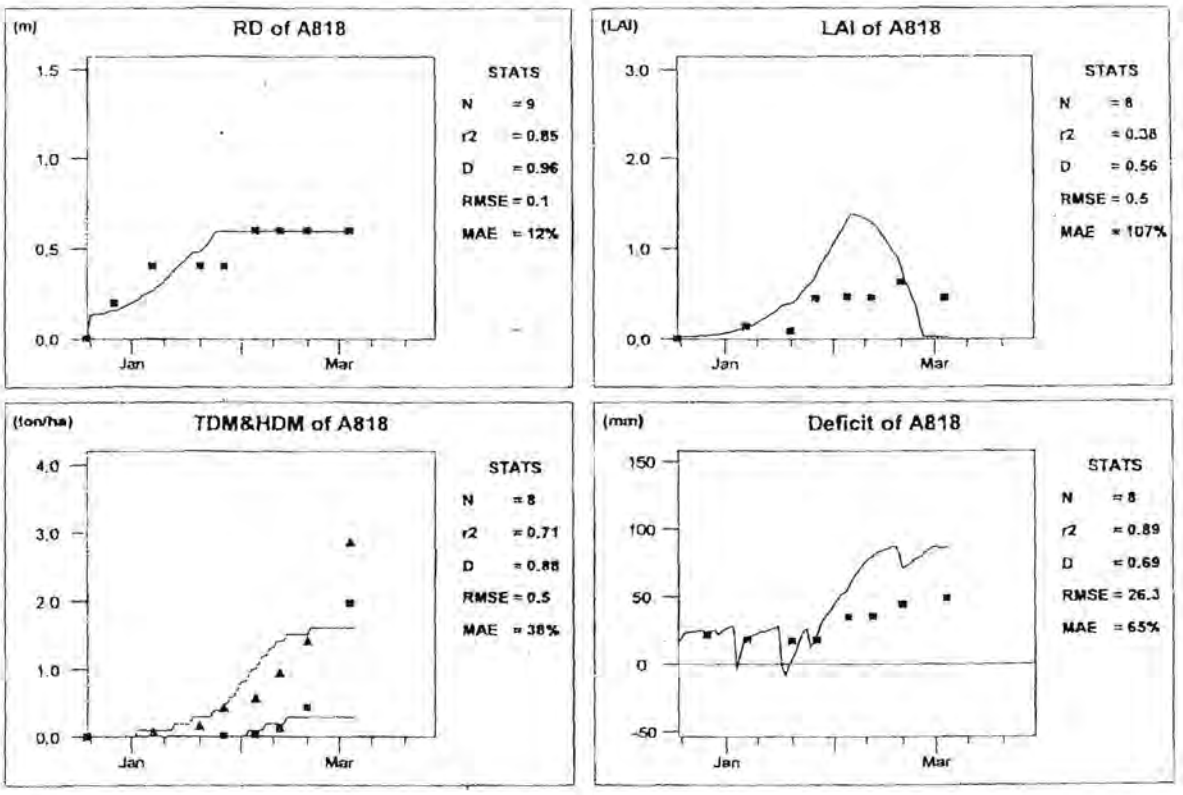
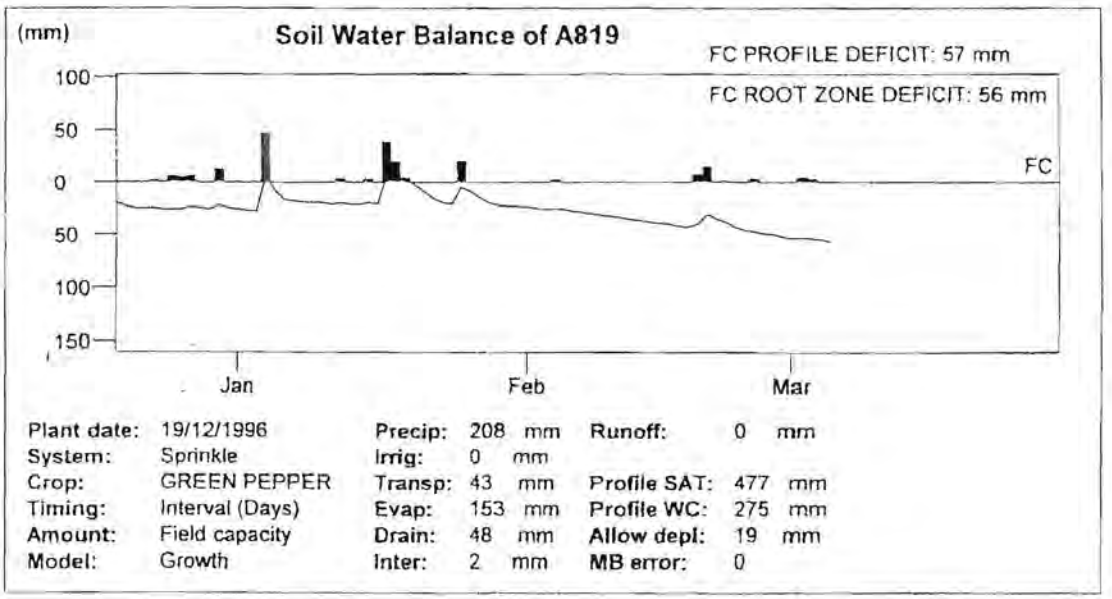


Figure 3.7 : Soil water balance output graph, simulated (solid lines) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit for eggplant



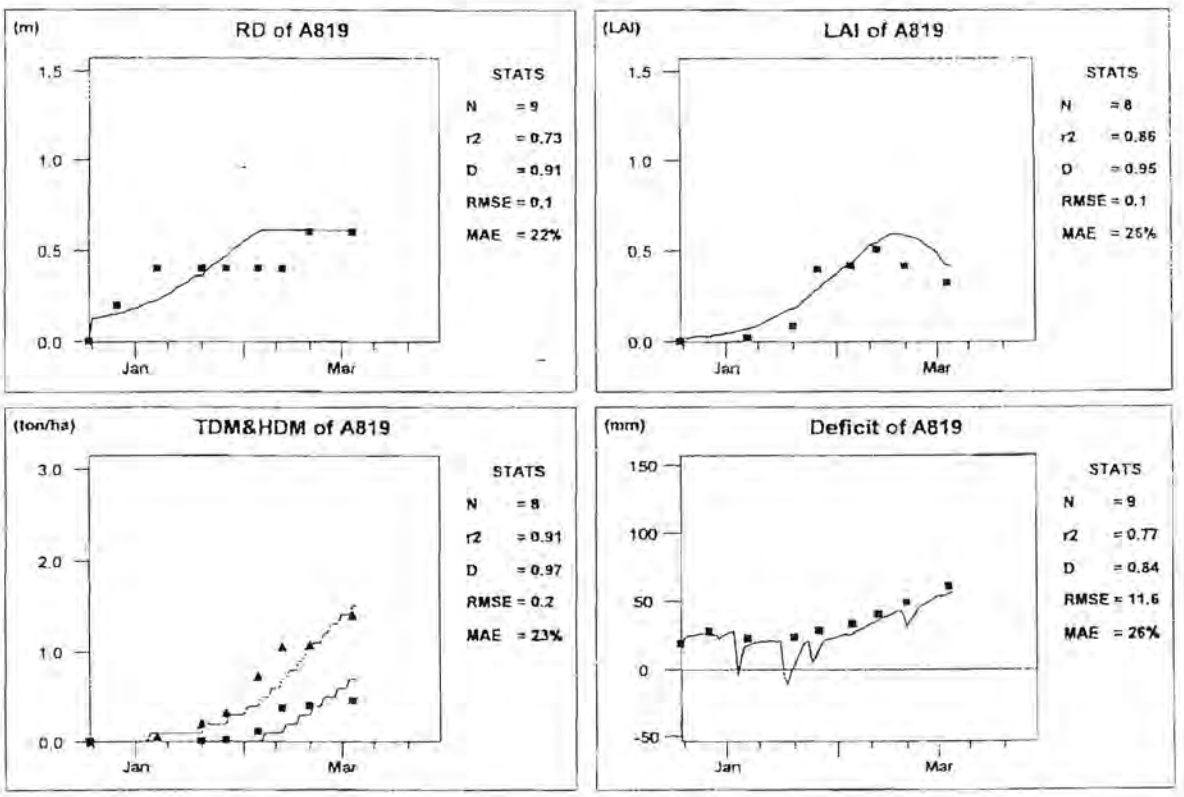


Figure 3.8 : Soil water balance output graph, simulated (solid lines) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit for green pepper

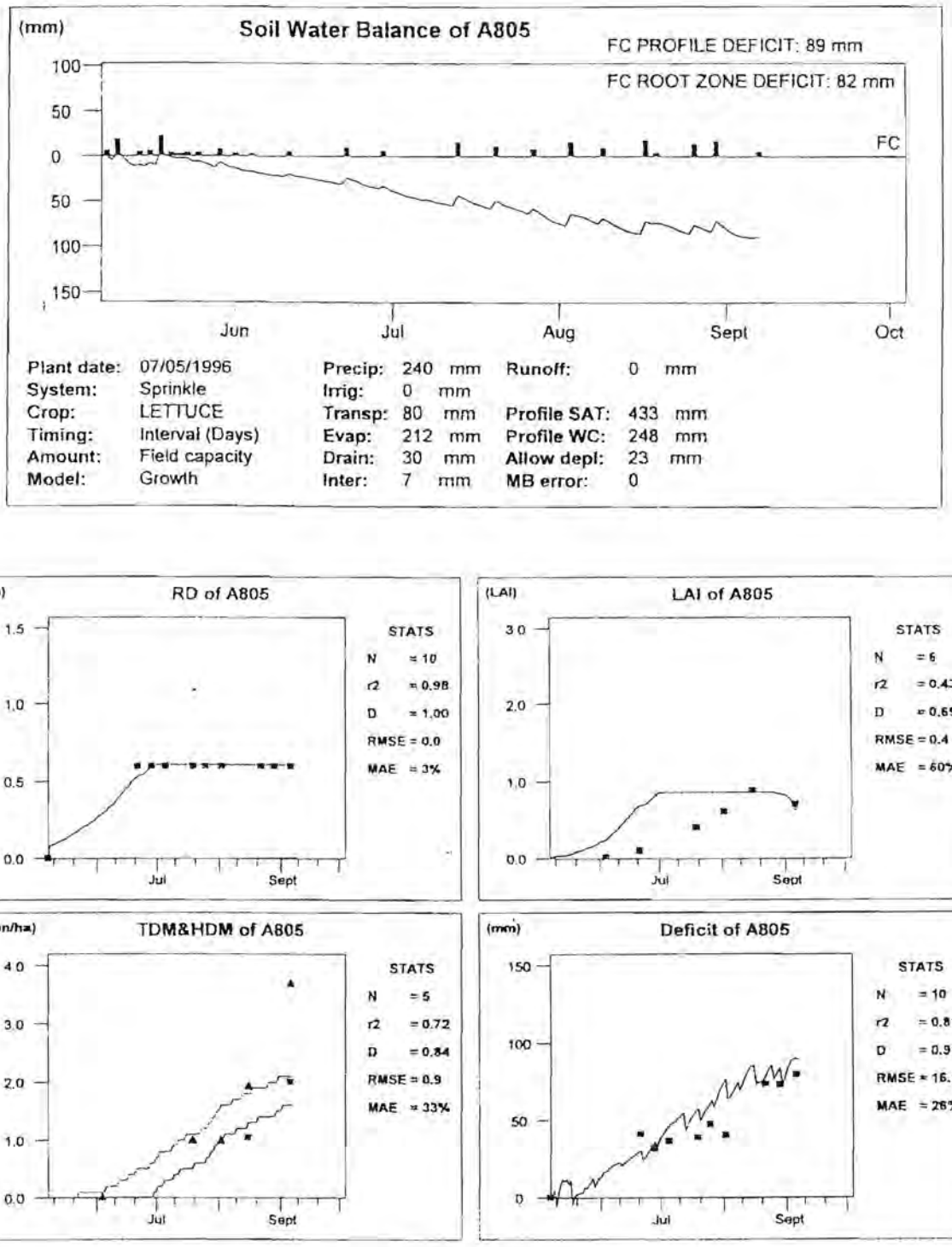


Figure 3.9 Soil water balance output graph, simulated (solid lines) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit for lettuce.

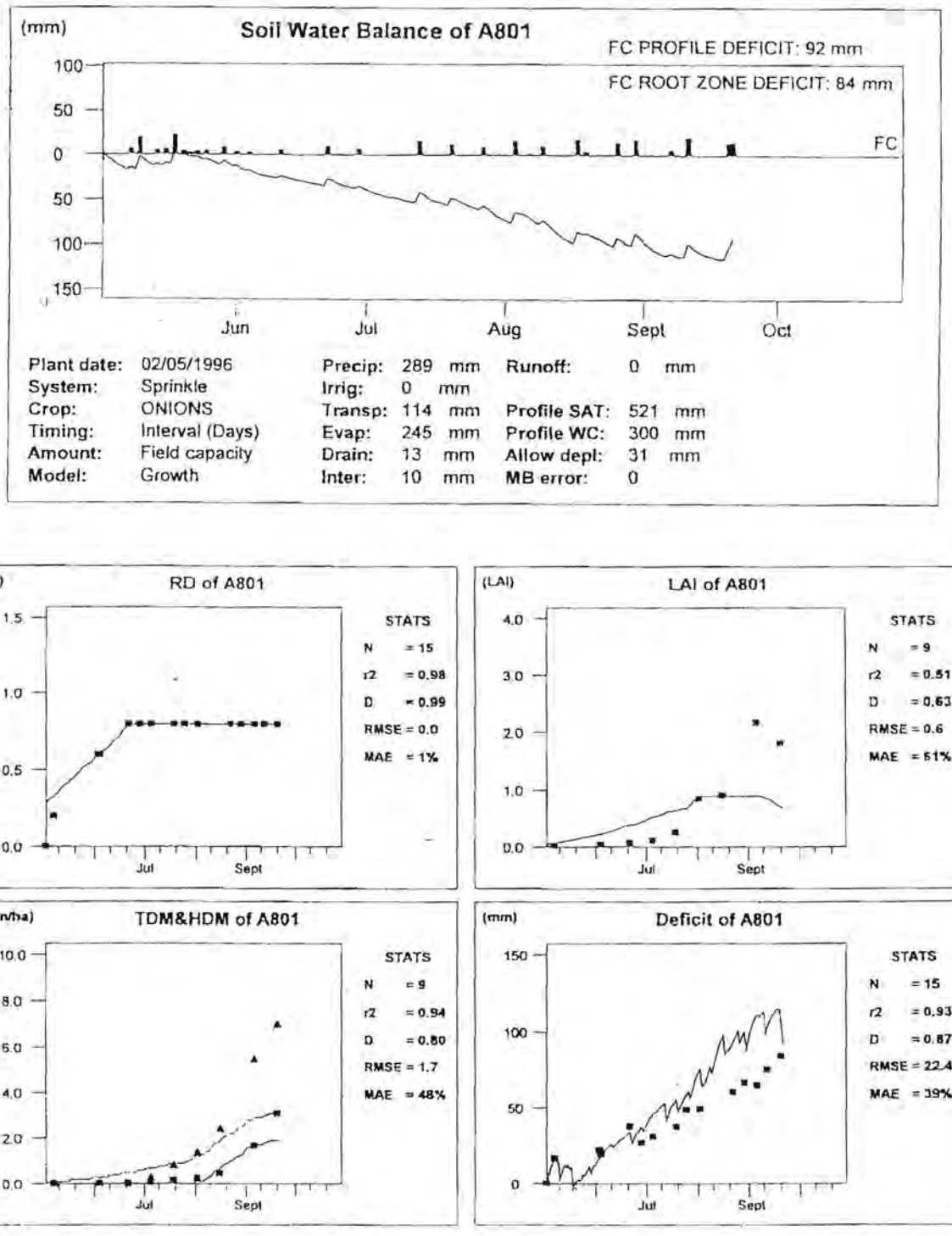


Figure 3.10 : Soil water balance output graph, simulated (solid lines) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit for onion.

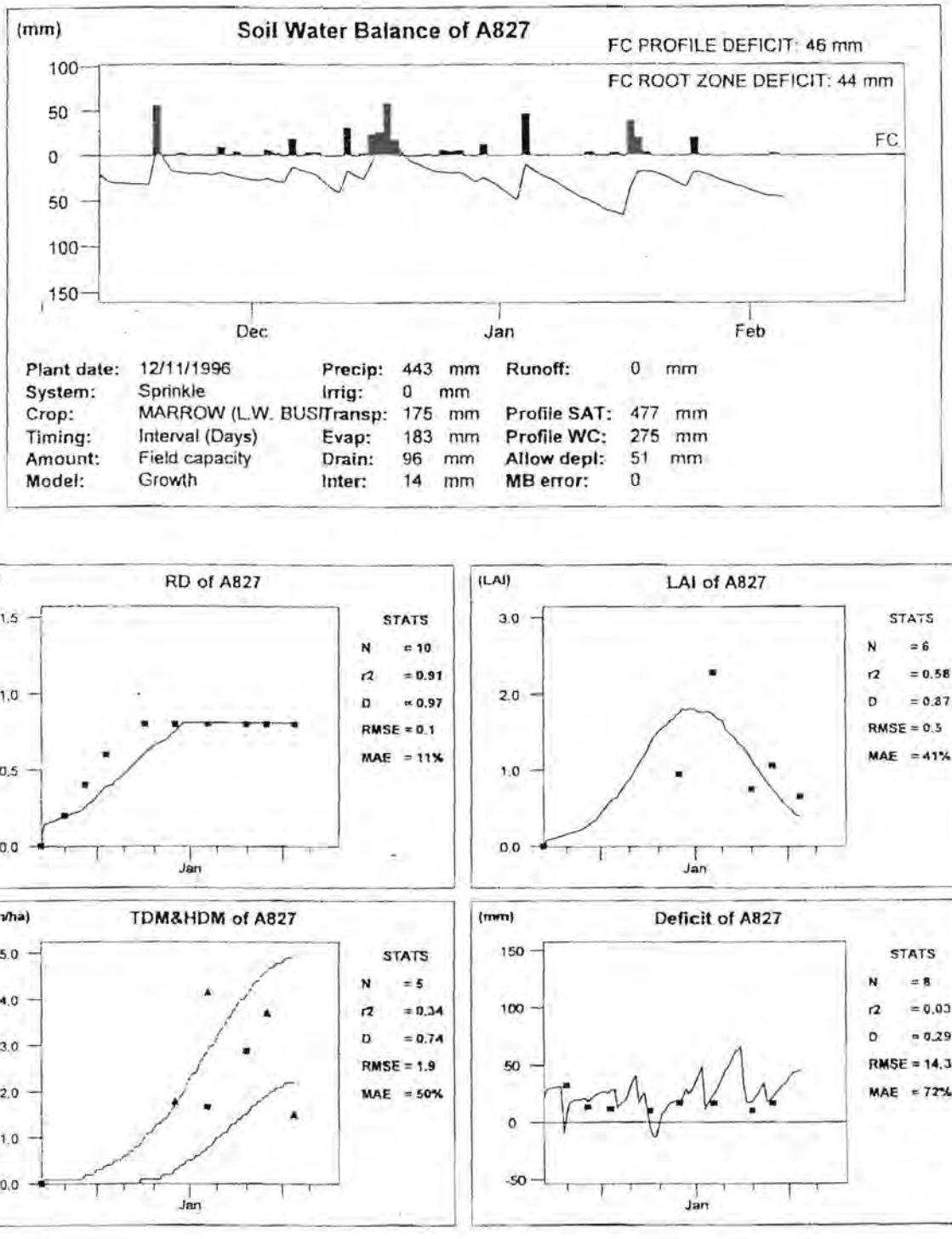
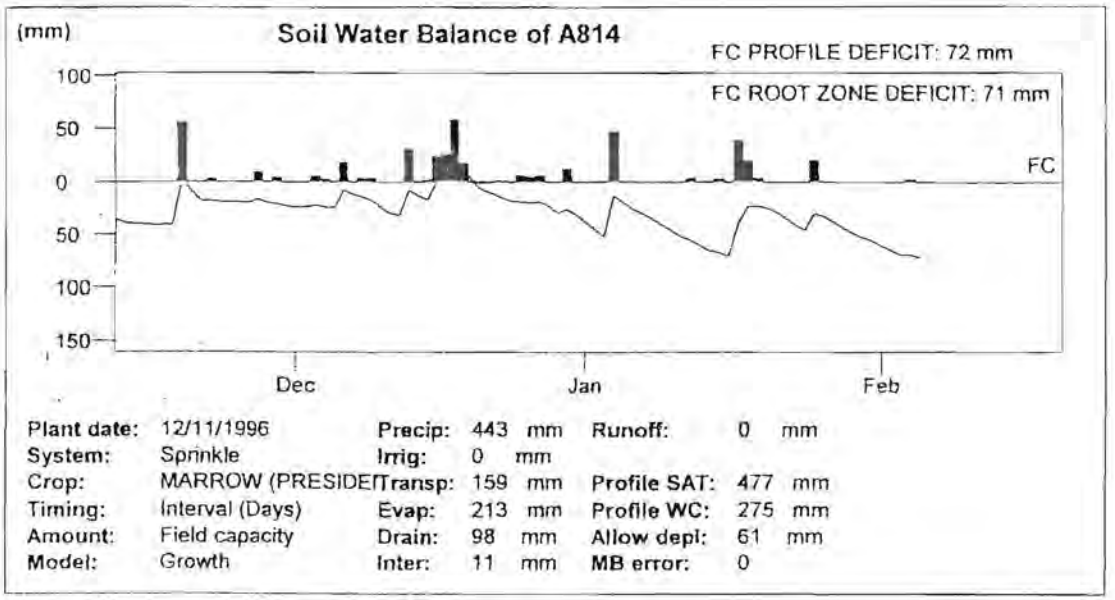


Figure 3.11 : Soil water balance output graph, simulated (solid lines) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit for marrow (cv. Long White Bush)



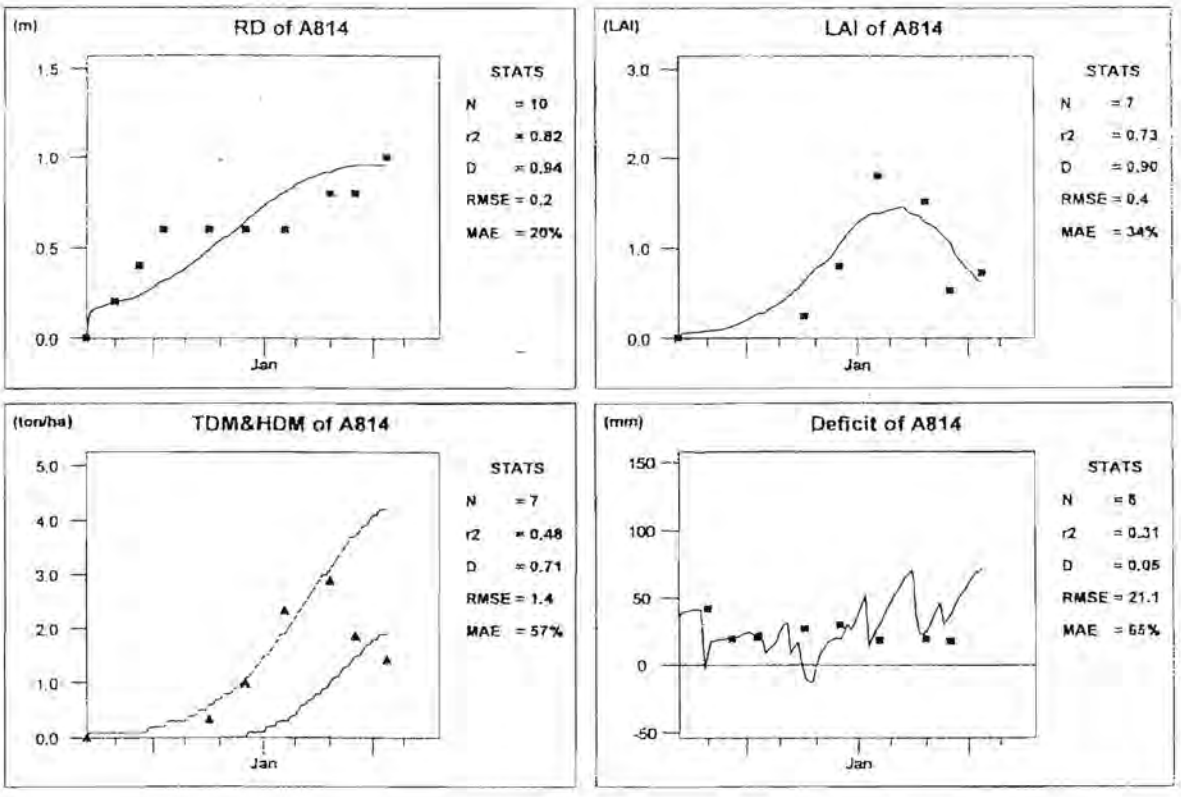


Figure 3.12 : Soil water balance output graph, simulated (solid lines) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit for marrow (cv. President).

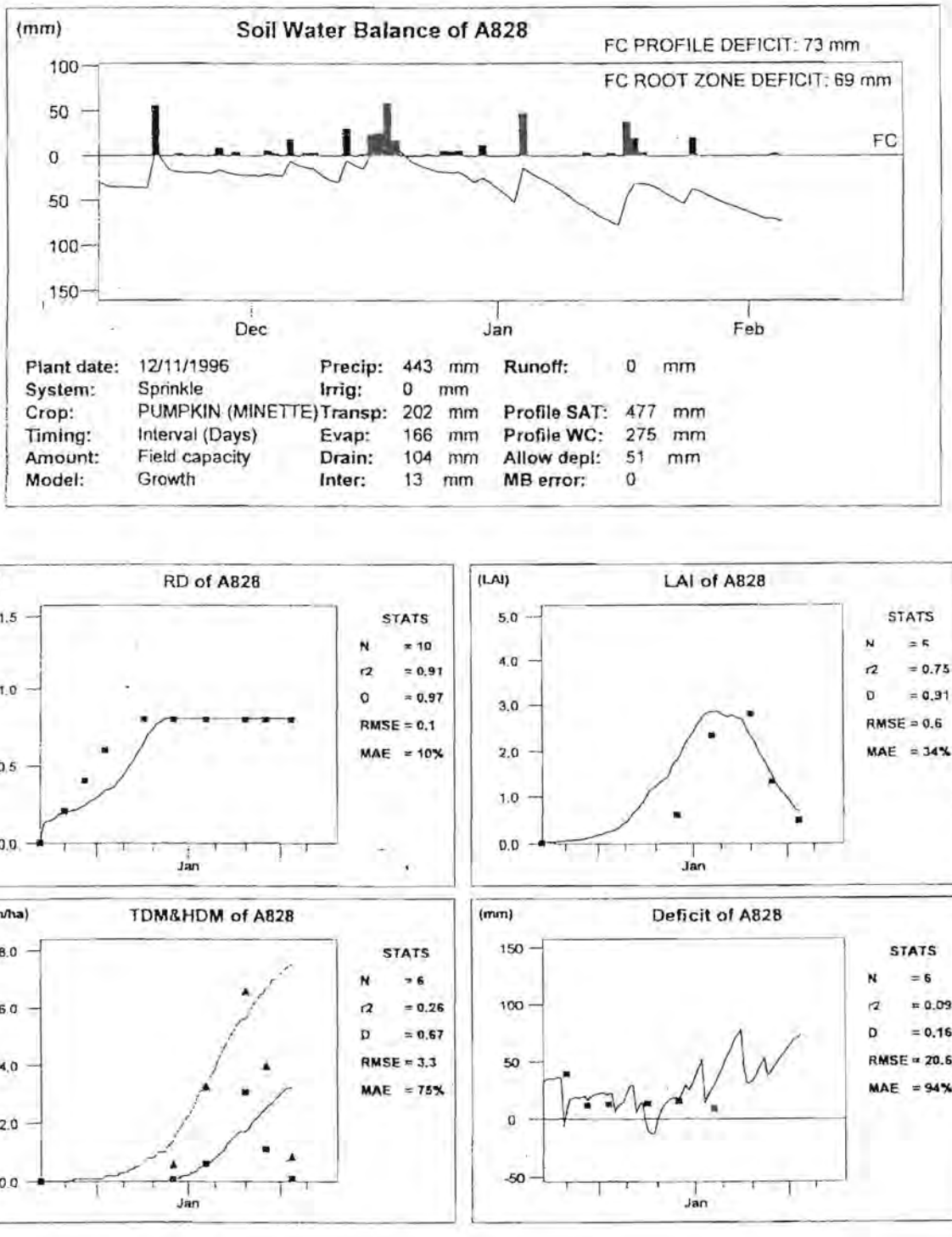


Figure 3.13 : Soil water balance output graph, simulated (solid lines) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit for pumpkin (cv. minette).

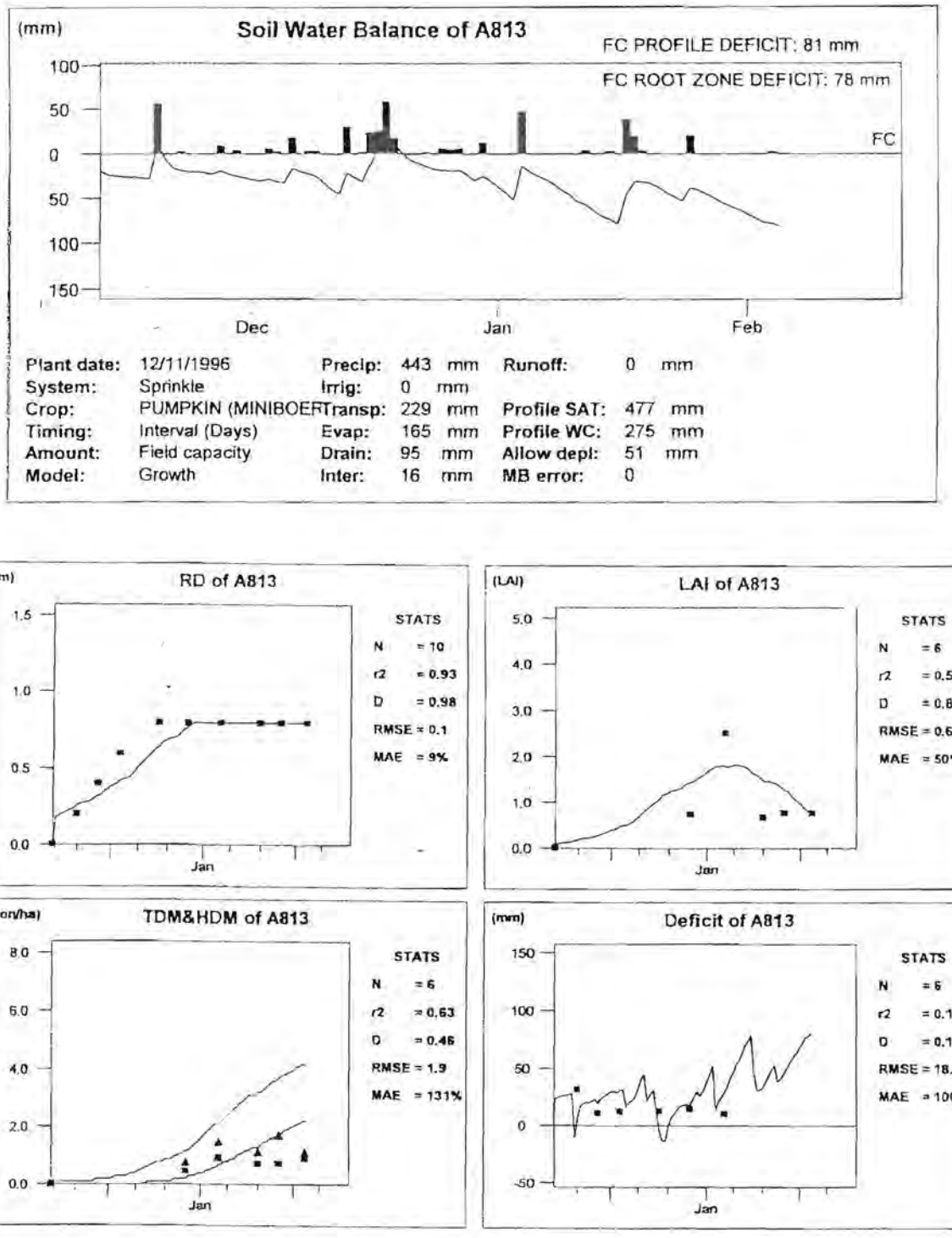


Figure 3.14 : Soil water balance output graph, simulated (solid lines) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit for pumpkin (cv. Miniboer).

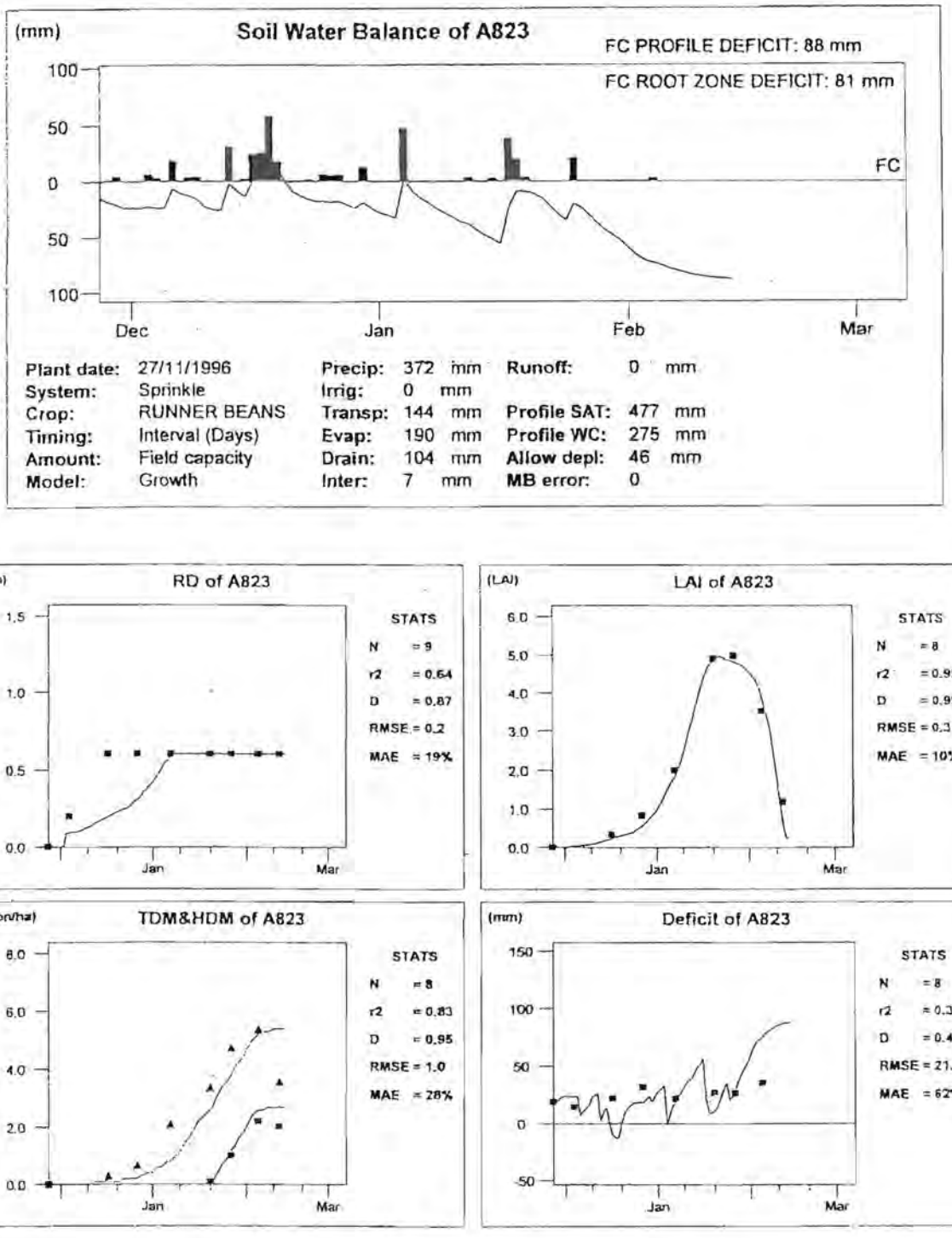


Figure 3.15 : Soil water balance output graph, simulated (solid lines) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit for runner bean

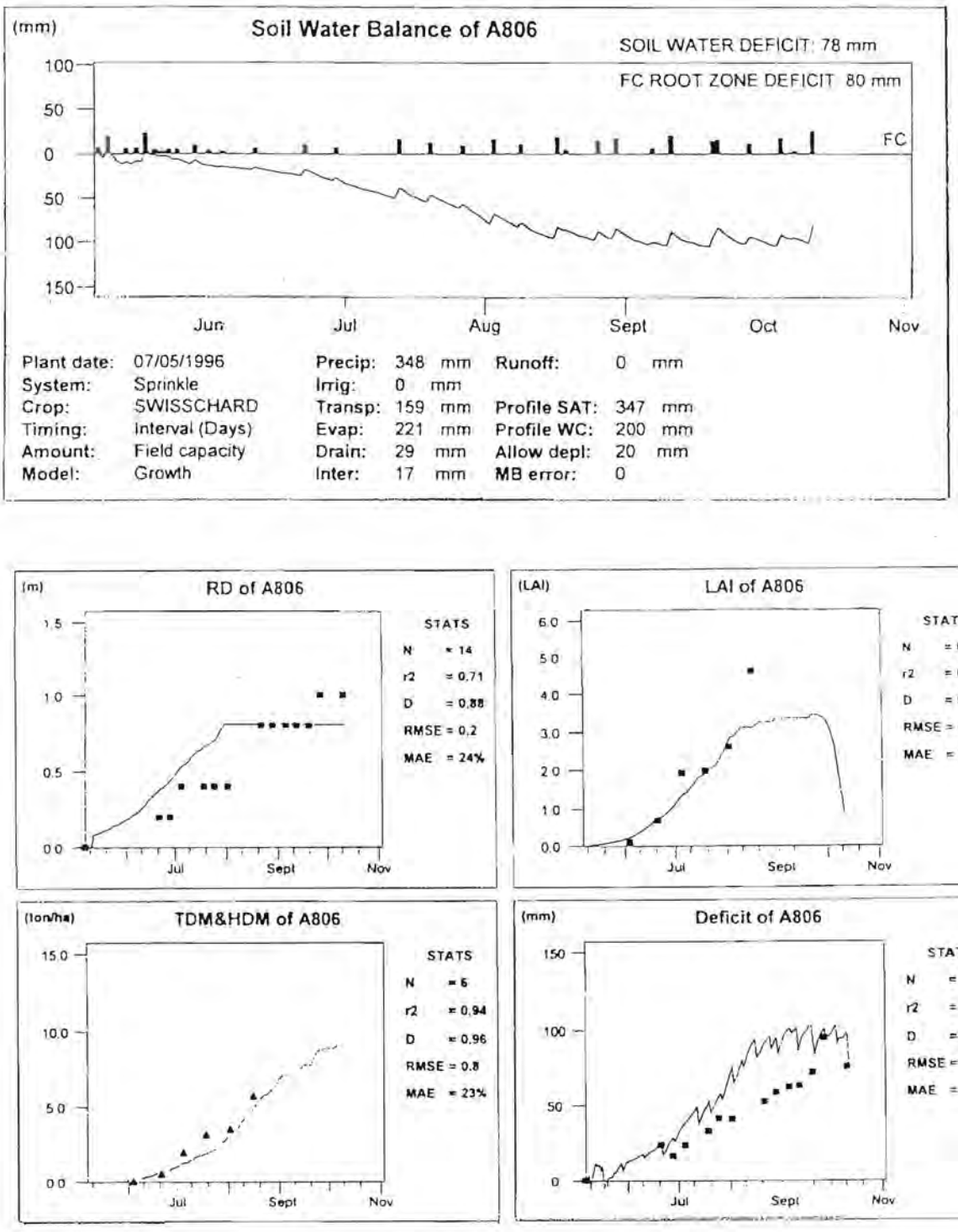


Figure 3.16 : Soil water balance output graph, simulated (solid lines) and measured (symbols0 root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit for swiss chard.

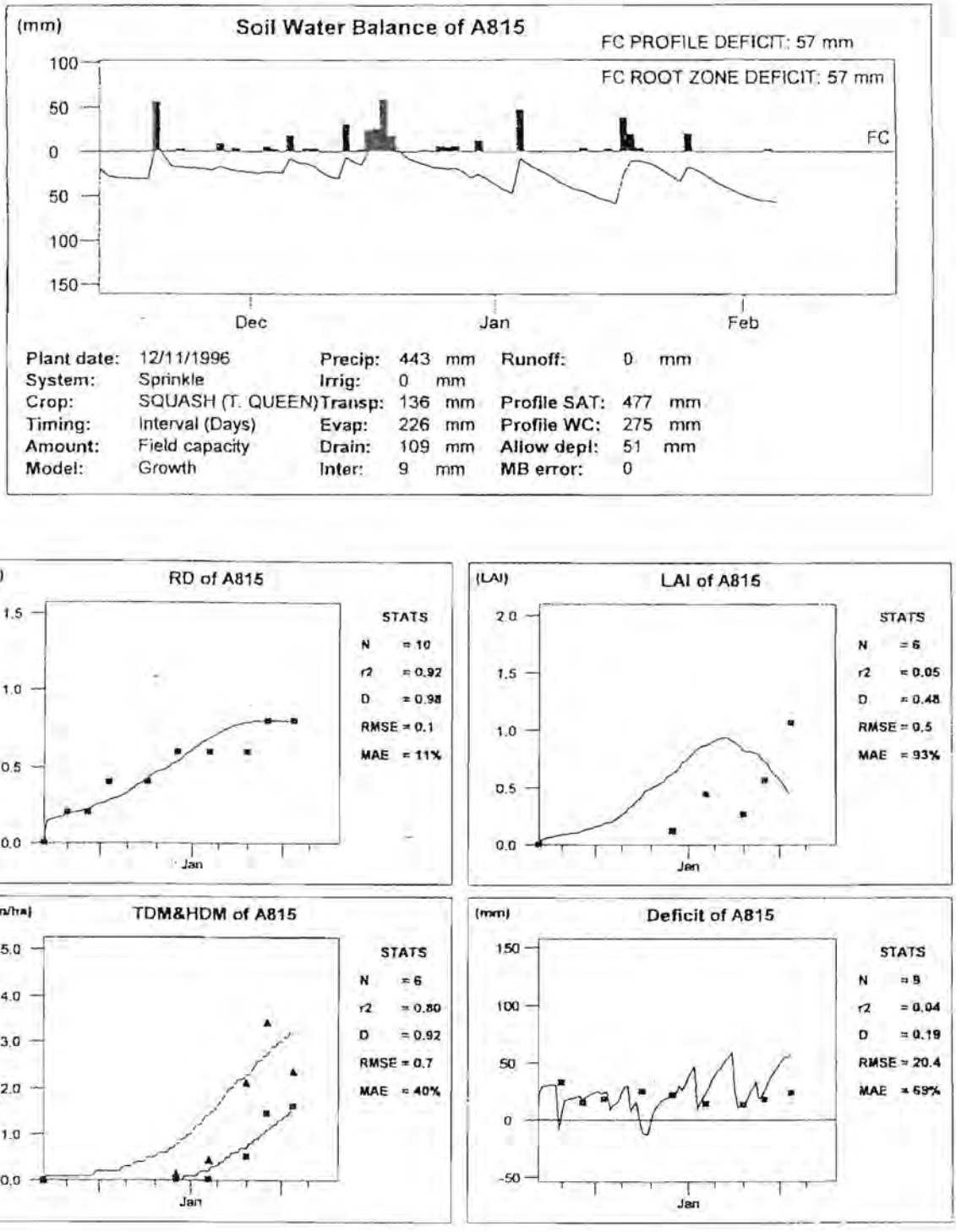
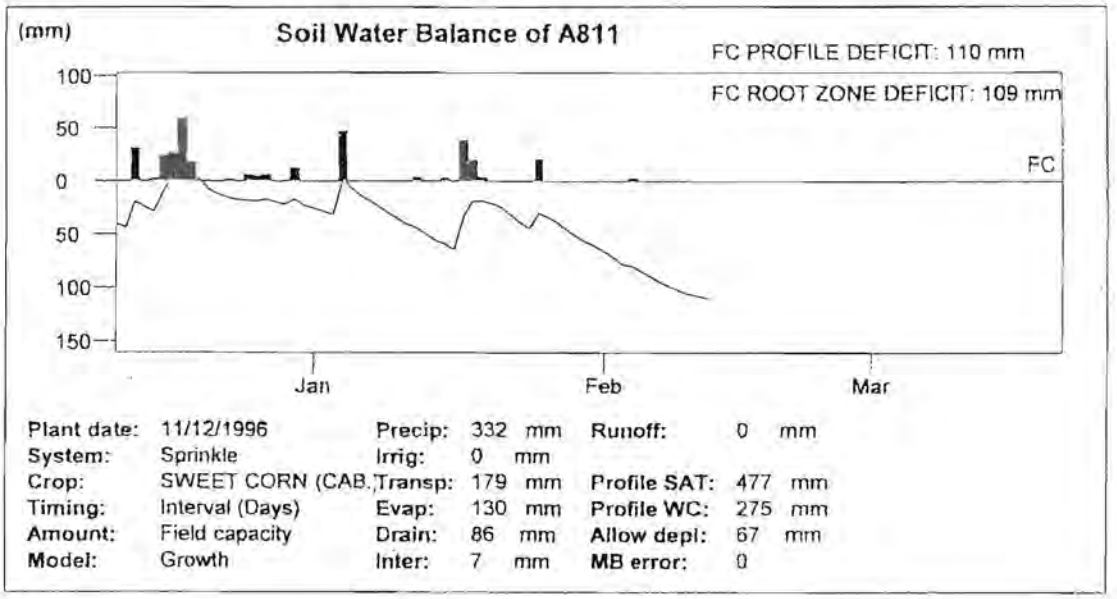


Figure 3.17 : Soil water balance output graph, simulated (solid lines) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit for squash (cv. Table Queen).



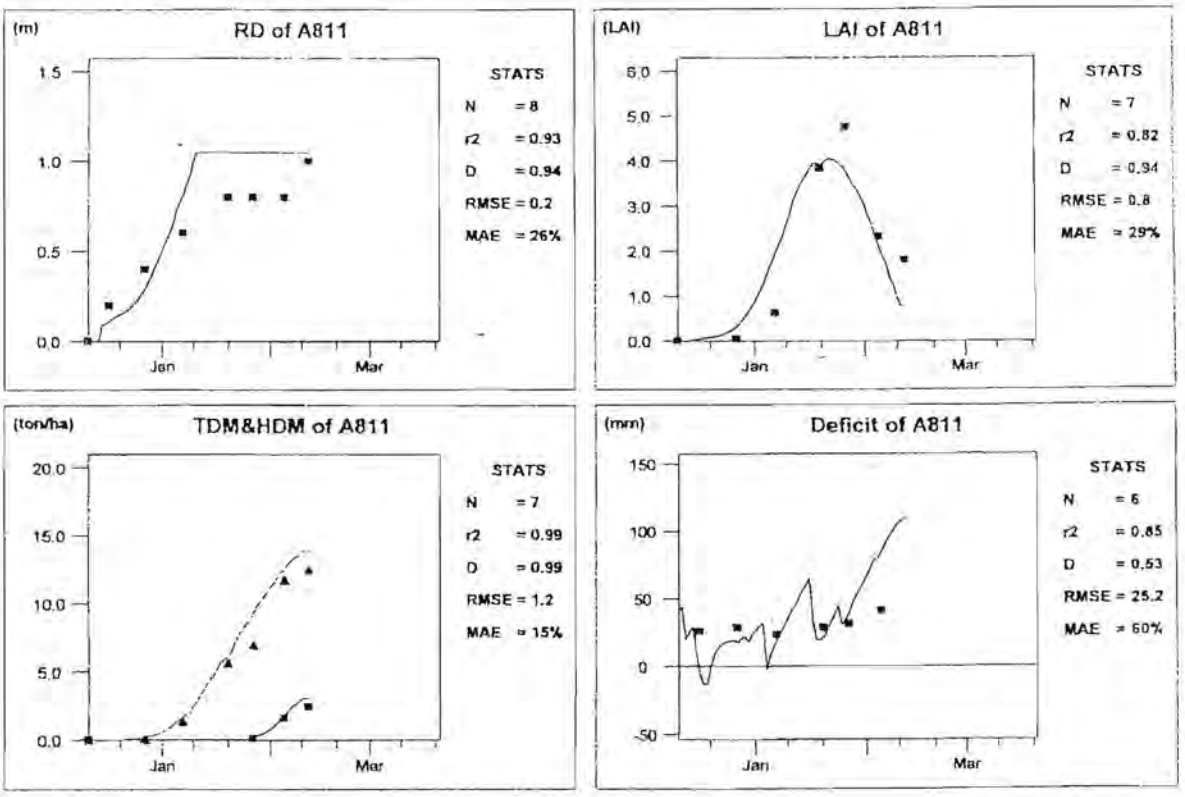


Figure 3.19 : Soil water balance output graph, simulated (solid lines) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit for sweet-corn (cv. Cabaret)

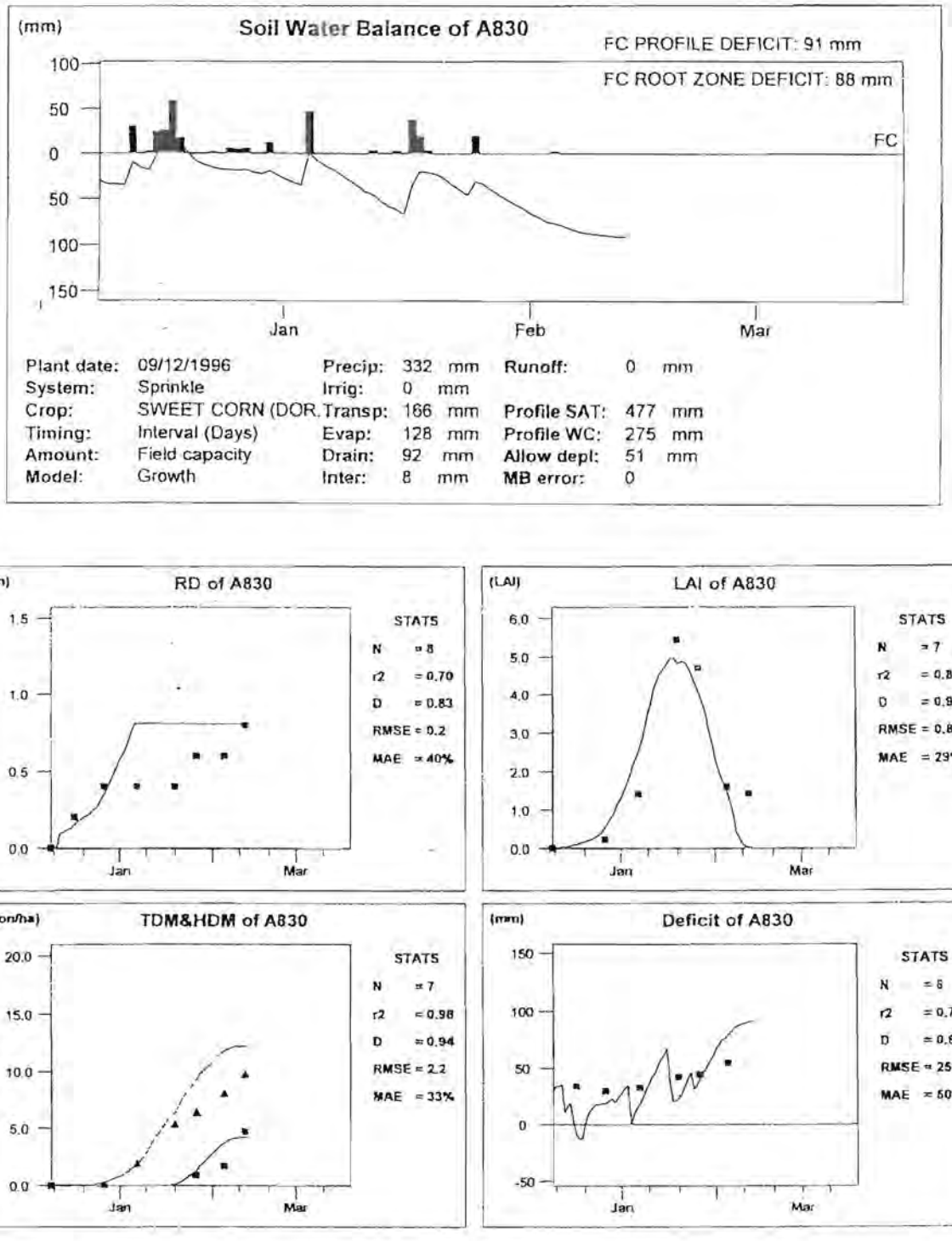


Figure 3.20 : Soil water balance output graph, simulated (solid lines) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit for sweet-corn (cv. Dorado).

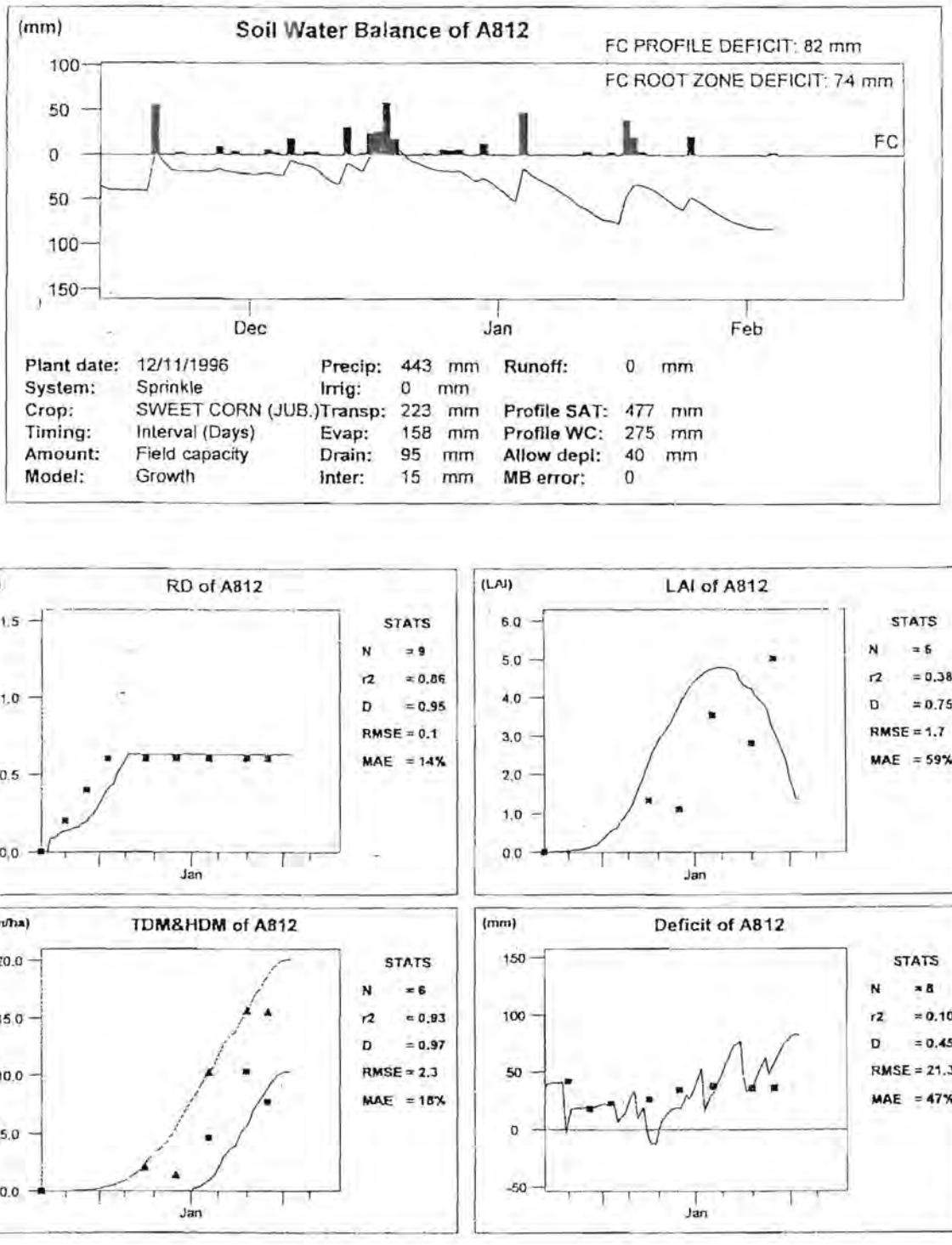
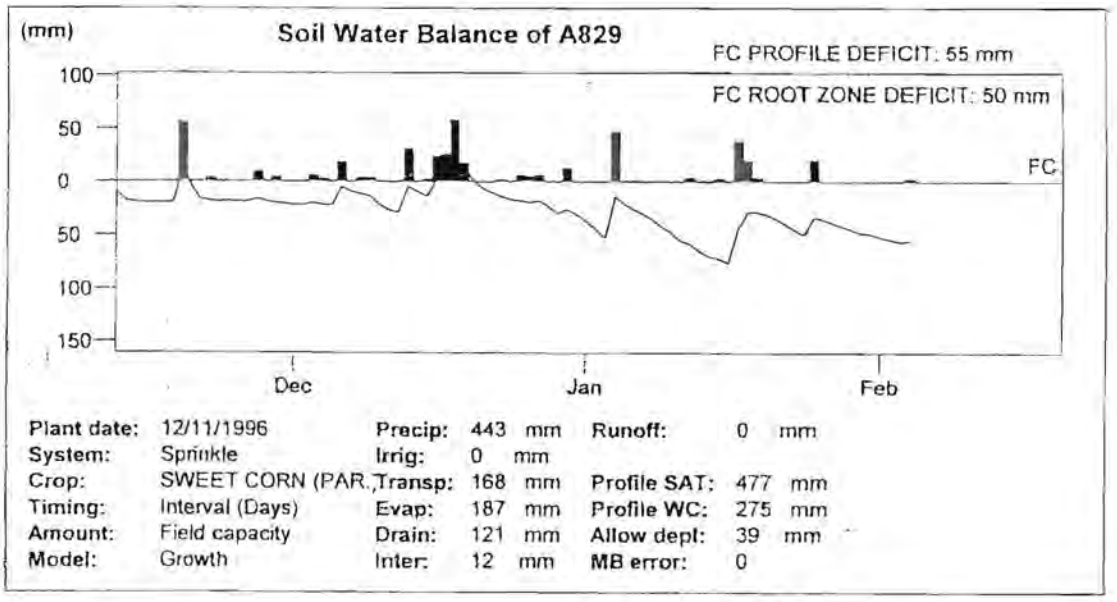


Figure 3.21 : Soil water balance output graph, simulated (solid lines) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit for sweet-corn (cv. Jubilee).



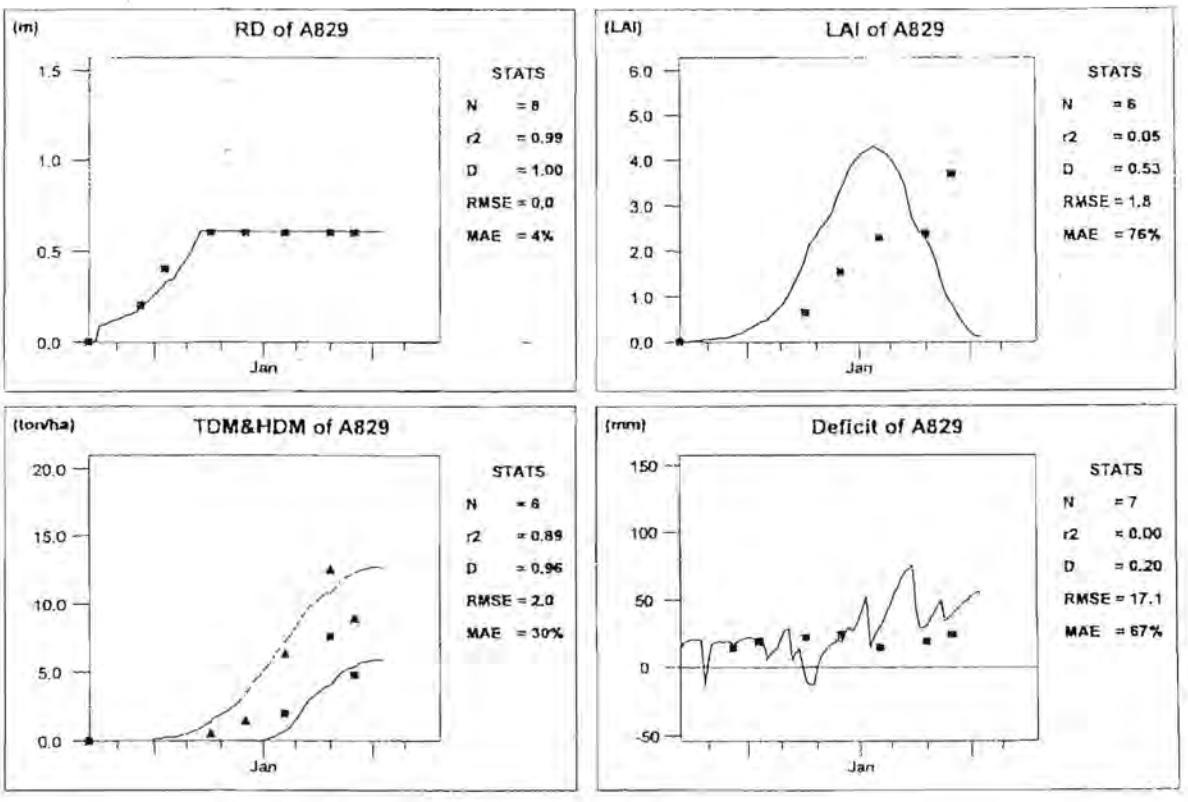


Figure 3.22 : Soil water balance output graph, simulated (solid lines) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit for sweet-corn (cv. Paradise).

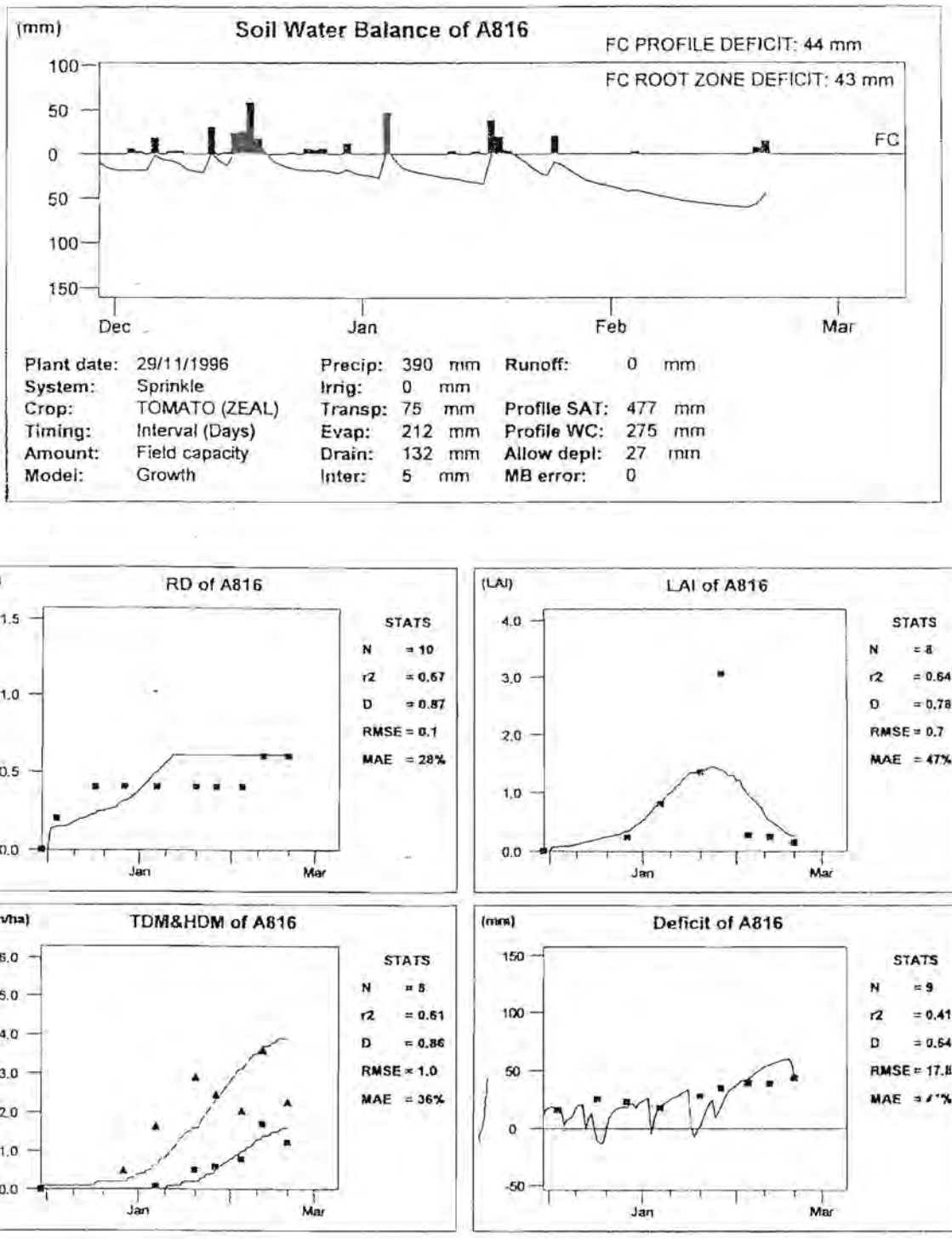


Figure 3.23 : Soil water balance output graph, simulated (solid lines) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit for tomato (cv. Zeal).

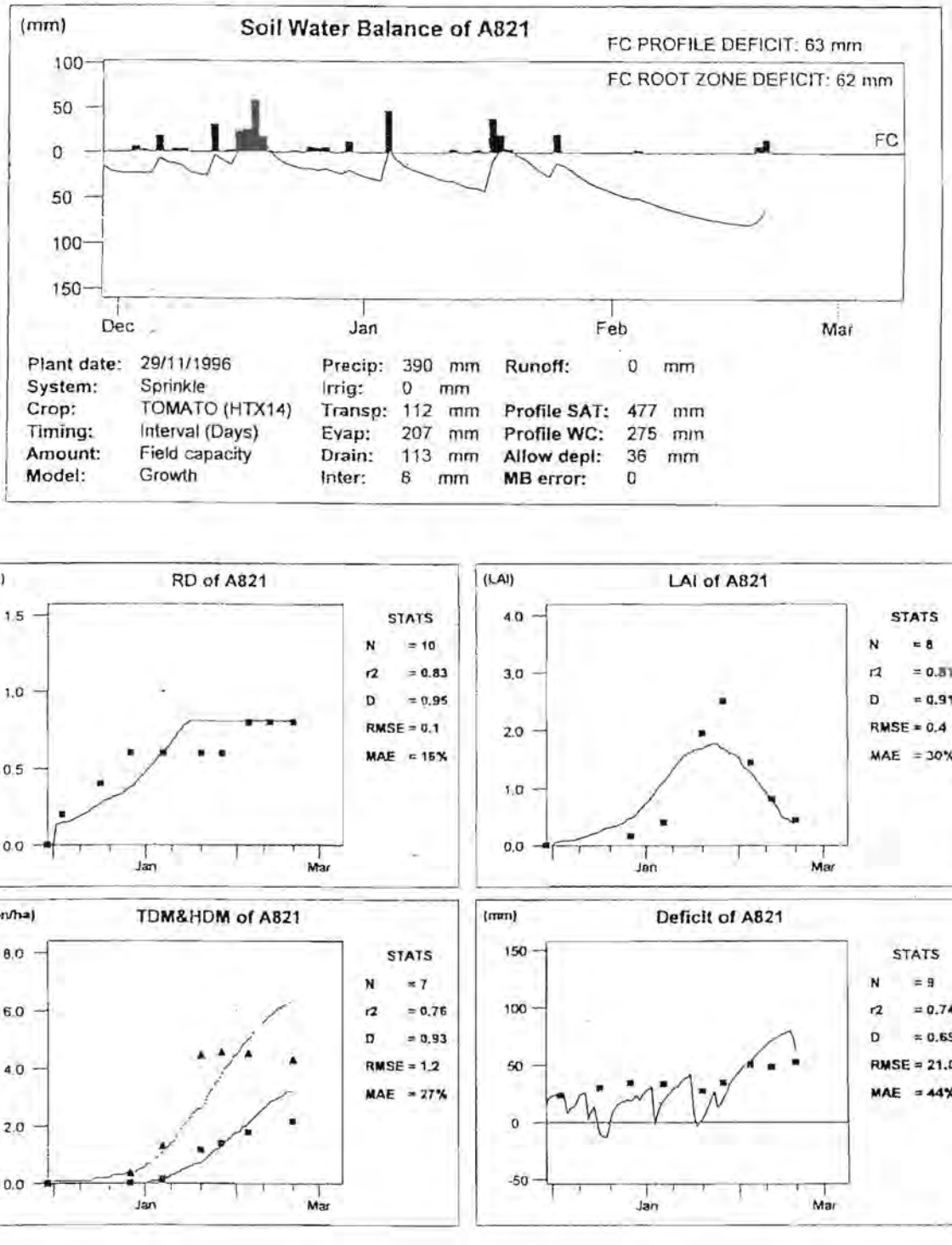


Figure 3.24 : Soil water balance output graph, simulated (solid lines) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit for tomato (cv. HTX4).

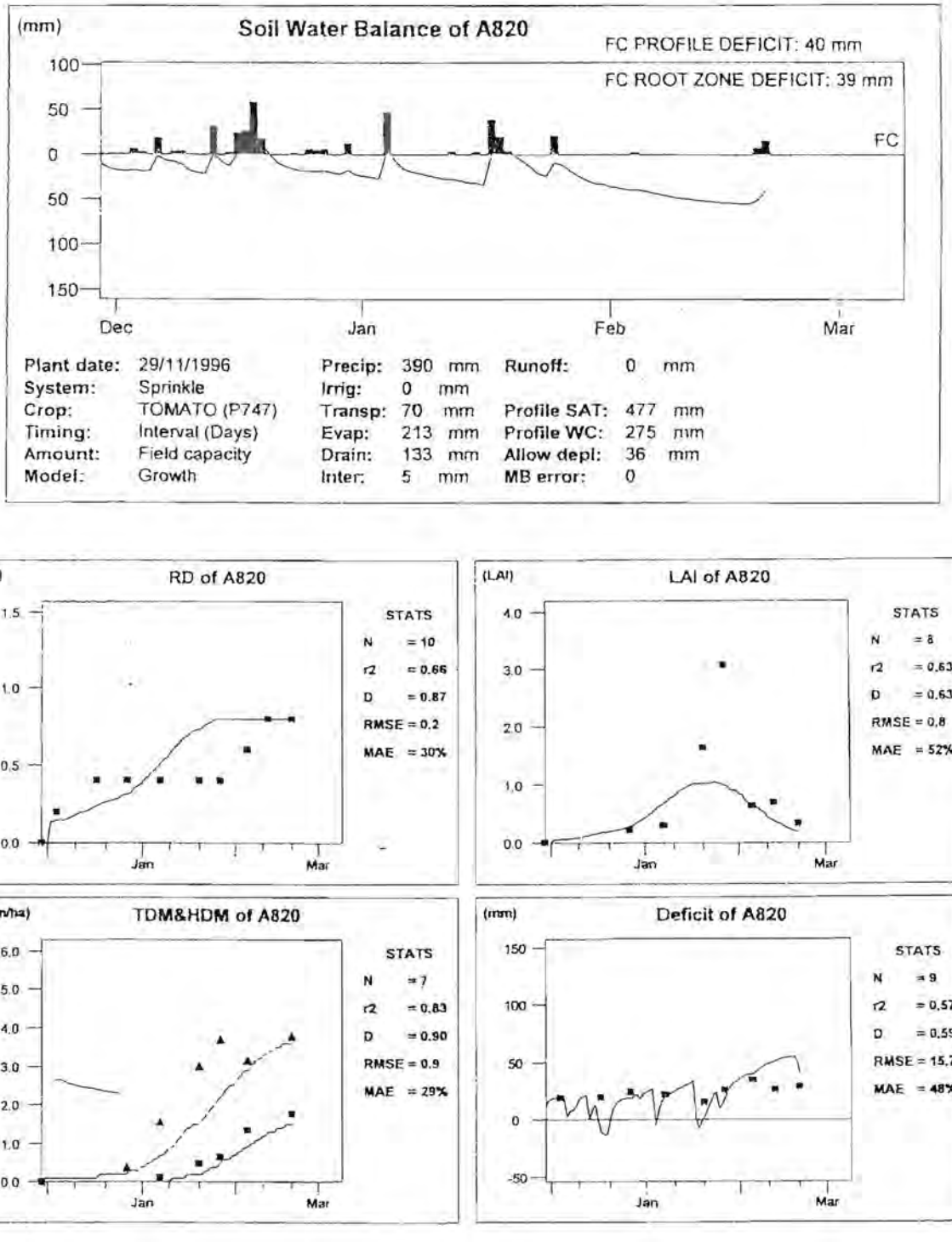


Figure 3.25 : Soil water balance output graph, simulated (solid lines) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit for tomato (cv. P747).

Appendix D : Climatic data for the duration of the trials

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 1996/97 at Roodeplaat

Date	R + I (mm)	Tmax (°C)	Tmin (°C)	Rs (MJm^{-2})	U (ms^{-1})	Td (°C)	Tw (°C)
7/5/96	6.6	22.4	9.8	12.2	-	15.1	13.0
8/5/96	0	24.4	7.9	15.1	-	14.8	12.1
9/5/96	19.1	23.4	7.9	12.9	-	14.3	11.8
10/5/96	0	23.8	6.5	14.4	-	13.9	11.2
11/5/96	0	22.3	6.9	15.2	-	15.0	11.6
12/5/96	0	25.4	5.7	14.9	-	14.6	11.0
13/5/96	5.5	22.7	8.0	10.9	-	13.2	11.1
14/5/96	0	21.2	8.5	10.6	-	13.2	11.3
15/5/96	6.2	21.2	5.9	7.9	-	13.5	11.6
16/5/96	0	21.9	10.3	9.3	-	16.1	13.0
17/5/96	22.3	21.5	11.9	9.6	-	15.7	13.4
18/5/96	0.2	20.4	9.5	11.9	-	13.7	12.2
19/5/96	4.6	21.4	8.3	9.5	-	13.6	11.9
20/5/96	2.7	22.3	6.6	13.9	-	13.6	11.5
21/5/96	2.2	21.8	5.9	10.2	-	12.9	10.9
22/5/96	4.4	20.0	7.6	10.2	-	12.9	11.3
23/5/96	0	23.1	4.8	14.3	-	12.3	9.7
24/5/96	4.4	23.8	3.6	14.5	-	12.7	9.6
25/5/96	0	23.1	4.9	14.7	-	13.3	9.7
26/5/96	0	16.7	10.6	6.2	-	13.0	10.5
27/5/96	0	15.7	8.5	5.6	-	11.6	10.0
28/5/96	8.5	18.3	4.5	4.5	-	10.1	7.9
29/5/96	0	20.0	2.4	2.4	-	10.0	7.6
30/5/96	0	21.2	1.5	1.5	-	10.1	7.5

Table A1 : Continued

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 1996/97 at Roodeplaat

Date	R + I (mm)	Tmax (°C)	Tmin (°C)	Rs (MJm^{-2})	U (ms^{-1})	Td (°C)	Tw (°C)
31/5/96	3.8	22.9	1.9	14.5	-	11.2	8.4
01/6/96	0	23.1	4.2	14.1	-	12.3	8.9
02/6/96	0	18.4	1.0	14.9	-	9.9	6.3
03/6/96	3.1	17.7	5.8	6.9	-	11.1	9.9
04/6/96	0	21.8	5.5	13.5	-	11.9	9.2
05/6/96	0	20.2	3.7	12.7	-	10.2	8.2
06/6/96	0	21.2	2.2	13.3	-	10.5	8.2
07/6/96	0	22.5	3.8	13.2	-	11.2	8.7
08/6/96	0	23.8	2.3	10.7	-	11.3	8.1
09/6/96	0	22.5	2.8	10.7	-	12.3	9.1
10/6/96	5.6	21.4	6.3	11.6	-	12.9	10.7
11/6/96	0	20.8	5.5	13.1	-	11.5	9.5
12/6/96	0	21.1	3.8	13.0	-	10.9	8.3
13/6/96	0	20.9	4.5	13.3	-	-	-
14/6/96	0	21.8	5.1	13.6	-	-	-
15/6/96	0	20.1	3.7	12.9	-	-	-
16/6/96	0	19.4	3.5	12.7	-	-	-
17/6/96	0	21.2	4.1	13.4	-	-	-
18/6/96	0	22.3	4.8	13.8	-	-	-
19/6/96	0	18.8	3.1	13.5	-	-	-
20/6/96	0	18.9	2.2	12.9	-	-	-
21/6/96	9.7	17.9	2.8	13.9	-	-	-
22/6/96	0	15.6	1.6	4.6	-	-	-

Table A1 : Continued

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 1996/97 at Roodeplaat

Date	R + I (mm)	Tmax (°C)	Tmin (°C)	Rs (MJm^{-2})	U (ms^{-1})	Td (°C)	Tw (°C)
23/6/96	0	17.8	1.6	11.5	-	8.1	6.2
24/6/96	0	17.2	1.4	8.2	-	8.5	6.2
25/6/96	0	20.3	0.9	12.4	-	9.9	6.9
26/6/96	0	20.8	0.3	13.4	-	8.9	5.4
27/6/96	0	20.9	1.4	13.4	-	8.5	5.2
28/6/96	6.6	20.1	1.0	13.4	-	8.9	5.0
29/6/96	0	21.2	0.8	13.4	-	8.9	5.2
30/6/96	0	21.6	0.3	13.4	-	9.0	5.6
01/7/96	0	23.7	0.0	13.6	-	8.8	5.4
02/7/96	0	23.9	0.5	13.7	-	10.2	5.9
03/7/96	0	22.4	0.2	14.1	-	9.4	5.3
04/7/96	0	22.6	0.1	13.7	-	9.9	5.9
05/7/96	0	21.0	0.4	13.5	-	9.7	5.6
06/7/96	0	15.2	1.8	14.5	-	7.9	4.5
07/7/96	0	11.8	4.3	8.2	-	7.4	5.5
08/7/96	0	13.4	1.1	12.6	-	5.9	3.6
09/7/96	0	18.8	0.3	14.0	-	7.7	4.2
10/7/96	0	20.2	1.0	14.5	-	10.2	6.8
11/7/96	0	21.1	-0.1	14.7	-	11.1	7.6
12/7/96	16.0	21.3	-0.1	14.6	-	10.3	6.7
13/7/96	0	21.1	-0.1	14.5	-	9.4	5.2
14/7/96	0.0	19.3	-0.1	14.0	-	8.7	5.0
15/7/96	0.0	17.9	0.8	14.6	-	8.3	5.0
16/7/96	0.0	17.5	-0.1	15.3	-	8.2	4.5

Table A1 : Continued

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 1996/97 at Roodeplaat

Date	R + I (mm)	Tmax (°C)	Tmin (°C)	Rs (MJm^{-2})	U (ms^{-1})	Td (°C)	Tw (°C)
17/7/96	0.4	7.8	5.3	13.0	-	6.9	5.5
18/7/96	0.0	15.2	2.4	14.3	-	7.4	5.2
19/7/96	12.0	16.0	-0.1	13.3	-	6.9	4.6
20/7/96	0.0	17.4	-0.1	14.4	-	7.6	4.9
21/7/96	0.0	17.8	-0.1	10.4	-	8.3	5.5
22/7/96	0.0	18.4	3.7	10.1	-	8.9	6.6
23/7/96	0.0	17.5	2.3	10.1	-	10.1	7.6
24/7/96	0.0	15.6	1.3	9.3	-	9.3	6.8
25/7/96	0.0	15.1	2.8	7.9	-	9.9	7.6
26/7/96	9.0	17.7	3.6	14.1	-	11.6	8.8
27/7/96	0.0	22.4	3.8	15.2	-	12.0	8.9
28/7/96	0.0	25.0	3.0	15.6	-	12.9	9.0
29/7/96	0.4	24.9	2.0	15.0	-	12.4	8.5
30/7/96	0.0	23.0	4.1	14.6	-	14.0	10.1
31/7/96	0.0	22.6	3.5	14.8	-	12.3	9.5
01/8/96	0.0	25.6	4.5	13.8	-	13.8	9.8
02/8/96	16.0	24.6	1.2	15.1	-	12.2	7.2
03/8/96	0.0	20.4	5.0	8.0	-	12.4	9.3
04/8/96	0.0	14.9	8.3	2.0	-	12.8	11.0
05/8/96	1.2	14.0	9.8	2.1	-	10.7	9.9
06/8/96	0.0	17.3	-0.1	16.9	-	8.0	4.6
07/8/96	0.0	19.2	-0.1	17.0	-	8.7	4.8
08/8/96	10.0	20.8	-0.1	17.4	-	9.7	5.3
09/8/96	0.0	23.4	-0.1	17.8	-	10.4	5.8

Table A1 : Continued

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 1996/97 at Roodeplaat

Date	R + I (mm)	Tmax (°C)	Tmin (°C)	Rs (MJm^{-2})	U (ms^{-1})	Td (°C)	Tw (°C)
10/8/96	0.0	26.1	1.5	16.9	-	13.1	8.4
11/8/96	0.0	27.4	6.4	15.7	-	16.4	11.2
12/8/96	0.0	26.4	11.1	13.5	-	16.6	12.7
13/8/96	0.0	26.8	6.0	16.8	-	15.3	10.4
14/8/96	0.0	22.0	-0.1	9.1	-	11.9	6.9
15/8/96	0.0	17.7	8.7	9.7	-	12.1	9.3
16/8/96	18.0	22.7	0.3	17.6	-	11.0	7.9
17/8/96	0.0	26.6	4.4	18.2	-	14.2	9.0
18/8/96	4.4	23.3	6.7	13.7	-	15.3	11.6
19/8/96	0.0	24.5	7.3	14.9	-	14.8	11.3
20/8/96	0.0	15.2	11.3	2.6	-	12.7	10.7
21/8/96	0.0	18.7	4.8	13.4	-	11.7	9.2
22/8/96	0.4	19.1	8.7	12.4	-	-	-
23/8/96	0.0	19.7	4.1	12.4	-	-	-
24/8/96	0.0	22.3	-0.1	12.4	-	-	-
25/8/96	14.0	25.1	4.3	12.4	-	-	-
26/8/96	0.0	29.2	3.7	12.4	-	-	-
27/8/96	0.0	26.2	4.2	12.4	-	-	-
28/8/96	0.0	26.2	4.2	12.4	-	-	-
29/8/96	17.2	23.2	4.7	11.4	0.8	12.8	7.9
30/8/96	0.0	23.1	2.5	21.3	1.3	12.2	7.7
31/8/96	0.0	25.4	2.3	21.3	1.8	13.3	7.9
01/9/96	0.0	28.3	4.2	21.5	1.6	16.4	9.8
02/9/96	0.0	29.4	5.5	21.4	1.8	16.5	11.1

Table A1 : Continued

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 1996/97 at Roodeplaat

Date	R + I (mm)	Tmax (°C)	Tmin (°C)	Rs (MJm^{-2})	U (ms^{-1})	Td (°C)	Tw (°C)
03/9/96	0.0	29.4	5.5	21.0	1.7	17.5	11.0
04/9/96	0.0	25.8	7.4	19.6	2.0	16.3	12.1
05/9/96	0.0	28.3	6.6	21.3	2.3	16.7	11.5
06/9/96	0.7	29.2	4.0	22.6	2.3	16.4	9.5
07/9/96	0.0	28.4	3.7	22.9	2.0	15.8	9.4
08/9/96	0.0	30.2	3.8	23.2	1.2	17.0	10.3
09/9/96	0.0	31.0	6.8	23.4	1.6	17.5	10.8
10/9/96	20.0	32.4	8.6	20.8	1.9	21.0	13.6
11/9/96	0.0	31.9	8.8	21.6	1.9	20.9	13.0
12/9/96	0.0	32.4	8.0	20.4	3.6	21.7	13.4
13/9/96	0.0	24.4	6.7	22.7	2.2	16.0	9.6
14/9/96	0.0	25.6	2.8	24.4	1.3	14.4	11.7
15/9/96	0.0	25.9	6.8	23.7	3.1	17.4	17.4
16/9/96	0.0	27.8	8.4	22.1	2.1	17.8	15.1
17/9/96	0.0	32.0	8.8	21.7	4.2	21.7	14.0
18/9/96	0.0	20.8	9.6	17.3	4.1	14.7	9.7
19/9/96	13.4	20.9	3.3	23.0	2.5	13.8	8.8
20/9/96	15.0	15.3	8.2	4.1	2.0	12.8	10.7
21/9/97	0.0	24.4	9.3	19.4	1.5	16.0	12.9
22/9/97	0.4	28.1	8.2	22.5	1.8	18.5	13.7
23/9/96	0.0	25.1	13.0	20.1	3.5	17.3	13.5
24/9/96	0.0	27.7	10.8	21.3	2.3	18.2	13.9
25/9/96	0.0	30.5	10.1	20.4	2.5	20.3	14.7
26/9/96	0.0	28.3	3.7	26.2	1.8	17.1	10.3
27/9/96	11.0	28.8	6.9	25.2	2.6	19.1	13.1

Table A1 : Continued

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 1996/97 at Roodeplaat

Date	R + I (mm)	Tmax (°C)	Tmin (°C)	Rs (MJm^{-2})	U (ms^{-1})	Td (°C)	Tw (°C)
28/9/96	0.0	28.0	8.0	22.5	1.6	17.4	13.7
29/9/96	0.0	29.1	8.6	25.4	1.2	18.2	13.9
30/9/96	0.0	31.2	9.4	25.8	1.5	20.2	14.6
01/10/96	0.0	32.5	9.9	26.4	1.5	20.8	13.8
02/10/96	0.0	34.1	9.4	26.1	2.6	22.5	14.1
03/10/96	0.0	32.2	9.8	26.2	3.5	22.5	14.8
04/10/96	17.6	32.0	10.9	25.3	3.3	23.4	15.9
05/10/96	0.6	28.4	16.4	12.7	2.5	22.0	16.4
06/10/96	1.6	30.0	15.2	21.7	3.1	21.9	15.8
07/10/96	3.2	31.8	11.8	21.7	1.8	22.5	15.9
08/10/96	0.0	31.7	13.6	23.5	1.6	22.6	16.6
09/10/96	0.0	31.9	15.1	19.3	1.7	22.7	16.8
10/10/96	0.0	27.7	16,5	23.9	3.6	21.5	16.7
11/10/96	25.0	30.6	10.7	24.8	2.3	20.7	15.7
12/10/96	0.0	25.7	15.1	10.4	2.3	20.3	15.9
13/10/96	0.0	29.6	12.7	21.5	3.0	21.3	16.7
14/10/96	0.0	32.1	13.6	23.6	2.1	23.5	17.9
15/10/96	0.6	33.0	15.8	26.1	2.6	23.4	17.8
16/10/96	9.6	21.4	12.3	14.1	3.2	16.8	13.2
17/10/96	0.0	26.2	7.0	27.2	1.6	16.8	13.1
18/10/96	0.0	30.2	10.2	26.3	1.4	20.3	15.3
19/10/96	0.0	32.5	12.4	28.4	2.4	22.4	16.3
20/10/96	0.0	32.1	11.1	26.4	2.5	22.4	15.9
21/10/96	0.0	28.6	15.7	24.6	4.8	21.2	16.0

Table A1 : Continued

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 1996/97 at Roodeplaat

Date	R + I (mm)	Tmax (°C)	Tmin (°C)	Rs (MJm^{-2})	U (ms^{-1})	Td (°C)	Tw (°C)
22/10/96	6.0	26.7	11.8	19.8	2.8	19.1	15.8
23/10/96	20.4	21.3	14.7	11.1	3.0	17.5	15.7
24/10/96	0.0	28.5	14.0	23.6	2.0	20.7	17.5
25/10/96	0.0	31.5	16.1	24.7	2.0	22.8	18.1
26/10/96	32.6	29.3	12.7	26.9	2.7	20.5	16.7
27/10/96	0.2	29.6	14.1	28.9	1.4	21.1	17.0
28/10/96	22.6	30.4	13.9	27.7	2.5	21.9	17.5
29/10/96	0.0	27.0	15.7	24.6	2.2	19.3	16.1
30/10/96	30.0	26.7	11.8	19.8	3.4	18.9	16.3
31/10/96	102.0	21.3	14.7	11.1	1.8	20.3	16.6
01/11/96	0.0	28.5	14.0	23.6	1.5	22.4	17.4
02/11/96	0.0	31.5	16.1	24.7	1.5	23.7	18.0
03/11/96	163.0	29.3	12.7	26.9	1.8	25.2	18.8
04/11/96	1.0	29.6	14.1	28.9	1.9	25.4	19.1
05/11/96	113.0	30.4	13.9	27.7	2.4	26.0	17.9
06/11/96	27.4	28.4	13.7	22.4	4.0	23.3	18.0
07/11/96	33.6	25.7	14.0	19.5	4.5	21.7	17.5
08/11/96	2.0	28.7	13.4	27.3	3.0	21.9	18.2
09/11/96	0.0	31.5	13.0	29.5	1.6	22.1	17.1
10/11/96	0.0	33.4	14.4	29.1	2.9	23.0	18.4
11/11/96	0.0	35.4	15.9	29.9	2.2	22.3	17.8
12/11/96	0.0	33.5	17.1	29.1	2.0	23.9	18.6
13/11/96	0.0	33.2	15.9	30.3	2.1	22.5	18.3
14/11/96	0.0	28.8	16.1	29.1	3.5	17.9	16.2

Table A1 : Continued

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 1996/97 at Roodeplaat

Date	R + I (mm)	Tmax (°C)	Tmin (°C)	Rs (MJm^{-2})	U (ms^{-1})	Td (°C)	Tw (°C)
15/11/96	0.0	27.1	16.7	24.0	3.5	17.8	15.5
16/11/96	0.0	28.4	17.6	17.3	2.8	17.5	16.4
17/11/96	0.0	30.2	13.4	27.4	1.7	18.9	16.5
18/11/96	0.0	31.0	15.2	25.9	2.4	18.9	15.2
19/11/96	55.8	28.3	18.1	20.6	2.6	17.5	15.0
20/11/96	0.0	30.8	16.8	25.7	3.4	19.5	16.0
21/11/96	0.0	29.5	18.7	14.8	3.6	20.0	16.1
22/11/96	2.8	22.6	14.9	14.1	1.6	15.6	10.1
23/11/96	0.2	23.0	13.7	14.4	1.7	19.0	13.4
24/11/96	1.2	19.9	16.1	6.8	2.5	18.3	15.7
25/11/96	0.6	22.8	14.4	15.7	2.0	18.3	16.0
26/11/96	0.6	28.1	13.4	26.6	2.0	19.7	16.0
27/11/96	9.4	26.5	14.0	22.9	1.8	18.2	15.9
28/11/96	0.6	25.9	12.0	22.1	2.8	14.4	15.8
29/11/96	4.6	28.5	13.4	23.3	2.3	18.3	13.8
30/11/96	0.0	25.1	4.5	32.5	1.9	21.1	16.3
01/12/96	0.0	28.0	7.3	32.4	1.6	21.9	18.0
02/12/96	0.0	25.0	13.2	18.5	2.7	22.2	18.6
03/12/96	6.3	26.1	12.3	22.9	1.9	24.1	18.8
04/12/96	2.8	30.9	12.7	26.3	2.6	22.1	18.4
05/12/96	0.0	21.4	15.7	9.4	2.1	20.0	18.1
06/12/96	18.4	16.0	13.7	4.5	2.5	14.8	14.7
07/12/96	0.2	24.8	14.4	22.9	1.7	20.7	17.9
08/12/96	3.6	28.5	14.6	23.0	1.4	19.2	17.6

Table A1 : Continued

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 1996/97 at Roodeplaat

Date	R + I (mm)	Tmax (°C)	Tmin (°C)	Rs (MJm^{-2})	U (ms^{-1})	Td (°C)	Tw (°C)
09/12/96	4.0	29.8	16.2	26.2	1.7	19.8	17.3
10/12/96	0.0	32.2	15.6	27.8	1.6	19.7	17.0
11/12/96	0.0	31.2	16.8	30.1	1.4	19.3	16.8
12/12/96	0.0	29.9	14.2	31.8	1.7	19.3	17.1
13/12/96	31.0	26.5	12.7	24.8	1.4	-	-
14/12/96	0.0	28.6	14.7	24.2	1.4	22.3	18.8
15/12/96	2.2	28.5	14.7	23.6	1.6	-	-
16/12/96	24.0	25.2	15.4	20.3	-	-	-
17/12/96	26.0	27.1	13.5	26.3	1.6	-	-
18/12/96	58.4	29.1	14.3	31.8	2.3	23.1	18.7
19/12/96	17.9	27.5	14.8	9.7	1.7	21.7	18.7
20/12/96	0.0	23.9	14.8	13.1	2.5	19.1	16.4
21/12/96	0.0	28.5	16.1	20.1	1.4	18.6	16.2
22/12/96	0.0	20.4	15.9	8.7	1.3	21.1	17.8
23/12/96	1.7	28.9	15.7	12.5	2.8	22.3	18.1
24/12/96	0.0	22.6	14.8	12.6	1.2	20.5	18.2
25/12/96	6.4	30.6	15.6	31.0	0.8	20.9	18.5
26/12/96	5.2	28.6	16.4	25.6	1.5	24.0	19.5
27/12/96	6.4	25.0	12.6	19.4	1.5	24.5	19.8
28/12/96	0.0	25.8	14.9	20.6	1.4	22.8	18.8
29/12/96	0.0	28.6	14.9	31.0	1.8	22.5	18.4
30/12/96	12.6	29.6	16.6	29.4	3.0	22.9	18.5
31/12/96	0.0	26.9	15.9	17.8	2.5	21.9	18.7

Table A1 : Continued

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 1996/97 at Roodeplaat

Date	R + I (mm)	Tmax (°C)	Tmin (°C)	Rs (MJm^{-2})	U (ms^{-1})	Td (°C)	Tw (°C)
25/01/97	20.6	28.4	18.3	18.1	1.5	23.8	19.7
26/01/97	0.0	26.0	17.6	15.0	1.3	23.1	19.5
27/01/97	0.0	30.2	15.8	26.8	1.2	23.0	19.1
28/01/97	0.0	30.6	16.7	26.1	1.1	22.9	19.8
29/01/97	0.2	29.1	20.0	24.2	2.0	23.8	19.2
30/01/97	0.0	28.9	17.5	19.4	2.0	22.1	18.1
31/01/97	0.0	27.7	18.6	17.1	1.6	23.1	19.0
01/02/97	0.0	31.8	16.6	30.3	1.4	23.5	19.1
02/02/97	0.0	29.8	17.0	19.8	1.7	23.9	18.1
03/02/97	2.8	31.6	14.9	28.7	1.6	23.7	19.5
04/02/97	0.0	28.9	18.6	16.0	1.9	24.7	20.3
05/02/97	0.0	29.5	18.1	22.2	1.3	23.4	18.7
06/02/97	0.0	31.2	15.2	28.3	1.1	23.7	18.7
07/02/97	0.0	32.8	13.6	27.5	1.3	23.8	19.1
08/02/97	0.0	32.9	17.3	28.9	1.9	23.8	20.0
09/02/97	0.0	33.4	13.1	31.4	2.1	22.4	18.8
10/02/97	0.0	32.1	15.5	29.0	2.4	21.8	18.5
11/02/97	0.0	31.1	18.3	22.9	2.5	22.0	18.6
12/02/97	0.0	33.0	15.7	27.5	1.5	22.2	19.8
13/02/97	0.0	33.0	14.6	26.1	1.7	22.2	19.8
14/02/97	0.0	32.6	14.8	24.0	2.6	-	-
15/02/97	0.2	32.4	17.0	26.3	2.0	22.9	19.8
16/02/97	0.0	28.6	18.3	21.3	1.3	21.0	17.9
17/02/97	0.0	30.1	17.4	25.1	1.3	21.6	18.1

Table A1 : Continued

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 1996/97 at Roodeplaat

Date	R + I (mm)	Tmax (°C)	Tmin (°C)	Rs (MJm^{-2})	U (ms^{-1})	Td (°C)	Tw (°C)
18/02/97	0.2	30.1	14.9	24.2	1.3	22.8	19.1
19/02/97	7.6	30.1	16.7	17.4	1.6	23.4	19.0
20/02/97	1.5	28.7	18.0	22.0	1.2	24.7	19.2
21/02/97	0.0	27.8	17.5	21.2	1.5	24.2	19.2
22/02/97	1.4	28.4	17.4	18.6	1.1	24.4	19.6
23/02/97	0.0	28.5	16.5	20.5	2.2	24.5	19.4
24/02/97	0.0	31.6	14.0	25.4	2.4	22.5	18.0
25/02/07	3.6	32.5	16.0	22.3	2.2	21.2	17.9
26/02/97	0.0	31.3	16.3	24.9	1.1	20.9	17.6
27/02/97	0.0	32.4	17.0	22.6	2.3	22.6	19.8
28/02/97	0.0	32.6	15.7	27.4	2.5	20.1	17.4
01/03/97	0.0	33.7	16.1	24.6	1.3	19.7	17.7
02/03/97	4.8	34.5	17.2	27.3	1.1	21.2	18.5
03/03/97	3.2	32.7	14.3	27.1	1.8	22.7	19.0
04/03/97	0.0	28.1	16.4	21.7	1.8	23.9	19.3

Appendix E : Growth analyses data

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 senesced leaves (LDMs), harvestable dry matter (HDM) and stem dry matter (SDM) during the 1996/97 season at Roodeplaat

CROP	DATE	FI	LAI	LAIs	LDM ($Mgha^{-1}$)	LDMs ($Mgha^{-1}$)	HDM ($Mgha^{-1}$)	SDM ($Mgha^{-1}$)
Onion	7/5/96	0	0.018	0	0.001	0	0.0005	0
(cv Mercedes)	4/6/96	0.009	0.036	0	0.0036	0	0.001	0
	21/6/96	0.04	0.072	0	0.0085	0	0.003	0
	28/6/96	0.15	-	0	-	0	-	0
	5/7/96	0.07	0.112	0	0.02	0	0.005	0
	12/7/96	0.21	-	0	-	0	-	0
	19/7/96	0.28	0.26	0	0.05	0	0.017	0.009
	2/8/96	0.37	0.85	0	0.073	0	0.026	0.011
	8/8/96	0.57	-	0	-	0	-	-
	16/8/96	0.73	0.905	0	0.14	0.0067	0.05	0.024
	6/9/96	-	2.18	0	0.22	-	0.17	0.079
	12/9/96	0.76	-	0	-	-	-	-
	20/9/96	-	1.81	0	0.26	0.019	0.308	0.065
	27/9/96	0.73	-	0	-	-	-	-
	11/10/96	0.44	0.43	0.004	0.071	0.039	4.34	0.034
Cabbage								
(cv. Grand	07/05/96	0	0.0085	0	0.0057	0	0	0.0002
Slam)	04/06/96	0.21	0.406	0.0009	0.031	0.00019	0	0.0029
	21/06/96	0.64	1.04	5	0.111	0.00063	0.004	0.0098
	28/06/96	0.82	-	-	-	-	-	-
	05/07/96	0.68	1.75	-	0.259	-	0.021	0.005
	12/07/96	0.69	-	-	-	-	-	-
	19/07/96	0.84	1.96	-	0.32	0.001	0.02	0.048
	02/08/96	0.94	2.14	-	0.39	0.009	0.05	0.069
	08/08/96	0.84	-	0.072	-	-	-	-
	16/08/96	0.91	2.22	-	0.47	0.021	0.367	0.85
	22/08/96	0.86	-	-	-	-	-	-
	06/09/96	-	2.44	-	0.48	0.019	0.91	0.15
	12/09/96	0.93	-	0.08	-	-	-	-
	20/09/96	-	2.66	-	0.38	-	0.92	0.11
	27/09/96	0.92	-	-	-	-	-	-
	11/10/96	0.98	2.43	- 0.16	0.51	0.025	4.69	0.856

CROP	DATE	FI	LAI	LAIs	LDM ($Mgha^{-1}$)	LDMs ($Mgha^{-1}$)	HDM ($Mgha^{-1}$)	SDM ($Mgha^{-1}$)
Lettuce	04/6/96	0.01	0.019	0.012	0.0008	0.0001	0	0
(cv. Great	21/6/96	0.02	0.10	-	0.0049	-	0	0
Lakes)	28/6/96	0.01	-	-	-	-	0	0
	05/7/96	0.26	-	-	0.006	-	0.0064	0
	12/7/96	0.03	-	-	-	-	-	0
	19/7/96	0.04	0.423	-	-	-	0.032	0.005
	02/8/96	0.03	0.615	-	-	0.003	0.041	0.008
	08/8/96	0.79	-	0.022	-	-	-	-
	16/8/96	0.69	0.88	-	0.04	0.006	0.104	0.013
	06/9/96	-	0.75	0.11	0.05	0.015	0.199	0.02
SPINACH	04/06/96	0.03	0.07	0	0.004	-	-	-
(cv. Fort Hook	21/06/96	0.08	0.07	0	0.05	-	-	-
Giant)	28/06096	0.07	-	0	-	-	-	-
	05/07/96	0.62	1.91	0	-	-	0.18	-
	12/07/96	0.38	-	0	-	-	-	-
	19/07/96	0.44	1.96	0.04	-	0.005	0.23	0.024
	02/08/96	0.74	2.6	0.056	-	0.01	0.27	0.024
	08/08/96	0.48	-	-	-	-	-	-
	16/08/96	0.96	4.62	-	-	0.02	0.4	0.17
	22/08/96	0.76	-	-	-	-	-	-
	06/09/96	-	10.5	0.87	-	0.13	0.9	0.48
	12/09/96	0.99	-	-	-	-	-	-
	20/09/96	-	8.71	1.01	-	0.16	0.74	0.68
	27/09/96	0.99	-	-	-	-	-	-
	11/10/96	0.99	11.1	2.12	-	0.37	1.44	1.03
Beetroot	04/6/96	0.06	0.046	0	0.0045	0	0	0
(cv. Kuroda)	21/6/96	0.34	0.28	0	0.024	0	0.0025	0
	28/6/96	0.25	-	0	-	0	-	0
	05/7/96	0.36	0.64	0	0.075	0	0.008	0
	12/7/96	0.65	-	0	-	0	-	0
	19/7/96	0.40	0.79	0.068	0.09	0.011	0.032	0.012
	02/8/96	0.98	1.58	0.04	0.11	0.007	0.072	0.043
	08/8/96	0.95	-	-	-	-	-	-
	16/8/96	0.97	2.93	-	0.23	0.029	0.128	0.086
	06/9/96	0.70	-	0.54	0.24	0.09	0.57	0.14
	20/9/96	0.89	5.66	0.87	0.46	0.25	1.2	0.28
	11/10/96	0.97	2.99	0.59	0.3	0.13	0.8	0.21

CARROT	04/06/96	0.05	0.044	0	0	0	0	0
(cv. KURODA)	21/06/96	0.09	0.27	0	0.012	0	0.0018	0.0053
	28/06/96	0.22	0.34	0	0.03	0	0.0096	0.01
	05/06/96	0.22	-	0	-	0	-	-
	12/07/96	0.11	0.64	0	0.052	0	0.04	0.017
	19/07/96	0.2	1.61	0	0.091	0	0.08	0.034
	02/08/96	0.64	-	0	-	0	-	-
	08/08/96	0.95	1.33	0	0.078	0	0.091	0.31
	16/08/96	0.62	-	0	-	0	-	-
	22/08/96	-	1.68	0.05	0.086	0.003	-	0.047
	06/09/96	0.99	-	-	-	-	-	-
	12/09/96	-	1.89	0.21	0.16	0.025	0.41	0.134
	20/09/96	0.99	-	-	-	-	-	-
	27/09/96	0.97	1.83	0.28	0.18	0.035	0.76	0.1
	11/10/96							
Bush beans	17/12/96	0.3	0.17	0	0.12	0	0	0
(cv. Bronco)	27/12/96	0.79	0.46	0.02	0.28	0.02	0	0.19
	01/01/97	0.74	1.24	0.04	1.91	0.06	0.82	0.93
	20/01/97	0.66	1.79	0.02	1.91	0.05	1.37	0.67
	27/01/97	0.65	1.83	0.29	1.25	0.48	1.73	1.27
Bush beans	17/12/96	0.44	0.68	0.02	0.44	0.03	0.02	0.27
(cv. Provider)	27/12/96	0.91	1.07	0.02	0.66	0.01	1.55	0.37
	07/01/97	0.7	1.48	0.02	0.67	0.03	1.17	0.70
	20/01/97	0.53	1.09	0.05	0.79	0.09	2.1	0.83
Chilli pepper	27/12/96	0.02	-	-	-	-	-	-
	07/01/97	0.04	0.02	0	0.04	0	-	0.02
	20/01/97	0.14	0.06	0	0.14	0	-	0.05
	27/01/97	0.1	0.34	0	0.2	0	-	0.13
	05/02/97	0.4	0.66	0	0.34	0	-	0.41
	12/02/97	0.33	0.52	0	0.41	0	-	0.51
	20/02/97	0.25	-	0	-	0	-	-
	04/03/97	0.25	0.52	0	0.6	0	-	0.67

CROP	DATE	FI	LAI	LAIs	LDM ($Mgha^{-1}$)	LDMs ($Mgha^{-1}$)	HDM ($Mgha^{-1}$)	SDM ($Mgha^{-1}$)
Green pepper	27/12/96	0	-	-	-	-	-	-
	07/01/97	0	0.02	0	0.03	0	-	0.02
	20/01/97	0.10	0.09	0	0.11	0	-	0.09
	27/01/97	0.10	0.40	0	0.19	0	-	0.12
	05/01/97	0.21	0.42	0	0.34	0	-	0.27
	12/01/97	0.29	0.51	0	0.35	0	-	0.32
	20/01/97	0.37	0.41	0	0.31	0	-	0.36
	04/03/97	0.35	0.33	0.01	0.34	0	-	0.60
Eggplant	27/12/96	0.02	-	-	-	-	-	-
	07/01/97	0.1	0.14	0	0.05	0	-	0.02
	20/01/97	0.2	0.09	0	0.12	0	-	0.05
	27/01/97	0.33	0.44	0.02	0.27	0.03	-	0.16
	05/02/97	0.46	0.46	0.01	0.27	0.02	-	0.28
	12/02/97	0.5	0.45	0.02	0.42	0.03	-	0.41
	20/02/97	0.46	0.63	0.02	0.48	0.03	-	0.49
	04/03/97	0.45	0.45	0.02	0.38	0.03	-	0.53
Marrow (cv. Long White Bush)	27/12/96	0.36	0.94	0.01	0.71	0	-	0.32
	07/01/97	0.85	2.28	0.04	0.71	0.27	-	0.55
	20/01/97	0.73	0.74	0.24	0.65	0.59	-	1.03
	27/01/97	0.74	1.05	0.77	0.8	0.98	-	1.47
	05/02/97	0.64	0.64	0.51	0.49	1.08	-	1.01
Marrow (cv. President)	17/12/96	0.23	0.24	0.01	0.22	0.02	-	0.11
	27/12/96	0.49	0.8	0.02	0.66	0.05	-	0.33
	07/02/97	0.63	1.8	0.24	1.33	0.44	-	1.01
	20/01/97	0.56	1.51	0.34	1.48	0.92	-	1.42
	27/01/97	0.7	0.53	0.62	0.49	1.22	-	1.37
	05/02/97	0.23	0.72	0.35	0.61	0.84	-	0.82
Pumpkin (cv. Minette)	27/12/96	0.6	0.6	0.03	0.35	0.06	-	0.16
	07/01/97	0.85	2.33	0.15	1.53	0.33	-	1.12
	20/01/97	0.84	2.79	0.36	1.74	0.44	-	1.80
	27/12/97	0.62	1.31	0.26	1.04	0.72	-	1.83
	05/12/97	0.44	0.48	0.26	0.26	0.35	-	0.5

CROP	DATE	FI	LAI	LAIs	LDM ($Mgha^{-1}$)	LDMs ($Mgha^{-1}$)	HDM ($Mgha^{-1}$)	SDM ($Mgha^{-1}$)
Pumpkin (cv. Miniboer)	27/12/96	0.47	0.74	0.02	0.58	0.04	-	0.19
	07/01/97	0.94	2.52	0.20	0.77	0.38	-	0.71
	20/01/97	0.73	0.67	0.15	0.50	0.41	-	0.64
	27/01/97	0.74	0.77	0.77	0.58	0.99	-	1.12
	05/02/97	0.91	0.77	0.39	0.50	0.42	-	0.64
Runner beans	17/12/96	0.35	0.33	0	0.20	0	0	0.08
	27/12/96	0.69	0.83	0.05	0.38	0.01	0	0.27
	07/01/97	0.82	2.0	0.07	1.32	0.11	0	0.75
	20/01/97	0.80	4.91	0.14	1.90	0.11	0.08	1.37
	27/01/97	0.92	5.0	0.08	1.89	0.14	0.98	1.85
	05/02/97	0.90	3.52	0.22	1.22	0.20	2.01	1.95
	12/02/97	0.62	1.18	0.13	0.45	0.14	2.20	1.09
Squash (cv. Table Queen)	27/12/96	0.39	0.12	0	0.09	0	-	0.04
	07/01/97	0.49	0.44	0.01	0.28	0.01	-	0.15
	20/01/97	0.50	0.26	0	0.86	0.05	-	0.74
	27/01/97	0.51	0.56	0.41	0.80	0.80	-	1.18
	05/02/97	0.52	1.06	0.17	0.22	0.30	-	0.54
Squash (cv. Waltham)	27/12/96	0.30	0.09	0	0.07	0	-	0.03
	07/01/97	0.72	1.12	0.04	0.37	0.24	-	0.24
	20/01/97	0.3	0.53	0.02	0.64	0.05	-	0.51
	27/01/97	0.67	0.61	0.12	0.68	0.22	-	0.59
	05/02/97	0.72	0.80	0.08	0.72	0.19	-	0.78
	12/02/97	0.5	0.38	0.02	0.49	0.11	-	0.78
Sweet-corn (cv. Cabaret)	27/12/96	0.01	0.05	0	0.02	0	0	0.01
	07.01/97	0.39	0.64	0	0.47	0.01	0	0.88
	20/01/97	0.82	3.83	0.01	1.80	0.06	0	3.72
	27/01/97	0.84	4.74	0.07	2.57	0.06	0.1	4.24
	05/02/97	0.90	2.32	0.14	3.21	0.22	1.61	6.89
	12/02/97	0.92	1.79	0.34	2.11	0.49	2.44	7.9
Sweet-corn (cv. Dorado)	27/12/96	0.11	0.22	0	0.07	0	0	0.03
	07/01/97	0.45	1.4	0.06	0.94	0	0	0.97
	20/01/97	0.63	5.44	0	2.40	0	0	2.93
	27/01/97	0.70	4.71	0.33	2.22	0.05	0.88	3.27
	05/02/97	0.69	1.61	0.16	2.57	0.28	1.69	3.77
	12/02/97	0.54	1.42	0.51	1.53	0.86	2.70	3.50

CROP	DATE	FI	LAI	LAIs	LDM ($Mgha^{-1}$)	LDMs ($Mgha^{-1}$)	HDM ($Mgha^{-1}$)	SDM ($Mgha^{-1}$)
Sweet-corn	17/12/96	0.35	1.33	0	0.9	0	0	1.19
(cv. Jubilee)	27/12/96	0.58	1.11	0.03	0.82	0	0	0.57
	07/01/97	0.87	3.54	0.09	2.52	0.07	4.59	3.13
	20/01/97	0.89	-	0	-	0	-	3.88
	27/01/97	0.86	5.01	0.05	3.08	0.07	-	4.76
	05/02/97	0.78	1.57	0.76	2.24	1.34	-	5.81
Sweet-corn	17/12/96	0.12	0.64	0	0.30	0	0	0.25
(cv. Paradise)	27/12/97	0.49	1.54	0.01	0.96	0.01	0	0.58
	07/01/97	0.83	2.29	0.03	1.45	0	1.97	2.89
	20/01/97	0.85	2.39	0	1.51	0	-	3.48
	27/01/97	0.75	3.69	0.17	1.87	0.13	4.73	2.29
	05/02/97	0.56	1.44	0.14	1.67	0.29	5.45	4.00
Tomato	27/12/96	0.04	0.16	0	0.17	0	-	0.18
(cv. HTX14)	07/01/97	0.19	0.40	0	0.75	0	-	0.40
	20/01/97	0.48	1.95	0.04	2.12	0.12	-	1.19
	27/01/97	0.72	2.5	0.28	1.73	0.57	-	1.44
	05/02/97	0.70	1.45	0.23	1.38	0.48	-	1.37
	12/02/97	0.57	0.81	0.24	0.88	0.73	-	2.07
	20/02/97	0.43	0.44	0.12	0.69	0.31	-	1.46
Tomato	27/12/96	0.04	0.22	0	0.20	0	-	0.17
(cv. P747)	07/01/97	0.39	0.30	0	0.66	0	-	0.76
	20/01/97	0.53	1.63	0.13	1.16	0.25	-	1.35
	27/01/97	0.56	3.06	0.23	1.46	0.42	-	1.58
	05/02/97	0.83	0.63	0.39	0.43	0.70	-	1.39
	12/02/97	0.63	0.69	0.29	0.74	0.77	-	1.55
	20/02/97	0.81	0.34	0.32	0.35	0.76	-	1.68
Tomato	27/12/96	0.07	0.24	0	0.23	0	-	0.25
(cv. Zeal)	07/01/97	0.19	0.80	0	0.60	0	-	0.95
	20/01/97	0.36	1.35	0.1	0.85	0	-	1.56
	27/01/97	0.53	3.06	0.11	0.75	0.26	-	1.12
	05/02/97	0.57	0.27	0.16	0.24	0.39	-	1.02
	12/02/97	0.49	0.25	0.20	0.32	0.63	-	1.58
	20/02/97	0.41	0.14	0.1	0.16	0.28	-	0.87