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MODELLING THE SOIL WATER BALANCE TO IMPROVE IRRIGATION MANAGEMENT OF TRADITIONAL IRRIGATION SCHEMES IN ETHIOPIA

By

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DECLARATION

I, Geremew Eticha Birdo declare that this dissertation, submitted for the degree of Doctor of Philosophy in ***Irrigation Agronomy*** at the University of Pretoria, is my own work and has not been previously submitted by me for a degree at any other university.

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Geremew Eticha Birdo

Date: January 2008

Place: Pretoria, Republic of South Africa

DEDICATION

"This work is dedicated to

my mother, harmee Likkitu Hundarraa,

who aspires to see me obtaining an education at the highest level."

PREFACE

This work was conducted in the Department of Plant Production and Soil Science at University of Pretoria, South Africa. The project involved two field experiments in Ethiopia and another two field experiments in South Africa. The aim of this work was to monitor and evaluate traditional irrigation schemes in Ethiopia in order to improve the country's productivity.

One of the works executed in Ethiopia was a survey conducted on traditional irrigation schemes to take stock of farmers' water management (amounts and intervals), major technical and social constrains hindering higher productivity, and to recommend possibilities for improvement. The result of this survey indicates the amount of water and intervals that farmers traditionally practice, as well as other technical and social constraints for future improvement.

The second activity in Ethiopia was to compare two traditional irrigation scheduling methods with two other, more scientific, methods under the furrow system, using standard crop cultivars. This activity helped the researcher to compare the performance of traditional water management to that of the scientific method, and identify the critical areas for further improvement or look for sound technologies that could replace the traditional practice.

The two activities performed in South Africa involved the use of detailed scientific methods to evaluate yield and quality performance of crops, crop growth stages for water stress, and calibrate and validate the mechanistic Soil Water Balance (SWB) model for large scale application, which could be a major tool to bring tradition and science together.

This thesis is compiled from chapters (articles) that were already published, accepted or submitted for publication and a few other publications in process. The dissertation is prepared in accordance to the guidelines set up for authors for the publication of manuscripts in the South African Journal of Plant and Soil.

1. Geremew, E.B., Steyn, J.M. & Annandale, J.G. 2007. Evaluation of growth performance and dry matter partitioning of four processing potato (*Solanum tuberosum*) cultivars. *New Zealand Journal of Crop and Horticultural Science,* 35, 385-393.

2. Geremew, E.B., Steyn, J.M., Annandale, J.G. & Steyn, P.J. 2007. Evaluation of tuber processing quality of four potato cultivars. (Re-submitted for publication in the *South African Journal of Plant & Soil,* after incorporating the reviewer's comments).

3. Geremew, E.B., Steyn, J.M. & Annandale, J.G. 2007. Comparison between traditional and scientific irrigation scheduling practices for furrow-irrigated potatoes (*Solanum tuberosum*) in Ethiopia. (Accepted for publication in the *South African Journal of Plant & Soil*).

4. Geremew, E.B., Steyn, J.M. & Annandale, J.G. 2007. Growth and yield response of onions (*Allium cepa*) to water stress at different growth stages. (Prepared for submission in the *South African Journal of Plant & Soil*).

5. Geremew, E.B., Steyn, J.M. & Annandale, J.G. 2007. The SWB model calibration and validation of onions water-stressed at different growth stages. (Prepared for submission in the *South African Journal of Plant & Soil*).

6. Geremew, E.B., Steyn, J.M. & Annandale, J.G. 2007. Traditional water management practices: merits and de-merits. A case study at Godino traditional irrigation scheme, Ethiopia. (Prepared for publication in the *Ethiopian Journal of Agricultural Science*).

In addition, the researcher expects to produce not less than four more articles from the remaining body of the thesis, in the area of soil water characteristics and model calibration and validation, for publication in various journals.

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The staff of the Department of Plant Production and Soil Science, including the farm workers who were so pleasant towards me – I am indebted to them.

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ABSTRACT

Traditional irrigation was practiced in Ethiopia since time immemorial. Despite this, water productivity in the sector remained low. A survey on the Godino irrigation scheme revealed that farmers used the same amount of water and intervals, regardless of crop species and growth stage. In an effort to improve the water productivity, two traditional irrigation scheduling methods were compared with two scientific methods, using furrow irrigation. The growth performance and tuber yield of potato (cv. Awash) revealed that irrigation scheduling using a neutron probe significantly outperformed the traditional methods, followed by the SWB model Irrigation Calendar. Since the NP method involves high initial cost and skills, the use of the SWB Calendar is suggested as replacement for the traditional methods.

SWB is a generic crop growth model that requires parameters specific to each crop, to be determined experimentally before it could be used for irrigation scheduling. It also accurately describes deficit irrigation strategies where water supply is limited. Field trials to evaluate four potato cultivars for growth performance and assimilate partitioning, and onions' critical growth stages to water stress were conducted. Crop-specific parameters were also generated. Potato and onion crops are widely grown at the Godino scheme where water scarcity is a major constraint. These crop-specific parameters were used to calibrate and evaluate SWB model simulations. Results revealed that SWB model simulations for Top dry matter (*TDM*), Harvestable dry matter (*HDM*), Leaf area index (*LAI*), soil water deficit (*SWD*) and Fractional interception (*FI*) fitted well with measured data, with a high degree of statistical accuracy.

The response of onions to water stress showed that bulb development (70-110 DATP) and bulb maturity (110-145) stages were most critical to water stress, which resulted in a significant reduction in onion growth and bulb yields. SWB also showed that onion yield was most sensitive to water stress during these two stages.

An irrigation calendar, using the SWB model, was developed for five different schemes in Ethiopia, using long-term weather data and crop-specific parameters for potatoes and onions. The calendars revealed that water depth varied, depending on climate, crop type and growth stage.

Keywords: canopy cover, dry matter partitioning, furrow irrigation, irrigation scheduling, leaf area index, neutron probe, onion bulb yield, potato tubers, Soil Water Balance model, traditional irrigation, water stress

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LIST OF SYMBOLS AND ABBREVIATIONS

a	Campbell's coefficient of the log-log water retention function
ADL	Allowable depletion level
Alt	Altitude (m)
ARC	Agricultural Research Council
CDM_i	Canopy dry matter daily increment (kg)
cv.	Cultivar
D	Index of agreement of willmott
DAP	Days after planting
DATP	Days after transplant
DM	Dry matter production (kg m^{-2})
DM_i	Daily increment of total dry matter (kg m^{-2})

Dr	Drainage (mm)
DWR	Dry matter water ratio (Pa)
dz	Soil layer thickness (m)
DZARC	Debre-Zeit agricultural research centre
E	Actual evaporation (mm)
e_a	Actual (atmospheric) vapour pressure (kPa)
E_c	Radiation conversion efficiency (kg MJ^{-1})
EMDD	Emergence day degree (d ^oC)
eq(s)	equation(s)
e_s	Saturated vapour pressure (kPa)
ET	Evapotranspiration (mm = kg m^{-2})
ETcrop	Crop evapotranspiration
ETo	(FAO) reference crop evapotranspiration (mm d^{-1})
f	Layer root fraction
FAO	Food and Agriculture Organization of the United Nation (Rome, Italy)
FI	Fractional interception
FI_{PAR}	Fractional interception of photosynthetically active radiation
FLDD	Day degrees at end of vegetative growth (d ^oC)
FL_{solar}	Fractional interception of solar radiation
f_r	Fraction of dry matter partitioned to roots
GDD	Growing day degrees (d ^oC)
H_C	Crop height (m)
H_{Cmax}	Maximum crop height (m)
HDM	Harvestable (tuber) dry matter (kg m^{-2})
I	Irrigation amount (mm)
I_C	Amount of precipitation intercepted by the canopy (mm)
IR	Irrigation requirement
IWMI	International Water Management Institute
IWUE	Irrigation water use efficiency
K	Canopy radiation extinction coefficient
K_{Cb}	Basal crop coefficient
K_{PAR}	Canopy extinction coefficient of photosynthetically active radiation
K_S	Canopy extinction coefficient of total solar radiation
LAD	Leaf area duration

LAI	Leaf area index (m^2 m^{-2})
*LAI*y	Leaf area index of senesced leaves
LDM	Leaf dry matter (kg m^{-2})
LSD	Least significant difference
MAE	Mean absolute error
MTDD	Maturity day degree (d ^oC)
NIR	Near infrared radiation (0.73 µm)
OARI	Oromiya Agricultural Research Institute
P	Precipitation (mm)
Pa	Atmospheric pressure for a given altitude (kPa)
PAR	Photosynthetically active radiation (0.4 0.7 µm)
PAW	Plant available water
PART	Stem-leaf partitioning parameter (m^2 kg^{-1})
PE	Potential evaporation (mm)
PET	Potential evapotranspiration (mm)
PT	Potential transpiration (mm)
PWP	Permanent wilting point
R	Runoff (mm)
r^2	Coefficient of determination
RD	Root depth (m)
RDM	Root dry matter (kg m^{-2})
RD_{max}	Maximum root depth (m)
RGR	Root growth rate (m^2 $kg^{-0.5}$)
RH	Relative humidity (%)
RH_{max}	Daily maximum relative humidity (%)
RH_{min}	Daily minimum relative humidity (%)
RMSE	Root mean square error
R_S	Solar radiation (MJ m^{-2} day^{-1} or W m^{-2})
SAR	Sodium adsorption ratio
S.a.	Sinno anno (no date)
SDM	Stem dry matter (kg m^{-2})
SG	Specific gravity
SI	Stress index
SLA	Specific leaf area (m^{-2} kg^{-1})

SWB	Soil Water Balance
SWD	Soil water deficit (mm = kg m^{-2})
T	Actual transpiration (mm = kg m^{-2})
T_a	Air temperature $T_a = T_d$ (^oC)
T_b	Base temperature (^oC)
$T_{cut\text{-}off}$	Cut-off temperature (^oC)
TDM	Top dry matter (kg m^{-2})
TDMstart	Top dry matter at emergence (kg m^{-2})
TFI	Tuber form index
T_o	Standard air temperature at sea level (293 ^oK)
TransDD	Day degrees of transition period from vegetative to reproductive growth stage (d ^oC)
T_W	Wet bulb air temperature (^oC)
U	Wind speed (m s^{-1})
U^*	Dimensionless root uptake rate
U_2	Wind speed measured at 2 m height (m s^{-1})
VPD	Vapour pressure deficit (Pa)
WC	Water content
WFD	Wetting front detector
WUE	Water use efficiency (kg ha^{-1} mm^{-1})
Y	Yield (kg ha^{-1})
Z	Soil depth (m)
α	Adiabatic lapse rate (K m^{-1})
γ	Psychrometer constant (kPa $^oC^{-1}$)
ΔS	Change in soil water storage (mm)
Δt	Duration (day)
θ	Volumetric soil water content (m^3 m^{-3})
θ_{fc}	Volumetric soil water content at field capacity (m^3 m^{-3})
θ_{pwp}	Volumetric soil water content at permanent wilting point (m^3 m^{-3})
θ_{sat}	Volumetric water content at saturation (m^3 m^{-3})
ρ_b	Bulk density (Mg m^{-3})
ρ_w	Water density (Mg m^{-3})
σ	Stefan-Boltzmann constant (5.6697×10^{-8} W m^{-2} K^{-4})

Ψ_{avg}	Root weighted average soil matric potential (J kg^{-1})
Ψ_{fc}	Soil matric potential at field capacity (J kg^{-1})
Ψ_{lm}	Leaf water potential at maximum transpiration (J kg^{-1})
Ψ_{m}	Soil matric potential (J kg^{-1})
Ψ_{pwp}	Soil matric potential at permanent wilting point (J kg^{-1})
Ψ_{x}	Xylem water potential (J kg^{-1})

CHAPTER 1

GENERAL INTRODUCTION

The potential irrigable land in Ethiopia is estimated at about 3.5 million hectares, of which about 180 000 to 400 000 hectares have the potential to be developed as small-scale irrigation schemes (Tillman, 1981). This figure could change as more reliable data emerge from more detailed studies. To date, less than 200 000 ha has been developed and yet more land has to come under irrigation to feed the fast growing population, provide raw materials for local industries and combat the effect of recurrent droughts. Ethiopia is known to have abundant water resources that can be used for irrigated agriculture (MWRC, 1999). There are nine major rivers, most of them flowing to neighbouring countries, and a number of lakes with good quality irrigation water. The country's total surface water availability is estimated at about 110 billion m^3 (WRDA, 1990). On the other hand, the nine major river systems have an estimated total annual discharge of 102 billion m^3 (WRDA, 1990). Despite this potential land and water resources for irrigation, the country has long been known to have periodic food deficiencies (Ndege, 1996). Table 1.1 indicates the irrigation potential of the country in comparison to the current developed land area.

Recurrent droughts have been one of the major problems in Ethiopia during the past three decades. The occurrence of drought in most parts of the country is caused by either insufficient or no rainfall to support the seasonal water requirements of the rain-fed crop production and this gap is to be filled by supplementary irrigation. About 80% of the Ethiopian population is dependent on rain-fed agriculture and inadequate seasonal rainfall can cause serious food shortages that can adversely de-stabilise the social and economic life of the people (CIDA, 1997).

Table 1.1 Irrigation potential and the area of land already developed in different river basins of Ethiopia (WRDA, 1990).

No	Basins	Potential irrigable land (ha)	Actual irrigated area (ha)	Actual land developed (%)
1	Blue Nile	977 915	21 010	2.10
2	Awash	207 400	69 900	34.00
3	Rift Valley Lakes	112 300	12 270	10.00
4	Omo Ghibe	450 120	27 310	6.10
5	Genale Dawa	435 300	80	0.02
6	Wabi Shebele	204 000	20 290	9.90
7	Baro Akobo	748 500	350	0.05
8	Tekeze	312 700	1 800	0.57
9	Mereb	37 560	8 000	21.30
	Total	3 495 795	161 010	4.07

In Ethiopia, it is well known that even in relatively good rainfall years, there can be pockets of land that do not get sufficient precipitation to see a crop through to full production (IFAD, 2005).

A critical review of the drought in the country shows different alternatives for mitigating the problem. One of the alternatives is to improve the potential of traditional irrigation schemes for enhanced productivity as a strategic intervention to resolve food insecurity in the country (World Bank, 1999). A number of factors led to choosing the improvement of traditional irrigation schemes, of which the most prominent one was that irrigation increased the potential for producing more food more consistently in the drought-prone food-insecure areas. During the raging drought in east Africa in the 1980s, irrigation has served as a means of rescue to several lives.

The improvement of small-scale and traditional irrigation comprises two major areas. The agronomic aspect of irrigation is one of the areas that requires a marked improvement, namely when to irrigate and how much water to apply. The other major activity, relevant to this issue, is the development of water-efficient and high-yielding crop varieties and the provision of these varieties and other crop management technologies to the farmer (MWRC, 1999).

In Ethiopia, traditional water diversions for irrigation were said to date far back. However, there is no recorded history that indicates where, when and how these traditional irrigation cultures were started and developed. At present, small-scale and traditional irrigation comprise about 40% of the total irrigated land in Ethiopia (Guijt & Thompson, 1994). Despite this, traditional water diversion, conveyance to farms, distribution and on-farm applications have not been improved and lead to a very low overall irrigation efficiency. Even though the management of traditional irrigation schemes were said to be more sustainable and environment-friendly in this country, there was no recorded information on which aspect of the management was sound, or on economic feasibility (Geremew, 1994; Geremew & Fentaw, 1994). The only known fact is that not much environmental degradation was observed under traditional irrigation practices compared to those of commercial schemes. The Natural Resources Management Department of the Ministry of Agriculture has tried to estimate the area of traditional irrigation that was only accessible by four-wheel drive vehicle (IFAD, 2005). In this brief estimation, irrigated lands that were less than a hectare were not included, because there were either too many of them or they were inaccessible. On the other hand, even for the inventoried irrigated land, there was no recorded information on the methods of irrigation used, the amount of water applied or the watering intervals. Personal communications revealed that furrow irrigation methods were commonly used for annual crops and a combination of basin and border methods for perennial crops. In all cases, estimates of the water applied to different crops at various growth stages were not known at all. Neither the water user nor the extension agent had tried to introduce the concept of irrigation water measurement. Personal observations indicated that there could be over-irrigation in the upper lands and under-irrigation in the lower parts of the scheme due to shortages of water because of overall low irrigation efficiency. There also seemed to be no watering variation among various crops with reference to both amount and interval.

Traditional irrigation schemes are not at all supported by improved water management practices. Not only irrigation technologies, but also improved crop varieties, appropriate plant nutrient management, effective crop protection methods, farm mechanisation and market accessibilities are not in favour of traditional irrigation schemes. The Soil and Water Management Research Division at the Melka Werer Research Centre, the only centre conducting research on water management, has tried to produce appropriate water management technologies for commercial farms. They have identified irrigation methods, irrigation intervals and amounts in the Awash Valley for major crops, including cotton, groundnut, sesame, maize, wheat and a few horticultural and forage crops. The Awash Basin is an area developed by the state to produce commercial crops under state holding. This scheme operates under full-time irrigation, with mostly continuous mono-cropping to cotton. Water management in the valley is performed by the State company, including the operation and maintenance of the system. Currently, only a few private producers are involved in the water management after secondary canals. Generally, it is unfortunate that the water management experience in this valley of more than 30 years could not be extrapolated to any part of the country out of that area. Even within the valley, salinities and sodicities are already developing, which require specialised management, depending on the nature and extent of the problem. Melka Werer Research Centre was advised by several consultants to concentrate on production of research technologies that can be used by farmers, rather than mechanised large-scale farms. Despite this, the Soil and Water Research Division of the Melka Werer Centre could not build enough manpower and facilities to cover the vast farmer-managed area.

It was deemed essential to monitor, evaluate and improve the water management practices of traditional irrigation schemes in Ethiopia. Before attempting to improve traditional irrigation, the actual constraints that require improvement needed to be identified. In addition, a brief insight into the current social structure was also important, since it has a significant effect on the performance of irrigation in the scheme. Hence, the following experiments were performed to achieve the desired goal of improved water management on traditional schemes.

1. A survey was conducted in Godino, a representative traditional irrigation scheme. This survey enabled the researcher to monitor and evaluate the current water management practices of the farmer, the irrigation method followed, irrigation intervals and application depth, and the form of existing

institutional structure of water management in the scheme. Two traditional practices were identified (Chapter 3);

2. Two traditional practices obtained from the survey were compared with two more scientific irrigation schedules to evaluate their performance. The result indicated that traditional methods performed poorly, which suggested that it be replaced by an efficient, simple and affordable method, namely the Soil Water Balance (SWB) model schedule (Chapter 4);
3. The suggested SWB scheduling method required determination of crop specific parameters in order to develop calendars. Therefore, four potato cultivars (one of the major crops in the scheme) were used and crop specific parameters were determined in order to develop future irrigation calendars (Chapter 5);
4. The processing quality of the four cultivars was evaluated as potatoes are mostly used for chipping (Chapter 6);
5. Since the SWB model provides deficit irrigation strategy and one major constraint recorded in the Godino scheme was the unavailability of irrigation water supply, crop-specific parameters were determined from the field experiment conducted on onions' critical growth stages to water stress. Onions are another important crop in the scheme (Chapter 7);
6. The SWB model simulations were calibrated and validated with the crop specific parameters generated from the three field experiments to evaluate model performance (Chapter 8); and
7. SWB irrigation calendars were developed, using the generated crop specific parameters for five different locations in Ethiopia, which could serve as a guideline for the extension services (Chapter 9).

A general discussion and recommendations follow in Chapter 10. Finally, results of this study indicate possible areas of improvement in developing a sustainable irrigation water management system for the traditionally irrigated schemes of Ethiopia.

CHAPTER 2

LITERATURE REVIEW

2.1 Community-based irrigation water management: the need for improved social structure

In the regions where agriculture has evolved from dry land farming to small-scale irrigation development, changes have occurred in the society, particularly in the economy and culture, where it led to the development of large and complex irrigation systems. One of the historical relationships between society and irrigation was reported to be situated along the southern edge of Mesopotamia at the foot of the Zagros Mountains and on the shores of the Persian Gulf (Thorne & Peterson, 1950). During this era, farmers and pastoralist communities of the Sahara, Arabia and Persia were forced to flee the droughts starting to occur in these vast areas, to take refuge in low alluvial valleys of the Indus, Euphrates, Tigres and Nile. Hailing from various backgrounds, these people, who were used to let their herds graze in these valleys, started to cultivate the edges and gradually made the necessary developments to ensure water delivery and draining of excess water (Thorne & Peterson, 1950). However, it took many centuries to set up the social organisations capable of building and maintaining these hydraulic developments and to ensure water management (David *et al.*, 1998). Settlements of such types later on developed into villages and major cities that were surrounded by intensively farmed gardens and orchards (David *et al.*, 1998).

Irrigation in many countries has been implemented to fulfil a combination of social and economic goals. In the process of enhancing the economic opportunities of rural populations, other problems are being alleviated in most communities of the world.

These include the slowdown of the farmer's migration from unrewarding farmlands to overcrowded urban areas as a result of providing increased supplies of irrigation water or settlement on newly developed irrigation schemes (Wester *et al*., 1995). The effect of the investment in irrigation projects are immediately visible in the form of newly constructed farms, canals and developed lands. However, the maturing of the social and economic complex initiated within the communal irrigation project development often takes years to happen. Along with the irrigation development, the local government has a vital role to play, mainly in providing important infrastructure such as roads and schools, and possibly assisting in the provision of medical and recreational facilities (Thorne & Peterson, 1950). In turn, it helps the society in providing social stability and economic sustainability, depending on the continuous and intensive monitoring and maintenance of the project.

Regarding the administrative aspect of irrigation, it is vitally important to consider the type of organisations formed to deliver irrigation water. The relationship between the organisation and water users and their legal powers is governed by these kind of organisations. Failures could be anticipated in good projects as wrong organisations are adopted. Hansen *et al.* (1980) reported that the most successful enterprises have been those owned and operated by water users and, when the water users are directly involved, their interest is keen and their services are rendered at a minimal cost.

In the planning and operation of irrigation projects, consideration of the social and economic aspects of the farming community is becoming increasingly important, mainly in developing countries. In such countries, farmers participating in irrigation water management might have been involved in ordinary or mixed agriculture and require strong guidance before they can be expected to make a significant contribution to the project. Several experiences in many parts of the world have shown that overlooking these issues has definitely affected the tangible and qualitative success of irrigation enterprises (Hansen *et al.*, 1980). It was repeatedly proved that the success of irrigation enterprises was the product of the careful use of a well-designed system by well-trained and equipped farmers. In this regard, the selection of appropriate farmers and the provision of training and other assistance will ensure the sustainability of the project. However, the degree of assistance given to a farmer varies, depending on the criteria used during the selection. In many countries, the assistance rendered to irrigation communities include improved agronomic practices, a supply of improved crop and animal species, microfinance credits and marketing. Here, the strong commitment of local governments is decisive in promoting marketing situations and especially collecting their dues in kind at farm-gate price when prices of commodities fall excessively. It is crucial that the government manages the adverse effects of irrigation, like environmental pollution, outbreak of malaria, parasitic weeds and diseases as part of regional health mitigation programmes (Hansen *et al.*, 1980).

The efficiency and sustainability of community-based water management systems were investigated at several pilot project schemes. The performance of various pilot schemes varies depending on the size and design of irrigation systems, socio-political perspectives, cultural values, agricultural practices and the status of existing administration. It is imperative for a pilot scheme to be truly representative, replicable and backed up with independent evaluation of its performance over a sufficient period.

The improvement of traditional small-scale irrigation schemes does not end only at the placement of a well-structured water users' association or the involvement of water users in the management of irrigation water, but also requires improvement of the water use efficiency of available water resources.

2.2 Water management and irrigation scheduling

Improving traditional small-scale irrigation schemes is not adequately performed by only involving the water users in the management of irrigation water, but also requires improving the water use efficiency of the scarce water resource. Traditional irrigation is mostly characterised by deteriorated irrigation networks that cause high water losses and the use of rudimentary methods to control water wastage and poor crop productivity (Waskom, 1994). These factors, coupled with the lack of appropriate water management technology has caused traditional irrigation schemes to keep on producing low yields (Waskom, 1994). Hence, the improvement of traditional irrigation schemes requires all-round interventions, starting with involving the community in the system management up to improving of water-measuring structures and supplying options for when and how much water to apply. With regard to the furrow irrigation system, the issue of when to irrigate and how much water to apply refers solely to the supply of a working irrigation schedule, depending on the ability of the community to practice (Raghuwanshi & Wallender, 1998).

2.2.1 Irrigation scheduling methods

Traditional irrigation farmers have been practicing their own scheduling methods since the inception of irrigated agriculture. At present, traditional irrigation scheduling, coupled with low yielding crop cultivars, remained solely subsistent and not economically feasible. Most of the traditional irrigation schedules are dependent upon monitoring the crop canopy, which only allows the farmer to decide when to irrigate (Waskom, 1994). The amount of water to be applied depends on the availability of the water resource, which may not vary between either the crop species or their growth stages. At present, however, scientific irrigation scheduling has developed to overcome various irrigation problems, where it helps the farmer to determine the exact amount of water to apply to the field and the exact timing of application (James, 1988). The amount of water applied is determined by using a criterion to determine irrigation need and a strategy to prescribe how much water to apply in any situation (James, 1988). Hence, the importance of irrigation scheduling is to enable the irrigator to apply the exact amount of water to achieve the goal and increase irrigation efficiency (James, 1988). The same author also explains that irrigation scheduling improves crop yield and quality, and conservation of water and energy, resulting in lower production costs.

Irrigation scheduling methods vary depending on the objective of individual farmers. Proper irrigation scheduling, based on timely measurements or estimation of soil water content and crop water needs, is one of the most important aspects of irrigation management (Waskom, 1994). Monitoring soil water in the crop root zone will allow better management of water application to the requirement of the crop. However, direct measurement of soil water in the field is tedious, mainly at large-scale production levels. At present, there are a number of devices, techniques and computer aids available to assist producers when to apply and how much water is required by a particular crop at a given growth stage (James, 1988). Even though each farmer envisages different goals in irrigation scheduling, they all have one goal in common, which is selecting a water management strategy that allows them to prevent over-application of water, while maximising the net return (Waskom, 1994). Many water balance approaches have been used to determine water availability to the crop and irrigation scheduling. However, few approaches consider crop development, from sowing to harvesting, through plant and soil evapotranspiration (ET) (Annandale *et al.,* 1999). Most of the time, calculations are based on potential ET values, estimated by locally tested formulae or, at best, on the Penman generalised expression (Tuzeti *et al.*, 1992).

According to Waskom (1994), irrigation-scheduling methods are grouped into three major categories, namely soil water monitoring, crop canopy index and the water budget approach (Table 2.1).

Table 2.1 Irrigation scheduling methods, tools required and the advantages and disadvantages of each method (Waskom, 1994).

Methods	Tools or parameters used	Advantages/Disadvantages
I. Soil water monitoring (Indicates when and how much to irrigate)		
Hand feel & appearance	Hand probe	Variable accuracy, requires experience
Soil water tension	Tensiometers	Good accuracy, easy to read, but narrow range
Electrical resistance tester	Gypsum block	Work over large range, but limited accuracy
Indirect soil water content	Neutron probe/TDR	Expensive, and requires many regulations
Gravimetric analysis	Oven and scale	Labour-intensive
II. Crop canopy index (Indicates when to irrigate, but not how much to apply)		
Visual appearance	Field observation	Variable accuracy, depending on the experience of the farmers
Water stress index	Infrared thermometer	Expensive
III. Water budget approach (Needs periodic calibration since it estimates the water use)		
Checkbook method	Computer/calculator	Indicates when and how much water to apply
Reference ET	Weather station data	Requires appropriate crop coefficient
Atmometer	Weather station data	Requires appropriate crop coefficient

Most of the soil water monitoring methods and devices do not measure soil water directly; they measure a property of the soil that is indirectly related to soil water status, and hence, these methods differ in ease of use, reliability, cost, and the labour requirement (Evans *et al.*, 1996). In all three of the broad categories of scheduling, however, the user has to have the knowledge of soil water holding capacity, the current available soil water content, the crop water use and effective root zone depth (Broner, 2005).

According to Al-Kaisi & Broner (2005), significant evaporation can take place only when the soil's top layer or the plant canopy is wet. Once the soil surface is dried out, evaporation decreases sharply. Thus, significant evaporation occurs after rain or irrigation. Furthermore, as the growing season progresses and the canopy cover increases, evaporation from the wet soil surface gradually decreases. When the crop reaches full cover, approximately 95% of the ET is due to transpiration from the crop canopy. At this growth stage, the crop canopy intercepts most of the incoming solar radiation, thereby reducing the amount of energy reaching the soil surface (Al-Kaisi & Broner, 2005). Crop water use (ET) is influenced by prevailing weather conditions, available water in the soil, crop species and growth stage. At full cover, a crop will have a maximum ET rate if soil water is not limited and the soil root zone is at field capacity. Soil characteristics are mainly influenced by soil texture, organic matter content, soil structure and permeability, which further limit producers' management and system options.

Crop root depth is primarily influenced by plant genetics, restrictions within the soil horizon and the maturity stage of the crop. Such circumstances create substantial management problems, especially with furrow/flood irrigation systems (Jones, 2004). Most surface irrigation systems have inherent inefficiencies due to deep percolation on the upper end and run-off at the lower end of the field, unless careful management decisions are involved (Jones, 2004). Efficient irrigation results when design and management enable producers to uniformly apply enough water to fill the effective crop root depth with minimal run-off. The correct amount of water applied at each irrigation varies due to changes in root depth, soil water status and the soil intake rate (Waskom, 1994). Waskom (1994) also indicates that irrigation set size, stream size, set time and the length of run can be optimised by irrigators to improve efficiency, that is, a well-designed and properly-managed surface system can attain efficiencies of 60% or better.

Identifying crop sensitivity to water stress at current growth stages, recording effective rainfall between two irrigations and the availability of water supply, help the user to make useful decisions (Raghuwanshi & Wallender, 1998). The same authors also emphasise the decision on irrigation, which should mostly be based upon an estimate of crop and soil water status, coupled with some indication of economic return. Hence, such proper scheduling allows producers to reduce the traditional number of irrigations, thereby conserving water, labour and plant nutrients (Waskom, 1994; Evans *et al.,* 1996; Papajorgji & Shatar, 2003; Broner, 2005).

Scheduling irrigation applications are often accomplished by using root zone water balance approaches (Waskom, 1994; Evans *et al.,* 1996), which uses the Checkbook or budgeting approach to account for all inputs and withdrawals of water from the soil (Scherer *et al.*, 1996; George *et al.*, 2000; Jones, 2004). The concept of root zone water balance approach is illustrated in a mathematical expression in equation 2.1 (Waskom, 1994):

$$I+P = ET+Dr+Ro \pm \Delta S \quad (2.1$$

where I = irrigation water applied, P = precipitation, ET = evapotranspiration, Dr = drainage of water percolation below the root zone, Ro = run-off; ΔS = change in soil water content

Many irrigation-scheduling methods provide the users good cost-effective, but may be too sophisticated to apply. For traditional irrigation users, however, water saving and cost-effectiveness alone should not be the only consideration for irrigation scheduling; it should be simple to understand and apply, and financially affordable.

2.3 Cultivation of some economically important crops under traditional irrigation

The dry period for most Ethiopian regions commences at the beginning of October to the end of May. During this period, short rainfalls occur in some parts of the country that cannot maintain crop production without supplementary irrigation. Most tree crops and medicinal perennial crops require supplementary irrigation during this period that would carry them through to the main rainy period. The high-value vegetable crops, however, require full irrigation, as the distribution of existing rainfall does not suffice the more frequent water demand of these shallow rooted crops. These crops include onions, tomatoes, potatoes, peppers, cabbages, lettuce, etc. In this study, only the cultivation of potatoes and onions by means of the traditional irrigation method is assessed.

2.3.1 Potatoes

Origin and history

Potatoes (Solanum tuberosum) originated in South America. Its native home is often claimed to be the Andean region of Peru and Bolivia, where the Incas cultivated the plant mainly for food. In these regions, the potato's close botanical relatives still flourish and make the gene pool abundant for improvement (Brown, 1993; Rolot & Seutin, 1999). Potatoes are highly diversified by their nature and, at early human settlement in the highlands of Bolivia; men started to select suitable cultivars for food. Potatoes are believed to have been introduced to Europe by the Spanish conquest in the 16th century and remained a botanical curiosity until it was popularised by Antoine-Augustine from 1780 onwards Smith, 1968 (Rolot & Seutin, 1999). It was taken to the United States in 1719 by Scottish-Irish settlers and, during the 19th century, thousands of varieties originated by plant breeders, among which only small numbers were accepted for large-scale production (Smith, 1968). Potatoes were introduced to Africa as recently as the end of the 19th century. The improved species of South American clones that were co-ordinated by the Centro Internacional de la Papa (CIP) in Peru have helped to introduce a wide range of adaptability worldwide.

A fresh potato contains about 80% water (SFC, 1992). The solids or dry matter are highly correlated with texture. Mealy textures are usually associated with high solids, while waxy textures are usually associated with low solids. Although individual tastes may vary greatly, varieties with high mealy texture are usually considered best for baking or french-frying. On the other hand, varieties that are of waxy texture are more often used for boiling or in salad. Potatoes are a rich source of carbohydrates and contain valuable amounts of protein, minerals and vitamins. The nutrient level varies not only by variety, but also according to the maturity of the crop and storage time (SFC, 1992).

Climatic requirements

The wild species of potatoes with some food value survive on the snow line as high as about 4 800 m and are more resistant to frost than the modern varieties (Smith, 1968). Potatoes grow in a wide range of climatic conditions and altitudes. In tropical Africa, it does well between 1 800 and 2 300 m as the climate is tempered by altitude, or at lower altitudes during the cool seasons (Smith, 1968; Brown, 1993; Rolot & Seutin, 1999). Potato vine growth is enhanced by day temperatures of more than 27^{o}C as well as by night temperatures higher than 23 ^{o}C. Vine growth is further enhanced by long days, while short days stimulate the production of tubers. Low night temperatures of about 16^{o}C are ideal for tuberisation, up to as high as 29^{o}C of day temperatures, above which tuber formation could be inhibited (Struik *et al.,* 1997). The ideal environment that stimulates flowering usually promotes the development of tubers.

Yields are usually lower in eastern tropical Africa than in temperate zones. It could be attributed to the detrimental effect of short day length and high air and soil temperature (Smith, 1968; Bradley *et al.,* 2005). Besides the night-time temperature, photoperiod plays an important role in tuberisation, which is triggered when the daylight falls below a certain critical threshold. Under short day-length conditions, tubers are initiated much earlier than under long-day conditions, making tuberisation more abrupt and leading to maturity much faster. Despite this, the origin and early cultivation of potatoes began in the Andes where the days are short throughout the year and where potatoes are especially adapted to short-day conditions. Smith (1968) suggests that short days hasten maturity, reduce growth of tops and increase the efficiency of tuber formation. However, it is more convenient and faster to develop European long-day cultivars under short-day conditions, especially for the production of commercial planting materials.

When long-day material is put under short-day conditions, it will undergo some physiological changes, namely stem elongation will terminate earlier, tubers initiate earlier and plants die earlier than under long-day conditions. In addition, the mass of leaves and stems, as well as the number of leaves per stem would be lower, while leaflets are larger (Brown, 1993; Struik *et al.*, 1997).

The ratio of leaf-stem mass is higher under short-day than under long-day conditions. Tuber mass is comparably higher in the early development stage under short-day conditions. However, when cultivars with a long maturity period are grown under long-day conditions, it attains a higher final production despite its later tuber initiation. Overall, the critical day length is severely influenced by temperature and light intensity and it decreases with an increase in temperature or a decrease in light intensity (Smith, 1968).

At low light intensity, tuber mass is higher at an average temperature of about 12^{o}C. Optimum tuber mass occurs with higher light intensity and temperatures higher than about 18^{o}C. However, tuber growth is most favoured by high day temperatures (18-24^{o}C) and low night temperatures of about 17^{o}C. The number of tubers decreases with increasing night temperatures. A high night temperature favours more growth above the ground than underground, during which plants develop many new leaves, many branches, and flowers. Under such conditions, stolons emerge above the soil, form new stems and leaves and result in a low tuber yield with a small number of tubers. At low temperatures, however, more growth occurs underground than above ground, where plants form a small number of leaves, few or no branches, no flowers, no stolons above ground, but a large number of tubers resulting in a high tuber yield.

Soil and water requirements

Selection of the right soil type is very important for potato crop production. Potatoes are shallow-rooted and sensitive to water stress. Hence, well-drained light-texture soils, such as sandy loams or loamy sands are generally suitable for the production of a high yield of good quality potatoes. Such soils can store large amounts of water and nutrients, even though any soil can become unproductive under poor management. Soils with good structure are loose and friable and the surface of these soils does not form a crust so that they remain open for air and water for further circulation in the crop root zone (Smith, 1968; Brown, 1993).

Potatoes should preferably not be planted in heavy soils. Under water logging conditions, the chemical reaction necessary for maintaining a proper environment for potato roots cannot take place and, when air is excluded, plant materials cannot decompose properly and the potato root cannot grow vigorously. When heavy soils are used, artificial drainage facilities need to be provided and an incorporation of organic matter also makes a big improvement. Studies conducted by Brown (1993) and Struik *et al.* (1997) confirm that potato yields increase as organic matter and bulk density on Caribu soils increase. Organic matter is important for most crops in general and for potatoes in particular. The ideal potato soil contains up to 3% organic matter, which helps in maintaining its granular structure (Smith, 1968). Organic matter is best maintained under well-mixed crop rotations. Potatoes are usually grown in rotation with other crops to maintain desirable soil structure, fertility status, build-up organic matter, reduce crop loss from insect and disease, and to increase yields (Smith, 1968). Many potato growers follow a crop rotation of not more than two years of potatoes, one year of small grain and one year of grasses. Soils under such rotation would have a good granular structure, high water-holding capacity, adequate aeration, and abundant available plant nutrients. Organic matter usually facilitates ploughing and cultivation, enables potato plants to penetrate the soil readily, retains soil water, provides food for the growth of desirable micro-organisms, and supplies plant nutrients to the crop (Smith, 1968; Brown, 1993). Potato tubers develop and maintain their normal shape better in soils with adequate organic matter. In conditions where continuous potato growing is desired, a breaking cover-crop should at least be seeded just after harvest (Smith, 1968; Brown, 1993).

Soil reaction is one of the important factors affecting the availability of various soil constituents and the absorption of available nutrients by the crop (Mengel & Kirkby 1982). Smith (1968) indicates that a certain relationship exists between soil reaction and rate of plant growth and development, tuberisation, and chemical composition of the potato. Results from potato crops planted on various soil reactions revealed that lower yields of plants grown on high pH were due to the accumulation of large amounts of calcium salt that resulted in a low supply of available manganese. The ideal soil reaction for potato growth and development is between 4.8 and 5.5 pH. In soils with a pH of 5.5 to 7.0, potatoes can be subjected to scab diseases. Potatoes are the only crop that loves soil reaction as low as 4.8 pH (Smith, 1968).

Potatoes respond well to both organic manure and mineral fertiliser applications. Most potato growers practise organic manure application at the rate of 20-30 t ha^{-1}. Chemical fertiliser application depends on the nutrient content of the soil, considering the heavy requirement of potash fertiliser by potato crops (McLaurin *et al*., 2002). The application of nitrogen and potassium is a determining factor of the qualitative and quantitative production of potatoes. An excess application of nitrogen may delay maturity of the crop, impair quality of the tubers and/or adversely affect their storage (Smith, 1968; Brown, 1993; Struik *et al*., 1997).

Potatoes require irrigation where soil water availability is not consistent through all the growth stages. High yield, earlier production and drought protection are the advantages of irrigating potatoes. Potatoes can be influenced critically with uneven water supply, affecting the development of knobs or growth cracks on the tubers. The plant does not use much water early or late in the season, but needs a lot of water when foliage is fully developed. According to the SFC (1992), the potato plant requires about 460-720 mm of water to mature. However, the frequency and amount of irrigation of the crop depend on the soil type, method of irrigation, the crop growth stage and the evaporative demand. In general, heavier soils need irrigation of adequate depth once a week, but more frequent irrigations may be necessary in the case of sandy soils. An ideal potato water management programme is to limit the wetting depth to the effective root zone, which is about 0.6 m, and the soil should not be allowed to dry below 65% of field capacity. On the other hand, soil water levels above field capacity will seriously affect yield and quality. Sprinkler-irrigated potatoes benefit from light, but frequent three to five day applications, especially when temperatures are higher than 26^{o}C. Irrigation should be reduced when the plant leaves begin to turn yellow and the plant starts to die. Too much water at maturity stage may predispose tubers to rot and vines need to be dead at least one week prior to harvesting. Generally, withholding water late in the growing season will help potatoes to store better (SFC, 1992).

The sensitivity of potatoes to water stress varies with the crop growth stage and to some extent, the cultivar. During tuber initiation, water stress could reduce the number of tubers produced per plant. During tuber bulking, however, tuber size and quality are closely related to water supply. Research has shown that the total yield of potatoes are most sensitive to water stress during mid-bulking, which occurs three to six weeks after tuber initiation, and water stress any time during this period will have a severe effect on the total yield (SFC, 1992). Furthermore, tuber growth is retarded by water stress and does not resume uniformity when water is replenished again. Under such conditions, new growth and enlargement will take place at the top stem end, while the other portions of the tuber remain stunted. In some potato varieties, tubers develop some constricted areas that are related to the stage of tuber growth at the time the water stress occurred. Other deficiencies in quality such as growth cracks and knobbiness are also related to water stress followed by periods of adequate or surplus soil water.

Planting and cultivation

The ideal planting depth for potatoes is about 10 cm deep. However, in areas where soil water is a limiting factor, the depth could go up to 13 cm. Potatoes are planted from seed pieces and the seed rate varies depending on seed piece size, the varietal characteristics and desired plant spacing (Scherer *et al.*, 1999). A spacing of 23-30 cm between plants is generally practised in most countries. A wider spacing (25-30 cm) is required for varieties with a heavy tuber set, smooth tubers and varieties resistant to the development of hollow heart and deformities. A closer spacing (20-25 cm) is recommended for varieties with poor tuber set to reduce the number of oversized tubers (Scherer *et al.*, 1999). The seeds are mostly cut into seed pieces for planting, even though whole seed is less sensitive to tuber decay. Cut seed pieces should be firm and with at least one or more eyes to secure germination and plant establishment. Plants from small seed pieces are generally slower to emerge and are less vigour ones.

Soil temperatures should be between 7-21°C at planting; as planting into cold soils delays emergence and increases the risk of seed piece decay (Scherer *et al.,* 1996).

The growth and development of potatoes are divided into four stages (Hayes & Thill, 2002).

The vegetative stage: This stage of growth begins when the seed breaks its dormancy and produces sprouts. This process usually requires 15-30 days, depending on the cultivar and temperature in the area.

Tuber initiation: This stage commences with the tuber initiation at the tip of stolons and takes approximately 10-14 days.

Tuber bulking: This is a stage where tubers are constantly increasing in size and mass. This stage usually lasts 60 to more than 90 days, depending on the length of the growing season and external factors such as the presence of pathogens.

Maturation: This is the stage where potato canopies begin to senesce in general and older leaves gradually turn brown and die. This condition generally spreads to the remaining plant parts, such as vines and younger leaves that lead to the final death of the crop. This stage is associated with less or no tuber growth and the crop is ready for harvest, depending on the purpose of production.

After planting, potatoes may be cultivated to control weeds and to reshape the beds. Potatoes are commonly hilled when they attain a height of 20-30 cm and soil is mounded around the plant base to prevent greening or sunburning of tubers. Potatoes are vulnerable to pests and diseases. Besides using certified seeds, it is also important to maintain proper soil fertility and water management, frequent sanitation and crop rotation and the use of resistant varieties.

Harvesting and storage

The harvesting of potatoes varies depending on the variety and the intended marketing. Potatoes may be harvested with vines still green and tubers comparatively immature when it is intended for immediate use as new potatoes. Most potatoes, however, are harvested at full maturity when their skins are set, they are big enough in tuber size and their vines have died. Mature tubers store better than immature tubers and resist bruising better.

Storage of potatoes is often complicated by the interdependence of light, heat, moisture, potato injuries and length of storage period. Storage temperatures are adjusted depending on the intended purpose of the tuber and length of storage period (Edgar, 1968). Temperatures above 21^{o}C are hazardous immediately after harvest, but advantageous for conditioning after long storage under low temperature. The ideal storage temperature is around 16^{o}C for about 90 days after harvest at 90% relative humidity (RH) before tubers start to sprout, and can be prolonged for about 6 months if sprout inhibiters were used (Edgar, 1968; Struik *et al.,* 1997). Despite this fact, other researchers agree that storage at 21^{o}C for the first three weeks results in reducing sugar, which is inversely proportional with chip quality (Smith & Davis, 1968). Potato storage conditions could vary depending on environmental complex and altitude. For tropical Africa, researchers agree that the ideal storage temperature would be from 2^{o}C to 3^{o}C for seed potatoes and from 6^{o}C to 8^{o}C for tubers for consumption (Rolot . *et al.,* 1983; Struik *et al.,* 1997).

Prolonged exposure of potatoes to sun or artificial light under storage causes greening of the tuber skin and tissue, and it becomes unfit for food. However, the greened tubers are not discriminated against for seed purposes. Generally, potatoes require ideal temperatures, humidity and adequate ventilation for minimum storage loss of yield and quality.

2.3.2 Onions

Origin and history

Onions (*Allium cepa* L.) are believed to have originated in west or central Asia and are small crops growing in association with other crops. For this reason, there is no conclusive opinion about the exact time and location of their origin. However, many researchers agree that onions originated in central Asia. Since onions are grown in a wide range of climates from temperate to tropics, they were probably consumed for thousands of years and simultaneously domesticated all over the world (Ehler, 2005). Onions may be one of the earliest cultivated crops because they were less perishable than other food crops, easily transportable, easily grown and produced in a variety of soils and climates. Even though the place and time of the onion's origin are not clear, there are many documents from early times which describe its importance as a food and its use in art, medicine and mummification.

Onion is a cool season biennial monocot with a prominent bulb, hollow cylindrical leaves and a strong odour when bruised (Casey & Garrison, 2003). The crop is said to be tolerant to frost. The optimum temperature for plant development varies between 13^{o}C and 24^{o}C, while, for raising seedlings, it requires up to 20-25 ^{o}C and generally require high temperatures for bulbing and curing (Kalb & Shanmugasundaram, 2001). The bulb onion cultivars are classified into three groups, depending on day lengths. The short-day onion cultivars are characterised by thresholds of 12-13 hours, the intermediate by 13.5-14.5 hours and the long-day cultivars by over 14.5 hours. If any of the groups go out of its range for cultivation, it will not form bulbs or it will form small bulbs, a little more than sets in size.

Soil and plant nutrient requirements

Onions grow on a variety of soils ranging from sand to clay loams. However, they prefer loamy soil that is fertile, well drained and high in organic matter, with a preferable pH range of between 6.0 and 6.5 (Sanders, 1997). Onions do not thrive in soils below pH 6.0 because of trace element deficiency, or occasionally, aluminium or manganese toxicity. Onions could be produced on slightly alkaline soils, but are sensitive to soil salinity. According to the FAO (2002), a soil salinity level of 4.3 dS m^{-1} could decrease the yield of onion by up to 50%.

Onions differ widely in plant nutrient consumption, depending on production history, soil type and the target of production. Generally, onions prefer soils with a high organic matter or an application of organic manure at the rate of 25-40 t ha^{-1} for high bulb yield production. The nutrient element in manure becomes available to plants over an extended period and the organic material in manure improves soil structure, while also helping to make other fertiliser elements more readily available to the plant (Corgan *et al.,* 2000). In conditions where mineral fertilisers are to be used, applications are practised, either as a broadcast or, more commonly, as a band dressing a few centimetres directly under the seed set or transplant. This crop usually requires a substantial dose of nutrients. According to Kalb and Shanmugasundaram (2001), onions with a bulb yield of 18 t ha^{-1} remove an average of 66, 11 and 70 kg ha^{-1} of N, P and K nutrients respectively. Some pre-plant nitrogen, usually about 120 kg ha^{-1} (Corgan *et al.,* 2000), is needed as a starter fertiliser to avoid losses through either leaching or volatilisation while the plant roots are not developed enough to absorb the bulk application. After plant establishment, one or two side dressings of nitrogen are required during the season. Insufficient nitrogen will induce early maturity and reduce bulb size, while high nitrogen may increase bulb size, but cause large nicks and soft bulbs with poor storage quality. Crop rotation has a more multi-beneficiary effect on onions more than on most other crops. Rotation helps to maintain good soil structure, resulting in improved crop growth, decreased incidence of pathogens causing disease and aid in weed management. In addition, crop rotation helps in balancing plant nutrients, as onions planted following legumes could benefit from nitrogen residues (Corgan *et al.,* 2000). In general, phosphorus fertilisers are applied before onion crop planting. Some soils may have a sufficient phosphorus content, but adhering to the available portion is required.

Water requirements

Onions require frequent irrigation throughout the growing season for several reasons. The root system is shallow, therefore, very little water is extracted from a soil depth deeper than 0.6 m, and most is from the top 0.3 m (Voss & Mayberry, 1997). Onion roots are mostly non-branching and all roots originate at the stem, or basal plate of the plant. This indicates that upper soil areas must be kept moist to stimulate root growth. Rates of transpiration, photosynthesis and growth are lowered by even mild water stress. Onions show little capacity for reducing leaf water potential by osmotic adjustment to compensate for reduced water availability at the root (Voss & Mayberry, 1997). Fields that frequently experience water stress would suffer growth retardation and produce excessive numbers of doubles or splits, reducing the number of grade one bulbs (Kalb & Shanmugasundaram, 2001). For optimum yield, onions require 350-550 mm of water, but may use more than that in tropical areas where ET is appreciably higher (FAO, 2002). However, onions are best grown when the managed allowable depletion is maintained above 70% of the total available water, after which a yield reduction will occur (Corgan *et al.*, 2000; FAO, 2002).

Managing the time and amount of applied irrigation is critical to achieve optimum yield and quality. Light and frequent irrigations are required through furrow, sprinkler or drip irrigation systems. Irrigation frequency varies with the planting time of the year, the size and development stage of crop, and the irrigation system used (Corgan *et al.*, 2000; FAO, 2002). Sprinkler irrigation is preferred during germination and early crop development, so that it permits small but frequent amounts and also deliver water to areas that are not levelled. Either drip or furrow irrigations are recommended at the latter stage of plant growth, as there is increasing concern that sprinklers are wetting the foliage, thereby promoting foliage diseases and subsequent increases in bulb disorders (Corgan *et al.*, 2000). In general, the choice of irrigation system depends on each individual merit of the system and the contrasted economic feasibility that must be the preferences of individual farmers.

Harvesting and storage

Onions are harvested when 80% of the bulbs become completely mature, which is evident by the collapse of the neck tissue and falling of the tops. After harvesting, the roots are trimmed and the tops cut away. Bulbs are usually put into an appropriate case and allowed to cure outdoors. After bulbs are properly cured, onions are graded according to the individual standards of the country. According to the USDA standard, onions are graded for size and shape, proper maturity and firmness. Onions must also be free of splits, seedstems, dry sunken areas, roots, tops, translucent or watery scales, moisture, disease and insects (Corgan *et al.*, 2000).

Harvested onions are dormant and will not sprout for a long period, depending on the cultivar. Storage conditions are an important factor in prolonging the dormancy. During storage, the sprouting of onions is most favourable between temperatures of 4^{o}C and 25^{o}C. For prolonged storage, onions may be treated in the field with maleic hydrazide (MH-30) at the rate of 2.2-3.4 kg ha^{-1} when the tops are still green but beginning to senesce (Kalb & Shanmugasundaram, 2001).

CHAPTER 3

MONITORING AND EVALUATION OF COMMUNITY-BASED IRRIGATION WATER MANAGEMENT AT THE GODINO SCHEME OF ETHIOPIA

3.1 Introduction

Irrigation is the provision of water to crops in the quantity and time controlled by farmers. In arid and semi-arid areas, where annual rainfall is not adequate for reasonable crop yields, irrigation can increase crop yield and farming profits. Even though irrigation is widely practised in arid and semi-arid climatic zones, supplementary irrigation is also becoming popular in sub-humid climates (Thorne & Peterson, 1950).

Irrigation was a well-known practice since the beginning of recorded history. In fact, many of the earliest civilisations developed in arid regions where irrigation was indispensable for human survival. These early cultures were so dependent on irrigation that historians referred to them as the hydraulic society (Thorne & Peterson, 1950). Since irrigation of any extent requires a highly organised society to build and maintain the water diversion and delivery systems, it may have catalysed the first community in which humankind evolved from the nomadic food-gathering society (Wynne, 1979).

At present, surface irrigation methods are dominantly being practised in developing countries due to their low energy requirement. This factor significantly influences the economic analysis required before a new irrigation supply can be set up and determines the water application method to be used (Stacy, 1999). Hence, due to their high energy costs, systems that are more modern have not replaced this irrigation method in most developing countries. Efficient surface irrigation management requires optimum knowledge of several variables: flow rate, cut-off time, watering intervals, depth of application, etc. Similarly, over-irrigation is one of the other extreme aspects of water management that promote water-logging, run-off and deep percolation, which all result in excessive nutrient loss and finally become unfriendly to the environment. Optimum irrigation water management is very important and, in fact, the base for irrigation system design, the saving of water resources, energy, and environmental protection (Samad & Vermillion, 1999). A quantitative determination of these variables explicitly leads to the details of crop water requirement and irrigation scheduling. Therefore, the determination of the amount of irrigation water to supply crops and the time interval required between applications could best prevent loss of water resources.

The objective of this study was to monitor and evaluate the traditional water management status of farmers at the Godino scheme to determine opportunities for potential further improvement.

3.2 Materials and methods

Site background information

Godino is situated in the East Shewa zone of the Oromiya region, Ethiopia, about 55 km north east of Addis Ababa, and 12 km from the adjacent town of Bushoftu at a latitude of 8° 48' N, and a longitude of 39° E. The area has an undulating topography and an altitude of 1895 m.a.s.l. According to the long-term meteorological data collected from Bushoftu, the area receives an average annual rainfall of 866 mm and has an average annual temperature of 18.7°C. This area is also known to have an average reference evapotranspiration (ETo) of 1443 mm/year, with a monthly peak of 138 mm in April (OWMERDB, 1996).

Farmers of the Godino scheme practise two cropping systems, one under rain-fed conditions and the other using irrigation. The rainy season is from mid-May to mid-September, which is suitable for tef, maize, potatoes, peppers, beetroot, carrots, tomatoes, cabbage, pulses and other cereal crop production. However, irrigation is practised during the dry period, from October to the end of April, which is suitable for most vegetable crops like onions, cabbages, potatoes, peppers, tomatoes and others. In addition, citrus and sugarcane are also grown as perennial crops. The predominant soil is clay with a bulk density of 1.12 Mg m^{-3}, field capacity of 0.45 kg kg^{-1} and permanent wilting point of 0.32 kg kg^{-1}, which gives a plant available water (PAW) of around 146 mm m^{-1} (OWMERDB, 1996). The irrigation water for the scheme is abstracted from the Wadecha Dam. According to the National Soil Service laboratory, the quality of water for irrigation was found to be excellent and suitable for any crop production, with an electrical conductivity of 14.2 mS m^{-1} and SAR of 0.31.

The water users

Societies sharing common water resources for irrigation need to have binding rules and regulations for equitable and efficient use of the resources. When the social aspect of a community sharing the same natural resource is overlooked, it is unlikely that an efficient utilisation of the communal water resource would be attained. Similarly, under community-based water management conditions, it is essential to assess the existing social structure and its functionalities before attempting to improve the water management in the scheme.

The existing social structure of water users in the project area was assessed through distributing questionnaires to about 15% (42 people) of the water user families. In addition, major constraints in the scheme, both social and technical, were included in the questionnaire. The farmers' responses on the existing agricultural constraints were summarised in three categories: none, some and severe. When a constraint was experienced by less than 10% of the total respondents, it was regarded as "none" or no constraint, from 10-40% as "some"; and above 40% as "severe" constraint.

Irrigation water supply

The main canal supplying Godino has no structure that enables the measurement of water supply to the scheme. Hence, a Parshall flume with a 9" (22.86 cm) throat width was installed on a concrete canal on 22 January 2004. Water delivery into the scheme was recorded three times a day, at 06:00, 12:00 and 18:00. This activity took place from the date of installation up to 15 April 2004 to estimate the average delivery of water into the scheme. Similarly, on-farm water application was measured using a 3" (7.62 cm) throat width Parshall flume for three major crops, namely onions, potatoes and tomatoes. This measurement provided information on the amount of water that a farmer typically applies to his crop. The soil water status was monitored before each irrigation, by collecting soil samples from 0-200 mm, 200-400 mm and 400-600 mm for the same crops. The soil samples were weighed and then oven-dried for 24 hrs at 105°C, whereafter they were weighed again to calculate the soil water content before the application of irrigation.

3.3 Results and discussion

The water user's organisation

Successful scheme irrigation water management not only requires knowledge, but also structural organisation of the society. Organised water users are bound to become increasingly concerned with balancing the farm budget and meeting the additional demands being placed upon them (Abernethy *et al.,* 2000). Hence, approaches to the development of water users' organisations and cost recovery need careful planning and implementation for a particular society and its conditions.

Strong community-based irrigation schemes consist of three-dimensional structural linkages, that is, research-extension-farmer linkages. These institutional linkages were observed to be missing at the Godino community scheme. In addition, this traditional irrigation scheme is not at all supported by improved management practices. The extension service department of the government organisation is linked to the water users' association without any improved technologies, mostly performing administrative and political-related activities. The Melka Werer Research Centre, the only centre dealing with water management research, is located far away from this scheme with the focus on the development of improved water management technologies for large-scale irrigated agriculture. Generally, the improved water management technologies developed under the Melka Werer climatic conditions could not be extrapolated to any other part of the country out of that area. So far, there is no committed organisation to develop improved water management technologies for traditional irrigation schemes in general and for Godino in particular.

At present, in the absence of a strong water users' organisation and improved water management technologies at the Godino traditional irrigation scheme, the situation is deteriorating and highly unsatisfactory. There is low irrigation efficiency, numerous inequalities in water distribution, complexity and lack of transparency among water users. In this context, the intervention of research in developing effective water management technologies that fully involve water users is decisive. This would help the society induce a collective rethinking on the management of water as a resource in the irrigation system and maintain economic feasibility and sustainability of irrigated agriculture.

A summary of the Godino irrigation scheme irrigation water-related constraints indicated that the required amount of water application and the irrigation interval were the major technical problems, as agreed upon by all the interviewed farmers (Fig. 3.1). In addition, about 80% of the farmers interviewed agreed that water distribution, water availability and irrigation methods were still important constraints on the scheme.

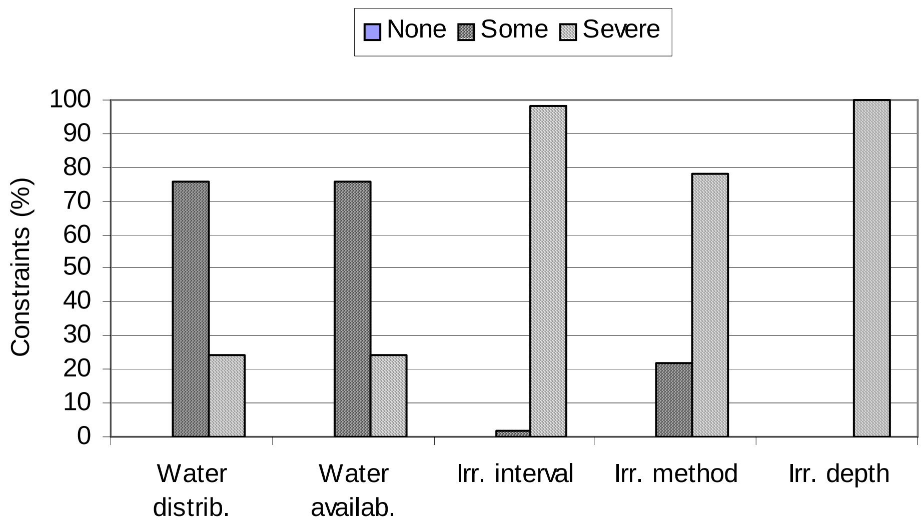

Figure 3.1 Water management related constraints and their extent at the Godino traditional irrigation scheme

Figures 1 and 3.2 further illustrates that about 80% of the respondents considered the method of irrigation and lack of land levelling as severe problems. More than 80% of the respondents claimed to have some problems with drainage and improper design of the land.

Figure 3.2 indicates the views of farmers on soil, maintenance and operation, and drainage-related constraints. In this respect, farmers claimed that the soil might be deficient in major plant nutrients and that they applied the same amount of nitrogen and phosphorus to all crops in the scheme, as fertiliser rates were not established. Similarly, the scheme was not properly designed from the start and surface drainage prevails as land levelling was not practiced at all. Maintenance of the existing infrastructure was also not carried out regularly as a result of poor coordination services.

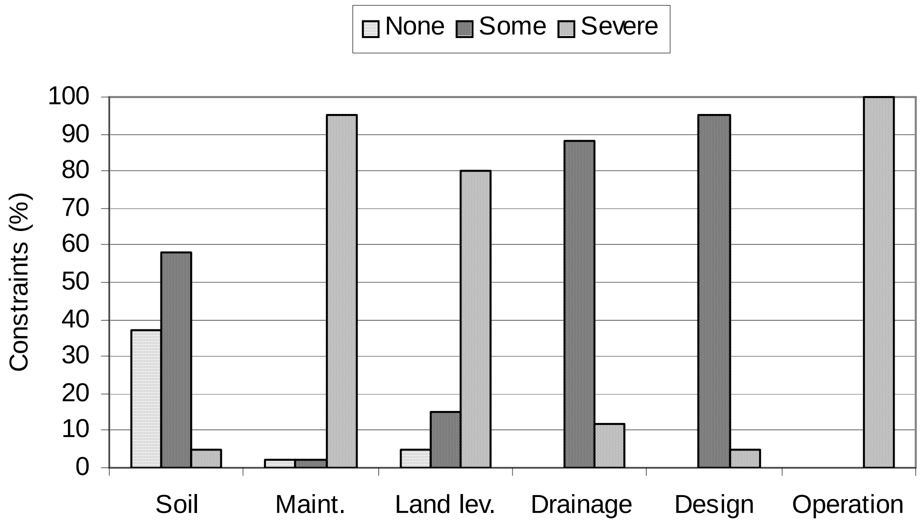

Figure 3.2 Soil and farm infrastructure related constraints and their extent at the Godino traditional irrigation scheme

On the other hand, the majority of the farmers encountered severe problems with regard to low crop productivity, inaccessibility of the scheme and inadequate extension services (Fig. 3.3). Marketing problems, shortage of labour during activity overlaps and wildlife menace were also considered as severe constraints to most farmers. In general, the overall loose farmers' organisation and poor extension services were found to be the major courses of most associated agricultural constraints on the scheme.

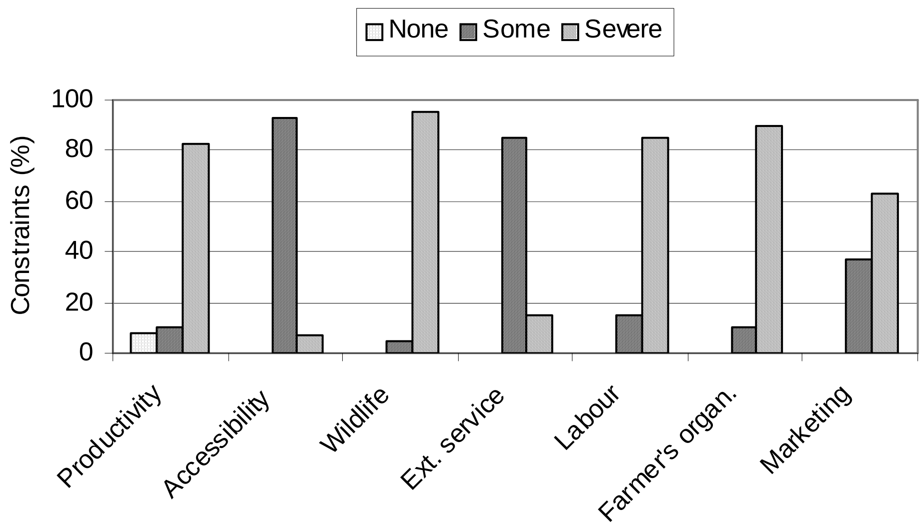

Figure 3.3 Productivity, wildlife and social related constraints and their extent at the Godino traditional irrigation scheme

Scheme water supply

Irrigation water is supplied to the Godino scheme from the Wadecha Dam, which is situated about 17 km north of the scheme. Since the watershed of the dam is situated in the central highlands of Ethiopia, the water is of good quality, there are no salinity problems and no other form of land degradation was observed (OWMERDB, 1996). However, since the sediment load of the river is high, sediment deposition in canals is very high and this, in turn, requires frequent desiltation.

The research result of the scheme's water supply indicated that January was the month with the highest water supply to the scheme to satisfy the peak water demand of the crops (Fig. 3.4).

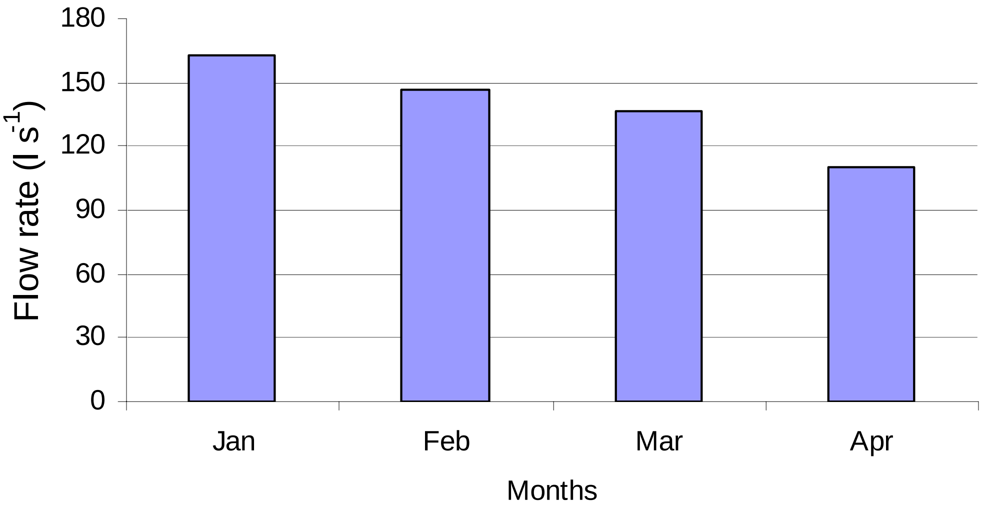

Figure 3.4 Average daily scheme water supply (l s^{-1}) for Godino traditional irrigation scheme

The scheme water supply gradually decreased from February to April. These months are very important for irrigation as most crops are then at their vegetative growth stages, requiring adequate water supply. These growth stages are most critical to water stress, which would significantly decrease the yield and quality of most produce.

The farmers' response to the questionnaire of water adequacy revealed that water supply was adequate at the head and middle of the scheme, while it was a serious constraint at the lower end of the scheme. Most of the respondents agreed that, for several fields, shortages of water were due to overlapping of irrigation schedules during the peak water demand. This was also substantiated by the fact that information on crop water demand (when to irrigate and how much water to apply) was not available to farmers. As a result, most of the farmers applied too much of the water amount that their crops needed at the head of the scheme, and too little water at the tail of the scheme. Most farmers at the tail end of the scheme overcame the shortages of water by using low yielding and less marketable crops. They also selected more stress-tolerant crops with low yields to avoid a total loss due to water shortage.

On-farm water application

The slope of the Godino irrigation scheme varies from flat to gentle slope, making the management of surface irrigation very difficult on top of water shortage (Fig. 3.1). Land levelling was not practiced in the past. Under such circumstances, systematic cropping and land terracing are essential to avoid overflow of water before the soil water deficit of the entire profile is replenished. No canals, from primary to tertiary, have water-regulating structures. Off-take gates were all made of earth and regulated by stop log or stones. This has created difficulty in limiting the amount of water to be distributed among the various sections of farmlands. Huge quantities of water will be delivered for a limited period to a group of farmers in the same direction. During this period, the farmer at the upper part of the scheme would have ample time and water to over-irrigate his/her crops, while the farmer at the lower end would have only limited water and time available. Water is in short supply to fully replenish the root zone profile, coupled with long irrigation intervals that resulted in frequent under-irrigation of crops in the lower scheme (Fig. 3.5 & 3.6). Consequently, most farmers at the lower end of the scheme were forced to use more drought-tolerant crop cultivars with low productivity.

The on-farm water application is also much dependent on water availability in both amount and interval. Farmers in the scheme have no water-measuring facilities. Most farmers apply the concept of irrigating the same amount of water to all crops at the same interval. The amount of water applied is mostly determined by visual observation of the water overflow or by the availability of water to the farmer. The farmers' response to the questions on the amount and interval of irrigation indicated that most of them applied the same water quantity to all crop species, but used relatively longer intervals for tree crops and sugarcane. Currently, due to the prevalence of water scarcity and the intention of the government of Ethiopia to charge for irrigation water, farmers are very concerned about the correct amount of irrigation water to use.

The farmers' traditional water application amount was recorded by using a three-inch (7.62 cm) throat-width Parshall flume for onions, potatoes and tomatoes.

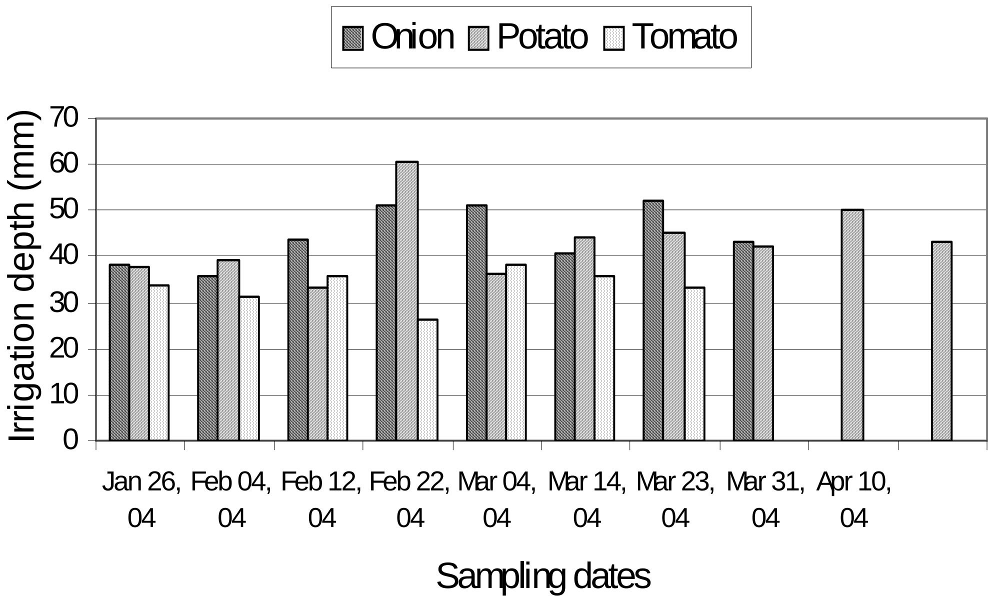

Figure 3.5 Farmers' irrigation water application depth (mm) for onion, potato and tomato crops at the Godino traditional irrigation scheme

As can be observed in Figure 3.5, the amount of water traditionally applied varies widely from time to time and from crop to crop, with the variation governed solely by water availability. The farmers' watering depth varied from less than 30 mm to 60 mm under furrow conditions (Fig. 3.5), where the overall irrigation efficiency is less than 50%. This amount seems to be too low to replenish the soil profile to the full rooting depth of crops, especially where irrigation intervals last up to or more than ten days.

Similarly, the irrigation interval traditionally practised at the Godino scheme varied from crop to crop and from time to time and, once again, depended on water availability in both amount and interval. The watering interval varied from 9-14 days for onions, 8-10 days for potatoes and 7-11 days for tomatoes (Fig. 3.6).

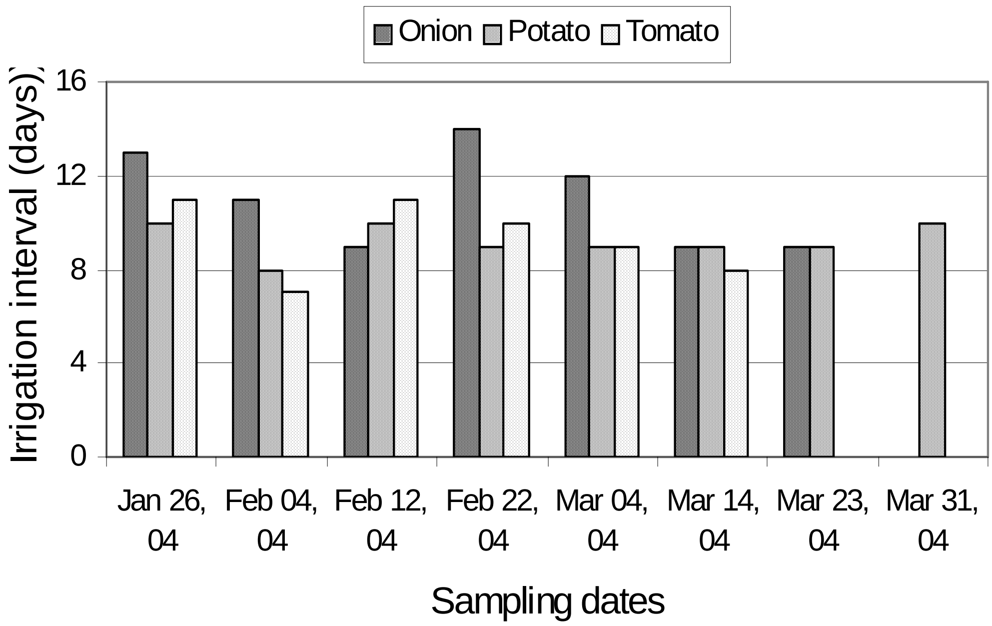

Figure 3.6 Farmers' traditional irrigation interval (days) for onion, potato and tomato crops at the Godino traditional irrigation scheme

A questionnaire was distributed to the farmers to identify reasons for the large variation in irrigation intervals. Most farmers responded that variations in both irrigation intervals and depth were not projected on either the basis of crop water demand or crop type itself, but were rather governed by the availability of water for intervals and during the peak crop water requirement. This practice often led to wilting of water sensitive crops. According to the perception of most farmers, crops were generally under-irrigated at the lower end of the scheme due to water unavailability, while there could be over-irrigation at the upper end of the scheme. In general, farmers assumed that applying large amounts of water will ensure high yield, regardless of crop species or maturity stage. On the other hand, researchers (Al-Kaisi & Broner, 2005) agree that crop water use is influenced by the evaporative demand, the crop stage and soil water content. As soil dries, it becomes more difficult for a plant to extract water from it. At field capacity, plants use water at the maximum rate and when the soil water content drops significantly below field capacity, plants use much less water.

The soil water status was recorded for onion, potato and tomato fields just before irrigation, to assess whether traditional irrigation depths correlate with the soil water deficit. The soil water content results indicated that the top soil layer (0-200 mm) was most dry and followed by the middle layer (200-400 mm), whilst the deepest soil layer (400-600 mm) contained relatively more soil water (Fig. 3.7).

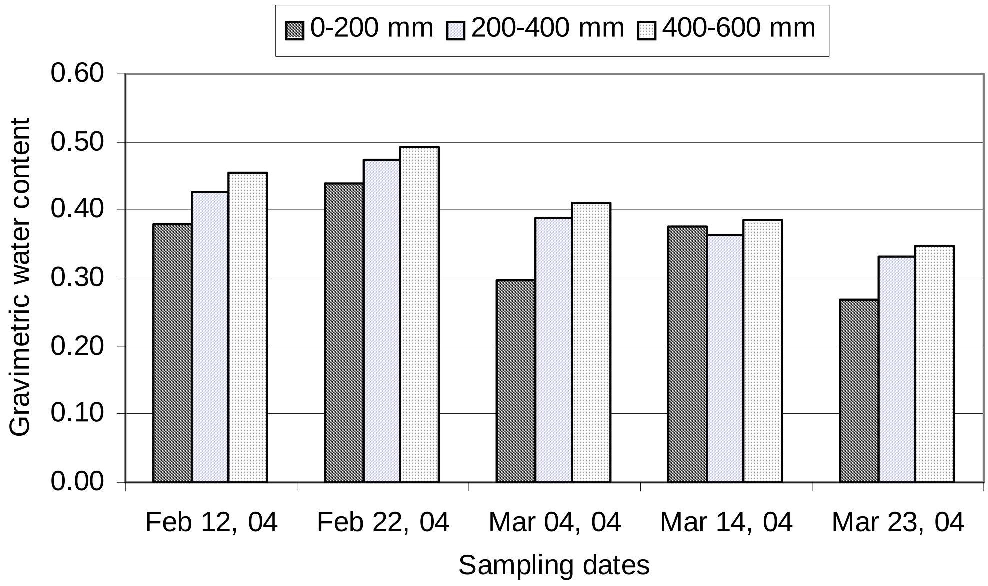

Figure 3.7 Gravimetric water content measured before irrigation water application at the Godino traditional irrigation scheme

The soil water deficit to field capacity/irrigation required was computed from the soil water measurement to compare it with the irrigation amount traditionally practised (Fig. 3.8).

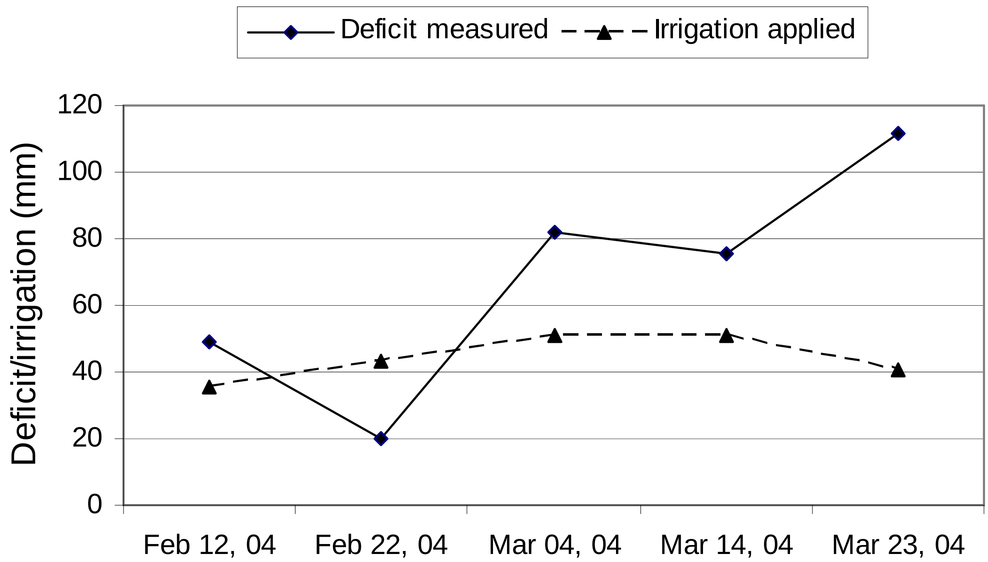

Figure 3.8 Soil water deficit before irrigation (irrigation requirement) in comparison with the water amount the farmer applied

The graph indicates that the irrigation required was greater than the applied water, except during one sampling occasion (February 22, 2004). The amount of water farmers traditionally applied was found to be very low compared to the irrigation required; sometimes more than twofold (Fig. 3.8). Once again, this confirmed that traditional irrigation application depth is much less than the soil water deficit to the field capacity. Most farmers on the scheme blamed the low scheme water supply for under-irrigation of their crops, coupled with too long intervals between water supply cycles.

Efficient irrigation is about refilling the soil profile to field capacity. Application of more than the soil deficit leads to wastage of water that reduces the application efficiency, whilst an irrigation amount less than the soil water deficit may lead to more frequent application or reduction of crop ET. According to Al-Kaisi & Broner (2005), significant evaporation can take place only when the soil's top layer or plant canopy is wet. Once the soil surface is dried out, evaporation decreases sharply until the next rain or irrigation. Crop water use is influenced by prevailing weather conditions, available water in the soil, crop species and growth stage. At full cover, crops will have maximum ET rate if soil water is not limited and the soil root zone is at field capacity.

3.4 Discussion and Conclusions

The irrigation water management at the Godino scheme remains solely traditional. Population growth and the diminishing irrigation water resources are becoming critical constraints for producing enough food in the region. The overall result indicated that traditional water management at the Godino scheme seemed to be poor: too long irrigation intervals and too low water depths per application. The application efficiency is poor due to lack of land levelling. Farmers at the Godino scheme blame the shortage in water supply and too long intervals between supply cycles for under-irrigation of their crops. In addition, the lack of a water users' organisation resulted in inequitable water distribution. Furthermore, a lack of improved irrigation technologies, high yielding crop cultivars and other agronomic practices also aggravate the production constraints on the scheme. Nowadays, irrigated crop production without proper plant nutrient management cannot be feasible. Therefore, traditional irrigation schemes need to be supported by improved water management techniques, improved crop cultivars, and proper fertility and crop protection managements.

The performance of scheme water management is widely dependent on scheme water supply and its efficient distribution. In areas where a water shortage exists, careful distribution is essential to avoid crop damage due to water stress. Crop choices and the determination of critical growth stages to water stress could promote optimum crop growth and finally reduce yield reduction. Different crops have various critical growth stages that respond to water stress. Once a critical growth stage to water stress is identified, it is possible to share the scarce water resource on a priority basis. Identification of appropriate irrigation intervals and depths also significantly helps to optimise water application. On the other hand, characterisation of soil water content before irrigation will also aid to determine the amount and intervals of water application. Under conditions of water scarcity, it is always advisable to avoid water movement below the plant's active root zone. Light irrigation, but more frequent application, may safeguard yield reduction and quality. Application during the evening or avoiding sunny conditions would minimise water evaporation and promote water storage in the crop root zone.

CHAPTER 4

COMPARISON BETWEEN TRADITIONAL AND SCIENTIFIC IRRIGATION SCHEDULING PRACTICES FOR FURROW IRRIGATED POTATOES IN ETHIOPIA

4.1 Introduction

In Ethiopia, small-scale traditional irrigation schemes constitute about 40% of the total irrigated land area. Despite this fact, the sector has largely been overlooked by authorities and was not supported by improved water management technologies. Due to land and water resource shortages and the need for food self-sufficiency in the region, it has become essential to improve the productivity of this sector. A recent survey conducted at Godino, one of the representative schemes, revealed that farmers applied irrigation water according to its availability, regardless of profile deficit, crop type and growth stage. This highlights the fact that scarce water resources are not being used optimally and emphasises the potential for improved water productivity by implementing efficient irrigation management practices.

Potatoes (*Solanum tuberosum* L.) are one of the most important crops grown on the Godino scheme. Potatoes are shallow-rooted and more sensitive to soil water stress than other deep-rooted crops (Canada Saskatchewan Irrigation Diversification Centre (CSIDC), 2005; Tekalign & Hammes, 2005a ; Tekalign & Hammes, 2005b). Most of the potato root system is confined to the top 0.2 - 0.3 m of the soil profile, although, depending on the soil type and available soil water, some roots may penetrate to a depth of 1 m. In addition to its shallow root system, the complex physiological response to water stress makes potatoes sensitive to even moderate plant water deficits (Bradley *et al.*, 2005). The major physiological responses of potatoes to water stress, next to stomatal closure, are reductions in leaf expansion, stem and tuber growth (Van Loon, 1981; Bradley *et al.*, 2005). Potatoes are particularly sensitive to water stress during tuber initiation, early tuber development and tuber bulking (Jefferies, 1993; Juzl & Stefl, 2002; Lahlou *et al.*, 2003; Tourneux *et al.*, 2003; Bradley *et al.*, 2005).

The goal of irrigation management is to maintain the water level in the root zone within a range where crop yield and quality are not hampered due to either insufficient or excess water. For potatoes, soil water content in the root zone should not be allowed to drop below 65% of the available soil water storage between irrigations (King & Stark, 2002).

Monitoring soil water in the crop root zone will allow better management of water applications in order to meet the requirements of the crop. However, direct measurement of soil water in the field is tedious and usually requires specialised equipment. Irrigation scheduling models can estimate how much water is needed and when best to apply it on different soil types and crops. Many water balance approaches have been used to estimate crop water availability and irrigation requirements. Most of the time, calculations are based on potential evapotranspiration values estimated by locally tested formulae or, at best, on the Penman generalised expression (Smith, 1992a; Allen *et al.*, 1998). The Soil Water Balance (SWB) model is a mechanistic, real-time, generic crop, and soil water balance irrigation scheduling model (Annandale *et al.*, 2000; Jovanovic *et al.*, 2002). It gives a detailed description of the soil-plant-atmosphere continuum, making use of weather, soil and crop management data. The model has been tested extensively and found to give reliable estimates of water use for a wide range of crops (Annandale *et al*., 2000; Jovanovic *et al*., 2002; Geremew *et al*., 2007). As an alternative to real-time scheduling, SWB can also be used to generate Irrigation Calendars, using site-specific soil and management inputs and long-term weather data. The generated irrigation calendar guides the user on when to irrigate and how much water to apply (Annandale *et al.,* 2005). This approach can be very useful to small-scale farmers, who may not have access to computers or the skills to use them.

The wetting front detector (WFD) is also another simple and affordable irrigation-scheduling tool that monitors the physical movement of water down the soil profile (Hanan *et al.*,1994; Stirzaker, 2003; Stirzaker *et al.,* 2004). It was suggested that the combined use of SWB and WFDs could provide a more useful recommendation to the user (Annandale *et al.,* 2005). Detectors are usually placed in pairs at different soil depths. Recommended placement depths for flood are 20 cm for the shallow WFD and 50 cm for the deeper WFD. Deeper placement may be considered for infrequent irrigations or very long furrows (Stirzaker, 2007). If the detectors are rarely activated, the crop is likely to be under-irrigated. If both shallow and deep detectors regularly respond to irrigation, the crop is likely to be over-irrigated (Stirzaker, 2003; Stirzaker *et al*., 2004). This information can then be used to adjust the calendar recommendation upwards or downwards, as necessary.

An experiment with potatoes as test crop was established at the Debre-Zeit Research Centre in Ethiopia. The objective was to compare two commonly- followed traditional irrigation regimes with two scientifically- based irrigation management methods, namely SWB Irrigation Calendars (with WFD feedback) and soil water monitoring, using a neutron probe. The hypothesis was that the use of scientific irrigation scheduling methods could improve water use efficiency.

4.2 Materials and methods

Site description

The study was conducted at the Debre-Zeit Agricultural Research Centre experimental farm from January to April 2005. The site is located at 8^o 44' N, 39^o 02' E at an altitude of 1 900 m. It receives an average annual rainfall of about 900 mm, with the highest average monthly maximum temperature of 28 ^{o}C in May and the lowest average minimum temperature of 9^{o}C in December. According to the data from the National Soil Laboratory Service (unpublished), the soil is classified as clay loam in texture, with a bulk density of 1.29 Mg m^{-3}, field capacity of 0.33 kg kg^{-1} and permanent wilting point of 0.18 kg kg^{-1}, which gives a plant available water (PAW) of around 200 mm m^{-1}.

Field procedures

The soil was thoroughly prepared using a mouldboard plough, then levelled and ridged, to give a row spacing of 0.75 m. Sprouted potato tubers (local variety Awash) were planted on 12 January 2005 at a spacing of 0.3 m within the row. Each plot consisted of six 5 m long rows. A ridge of about 25 cm high was constructed around each plot to facilitate the even distribution of furrow- applied water within the plot and to avoid water from flowing out of the plot. Fertilisers were applied according to recommended guidelines (W.G. Gebremedhin, 2003, HARC, Ethiopia). The crop received 110 kg ha^{-1} N in a split application, half at planting and the rest 30 days later, in the form of urea. The crop also received 92 kg ha^{-1} P as di-ammonium phosphate at planting. The experiment was arranged in a randomised complete block design (RCBD) with four replications. Since the soil was dry at planting, four weekly irrigations of 60 mm each were applied to all plots before treatments were imposed, to ensure uniform plant establishment. There was no obvious pest infestation, except for tuber moth at levels far below the threshold for chemical control. Three fungicide sprays were applied at fortnightly intervals for the control of early and late blight. Weeding and inter-row cultivations were performed by hand hoeing when deemed necessary.

Irrigation treatments

1. *SWB treatment*: the 29- year average daily maximum and minimum temperatures, as well as soil physical properties, planting date and irrigation management options were used as inputs to the SWB model (Jovanovic *et al.*, 2002) to produce a site- specific seasonal Irrigation Calendar. For the first part of the growing season (until about 40 days after planting (DAP)) an irrigation interval of once every five days was used, whereafter the interval was increased to once every seven days. Two WFDs were installed in each plot, one at 0.3 m soil depth (Shallow WFD) and the second at 0.5 m (Deep WFD). These depths were slightly deeper than the most recent recommendations (Stirzaker, 2007). The WFDs were used as feedback to decide whether the irrigation amount recommended by the SWB calendar needed upward or downward adjustment. Ideally, all shallow WFDs should respond after each irrigation event, while deep WFDs should only respond occasionally. A simple algorithm was used to decide when to adjust the recommended irrigation amount, depending on the number of shallow and deep WFDs responding after

the previous irrigation event (Annandale *et al*., 2005). When the WFDs indicated under- irrigation, the recommended water amount for the next irrigation was increased by 20%. Likewise, when the detectors indicated over-irrigation, the next irrigation amount was reduced by 20%.

2. The *Farmers' Traditional Practice* (FTP) was based on the average irrigation depth and interval practised by the Godino scheme farmers close to the experimental station. For this treatment 50 mm of water was applied once every 10 days.
3. The *Research Centre Practice* (RCP) treatment was implemented, using the average irrigation depth and interval as practised by the Debre-Zeit Agricultural Research Centre, namely 60 mm of irrigation applied every six days.
4. In the fourth treatment, soil water content was monitored weekly using a *Neutron Probe* (NP), and the profile was refilled to field capacity. However, for the first part of the growing season (until about 50 DAP) the NP instrument was not functional. During this period a water amount of about 40 mm was applied every seven days, including rainfall.

Data recorded

Soil water content (WC) was measured with a neutron probe (Model 503DR CPN Hydroprobe, Campbell Pacific Nuclear, California, USA). The neutron probe was calibrated for the site and weekly readings were taken before irrigation. One access tube was installed in the middle of each plot and readings were taken to 1.2 m depths at 30 cm intervals. Furrow-flood irrigation was used to irrigate the plots, according to the treatments. Irrigation water was measured using a three-inch (76.2 mm) throat-width Parshall flume and the duration of irrigation was calculated according to equation 4.1 (Kandiah, 1981). The Parshall flume was installed at the entrance to the plot to minimise water loss during conveyance and distribution.

$$T = AD/60Q \qquad (4.1)$$

where

T = time in minutes, A = plot area (m^2), D = application depth (mm) and

Q = discharge rate ($l\ s^{-1}$)

.

Fractional interception (FI) of photosynthetically active radiation (PAR) was measured weekly with a Decagon sunfleck ceptometer (Decagon, Pullman, WA, USA), making one reference reading above and 10 readings beneath each canopy. Growth analyses were carried out weekly by harvesting plant material from a 1 m^2 representative surface area from each plot. Fresh mass was measured directly after sampling and separated into leaves, stems and tubers. Leaf areas were measured on the fresh leaf samples, using a CI-202 leaf area meter (CID Inc., Vancouver, WA, USA). Dry masses were determined after drying samples in an oven at 60°C for four to five days. Phenological development was monitored during the growing season. Weather data was obtained from a weather station located about 200 m from the experimental field. Water use efficiency (WUE) was calculated for all treatments using the net seasonal irrigation plus rainfall amount during the growing period and the tuber yield obtained (equation 4.2):

$$IWUE = \frac{FTY}{(I + P + \Delta SWC)} \qquad (4.2)$$

where

WUE = water use efficiency (kg ha^{-1} mm^{-1}), FTY = the fresh tuber yield (kg ha^{-1}), I = the total seasonal irrigation amount (mm),

P = the total amount of precipitation during the growing season (mm) and

ΔSWC = the change in soil water content between the last and first day of crop growth (mm).

Statistical analysis

Analysis of variance was performed, using the SAS system for Windows 2002 (SAS Institute Inc. Cary, NC, USA). Means were compared using the least significant difference (LSD) test at p=0.05.

4.3 Results and discussion

Leaf area index (m^2 m^{-2})

The maximum leaf area index (LAI) obtained per treatment and the overall seasonal LAI trends are given in Table 4.1 and Figure 4.1. In general, potato yield and other agronomic parameters obtained from this experiment were relatively low compared to values achieved for temperate regions. Smith (1968) and Kooman *et al.* (1996a) indicated that potato yields are usually lower in eastern and tropical Africa, compared to those obtained in temperate zones. Smith (1968) suggested that it could be attributed to the detrimental effects of short-day length and high air and soil temperatures. Photoperiod plays an important role in potatoes, as tuberisation is triggered when the day-length falls below a certain critical threshold. Under short day-length conditions, tubers are initiated much earlier than under long-day conditions, making tuberisation more abrupt and, consequently, leading to much faster maturity and lower tuber yields (Smith, 1968; Juzl & Stefl, 2002).

Leaf area index (LAI) data revealed that the NP treatment for most of the growing season produced the highest LAI, followed closely by the SWB treatment (Fig. 4.1). Significant differences in LAI occurred between emergence and peak vegetative growth (about 68 DAP). The two traditional treatments, FTP and RCP, produced similar but lower LAI values, compared to the NP and SWB treatments (Fig. 4.1). However, the NP and SWB treatments resulted in similar LAI values, which were significantly higher than those of the two traditional practices. After reaching peak LAI values at about 68 DAP, the LAIs for all treatments declined drastically to reach similar minimum values at about 90 DAP. In general, the NP and SWB treatments were similar and consistently superior to the traditional treatments until about 76 DAP.

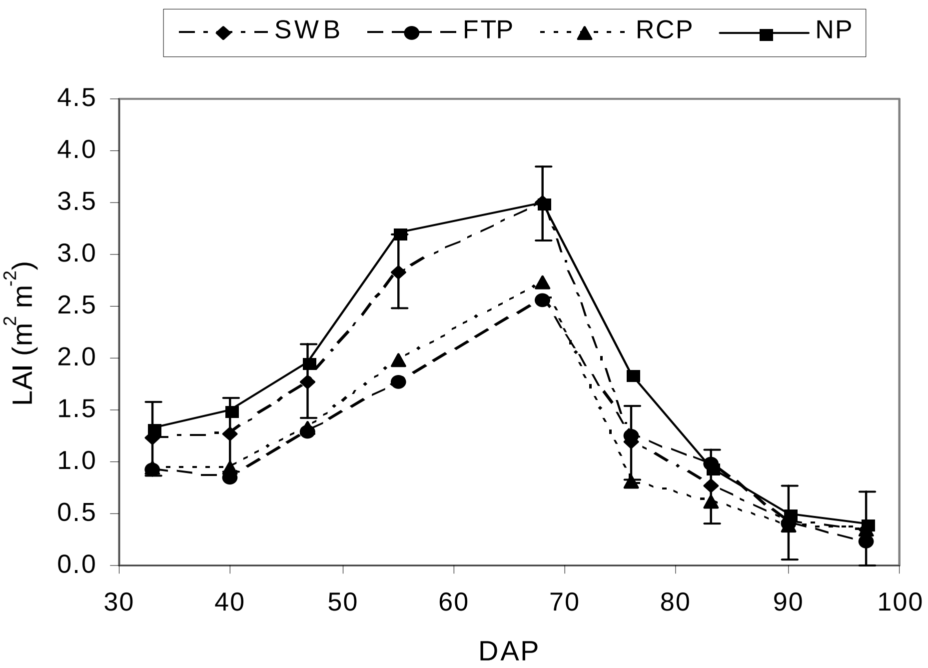

Figure 4.1 Leaf area index (LAI) for four irrigation treatments: Soil Water Balance (SWB), farmers' traditional practice (FTP), research centre practice (RCP) and neutron probe (NP) treatments.

The maximum LAI values obtained from the four irrigation regimes also confirmed that the two traditional practices were inferior (p>0.05) to the scientific scheduling practices (Table 4.1).

Table 4.1 Potato fresh tuber yield (FTY), average leaf dry mass (LDM), average canopy dry mass (CDM), average tuber dry mass (TDM), maximum leaf area index (LAI), average fractional interception (FI) of PAR and standard error of mean (SEM) for the irrigation treatments compared.

Treat-ment	FTY $kg\ m^{-2}$	LDM $kg\ m^{-2}$	CDM $kg\ m^{-2}$	TDM $kg\ m^{-2}$	LAI $m^2\ m^{-2}$	FI
NP	2.37a	0.11a	0.14a	0.44a	3.50a	0.58a
SWB	2.34a	0.09b	0.12b	0.39a	3.49a	0.52b
RCP	2.14ab	0.08bc	0.10bc	0.38a	2.73b	0.43c
FTP	1.79b	0.07c	0.09c	0.28b	2.55b	0.40c
SEM	0.076	0.004	0.005	0.017	0.013	0.022
CV %	9.99	9.42	9.73	9.90	18.02	8.01

Means followed by the same letter are not significantly different at p=0.05

NP = Neutron Probe

SWB = Soil Water Balance

RCP = Research Centre Practice

FTP = Farmers' Traditional Practice

Leaf area index is one of the important parameters indicating potential crop growth performance and yield. Many researchers (Lahlou *et al.*, 2003; Anita & Giovanni, 2005; Bradley *et al.*, 2005) agree that the maximum LAI achieved by a crop gives an indication of the total fraction of solar radiation interception, which determines photosynthetic production and tuber yield. For potatoes, a larger photosynthetically active leaf surface is important to maintain high tuber bulking rates for extended periods (Bradley *et al.*, 2005), which is required for high tuber yields.

Leaf dry mass (LDM), canopy dry mass (CDM) and total dry mass (TDM)

Leaf dry mass (LDM) yield is usually a good indicator of potential plant growth and yield. As indicated by David *et al.* (1983), Jefferies & MacKerron (1987) and Tourneux *et al.* (2003), tuber growth and development are dependent on the presence of sufficient foliage to produce the necessary assimilates and roots for adequate supply of water and nutrients to the canopy. In this experiment, seasonal LDM increment followed the same trend as that of LAI and reached maximum values at about 68 DAP, regardless of the irrigation treatment (Fig. 4.2). The highest LDM was produced by the NP treatment, followed by SWB. LDMs started declining for all treatments after 68 DAP and converged to similar values from 76 DAP (Fig. 4.2). This period coincided with the stage when maximum assimilate partitioning to the tubers occurred, and when tubers gained substantial mass in a relatively short period of time.

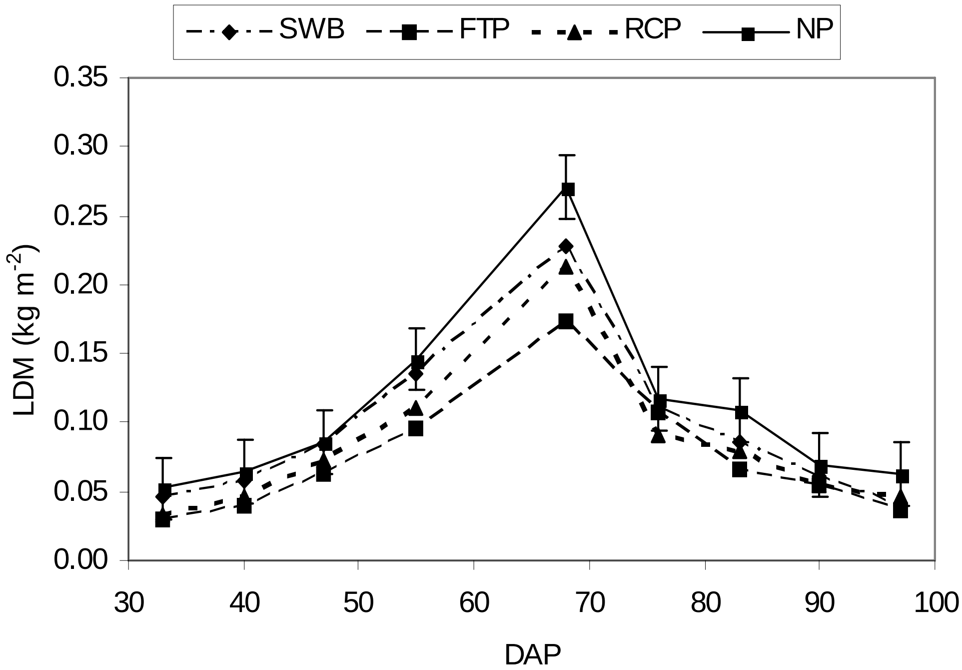

Figure 4.2 Leaf dry matter (LDM) for four irrigation treatments: Soil Water Balance (SWB), farmers' traditional practice (FTP), research centre practice (RCP) and neutron probe (NP) treatments.

Canopy biomass production is proportional to the fraction of solar radiation intercepted, which influence photosynthetic production and final tuber yield. Juzl & Stefl (2002) found that potato cultivars with significantly higher canopy biomass also resulted in significantly higher tuber yields. Research has also proven that water shortage at any growth stage results in reduced canopy dry matter and tuber yield (Epstein & Grant, 1973; MacKerron & Jefferies, 1988; Deblonde & Ledent, 2000; Juzl & Stefl, 2002). The average LDM and CDM obtained in this experiment confirmed these findings, where the NP treatment significantly out-yielded ($p<0.05$) the other treatments, followed by SWB (Table 4.1). Treatment FTP produced the lowest TDM yield ($p<0.05$), while the other three treatments did not differ significantly from each other ($p>0.05$).

Fresh tuber yield (FTY)

The fresh tuber yield (FTY) followed more or less the same trend as for the above-ground dry mass yield (CDM) and LAI during the growth period (Table 4.1). Hence, treatments NP and SWB resulted in the highest fresh tuber yields, compared to the FTP treatment ($p<0.05$). Similar findings were also obtained by Deblonde & Ledent (2000), who reported that most agronomic parameters, photosynthetic production and yield were affected by levels of water supply. Tourneux *et al*. (2003) also stated that water stress slightly reduced LAI and canopy cover in all the genotypes they tested, and that final dry matter production was greatly affected.

In general, the NP and SWB treatments produced the highest final fresh tuber yields, LDM, CDM and TDM, compared to the two traditional practices (RCP & FTP) (Table 4.1). The fresh tuber yield obtained by FTP was inferior by 32% to that of NP and by 31% to that of SWB. Differences were statistically significant at $p<0.05$ (Table 4.1). Irrigating less than the crop water requirements was primarily responsible for the reduction in LDM, which negatively affected CDM and consequently tuber yield (Table 4.1).

Figure 4.3 shows the reference evapotranspiration of the cropping season in comparison to water applied for each treatment.

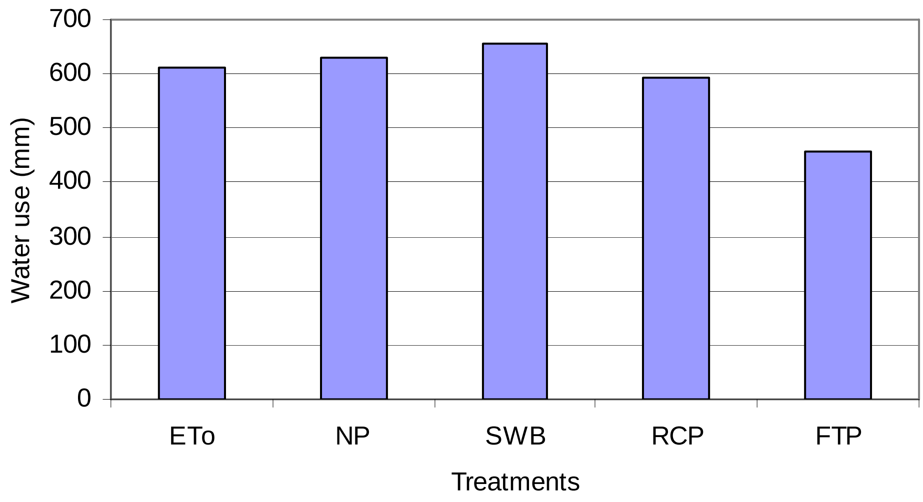

Figure 4.3 ETo (reference) for the cropping period at Debre-Zeit as compared to water applied for each treatments.

Fractional interception (FI)

The fractional interception (FI) of PAR is an important indicator of biomass production and tuber yield (Williams *et al.,* 1996; Lahlou *et al*., 2003). FI results (Table 4.1) show that the NP and SWB treatments had significantly higher canopy cover or FI values ($P<0.05$), compared to the two traditional treatments, implying that they intercepted the highest average fractions of solar radiation. Lahlou *et al*. (2003) reported that the first manifestation of water shortage is a reduction in potato leaf size, resulting in a reduced amount of radiation intercepted, which finally leads to a decrease in tuber dry mass accumulation. The same authors further explained that reduced leaf growth and accelerated leaf senescence are common responses to water deficits and are adaptations of plants to water deficit. Deblonde & Ledent (2000) also reported that intercepted radiation is mostly influenced by the level of water application and to a lesser extent by other factors such as ambient conditions. Measured FI values over the growing season revealed a sharp increase in FI until 47

DAP, whereafter it levelled off and reached peak values at about 68 DAP (Fig. 4.3). A gradual decline in FI was observed between 68 and 90 DAP, whereafter FI declined sharply. Treatments NP and SWB maintained the highest FI values throughout the growing season, while FTP demonstrated the lowest values.

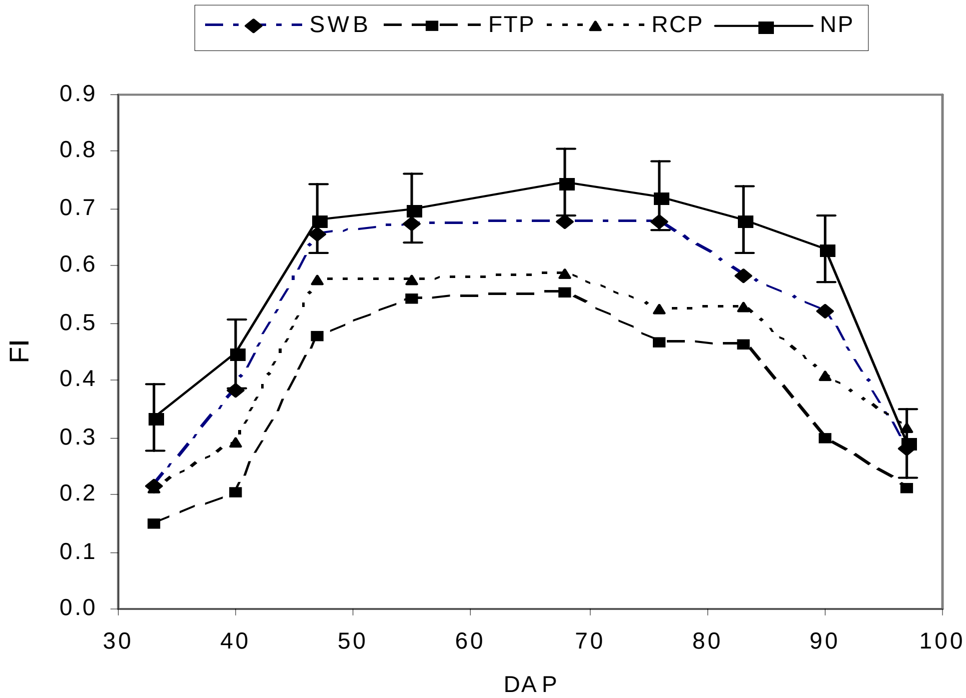

Figure 4.4 Fractional interception (FI) of the photosynthetically active radiation (PAR) for four irrigation treatments: Soil Water Balance (SWB), farmers' traditional practice (FTP), research centre practice (RCP) and the neutron probe (NP) treatments.

Irrigation water use and water use efficiency (WUE)

The difference in total water use is one of the main reasons for yield variation in crops in general and potatoes in particular. For this experiment, irrigation water use for the different scheduling treatments ranged from 456 mm for FTP to 654 mm for SWB (Table 4.2). The treatment (SWB) with the highest total irrigation amount resulted in the second highest tuber yield. Irrigation amounts recommended by the SWB calendar were often adjusted upwards by 20%, due to the fact that WFDs responded rarely

(Fig. 4.4). This adjustment most probably resulted in over-irrigation of the SWB treatment at times, which could have resulted in leaching of nutrients and a slight lowering in tuber yields. The poor WFD response could possibly be attributed to detectors being placed too deep for the specific soil, which is known to reduce WFD sensitivity. The FTP treatment had the lowest water application, but it resulted in the smallest canopy size and lowest tuber yield ($p<0.05$).

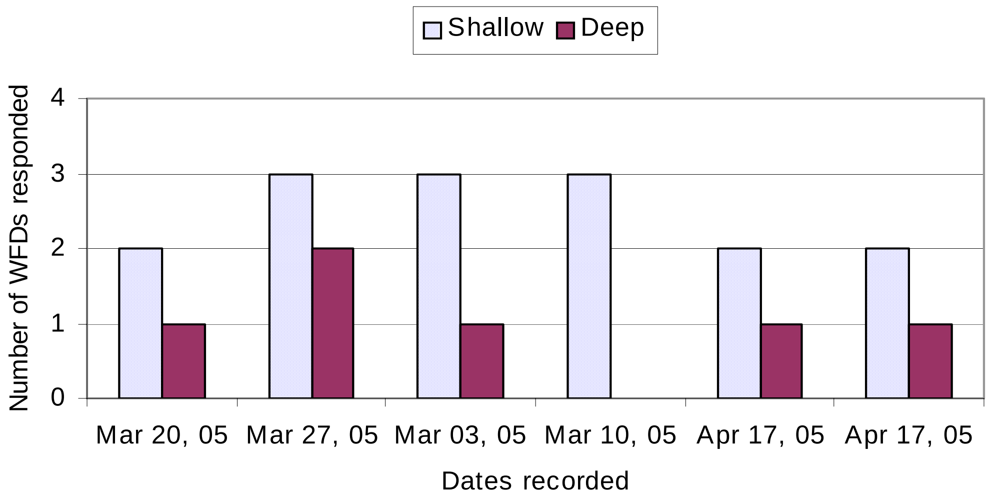

Figure 4.5 Response of wetting front detectors (WFDs) responding 24 hrs after irrigation to correct the SWB model Irrigation Calendar

Irrigation water use efficiency (WUE) gives the relationship between the quantity of water applied ($I + P \pm \Delta SWC$) and yield or dry matter produced (Della Costa *et al.*, 1997). Table 4.2 shows the calculated WUEs expressed per fresh tuber yields obtained for each treatment. The results revealed that the highest WUE was obtained for the FTP treatment, followed by the NP treatment (Table 4.2). WUEs did not vary much between treatments and ranged from 35.8 kg ha^{-1} mm^{-1} for the SWB treatment to 39.2 kg ha^{-1} mm^{-1} for the FTP treatment. The lower WUE achieved by the SWB treatment can probably be explained by occasional over-irrigation, as explained above.

Table 4.2 Total seasonal water applied, tuber yield and irrigation water use efficiency (WUE) for four irrigation treatments: re-filling to field capacity as per the neutron probe reading (NP), Soil Water Balance (SWB), research centre practice (RCP) and farmers' traditional practice (FTP) treatments.

Irrigation treatment	Tuber yield (kg ha^{-1})	Total water applied (mm)	WUE (kg ha^{-1} mm^{-1})
NP	23700a	631	37.6
SWB	23400a	654	35.8
RCP	21400ab	594	36.0
FTP	17900b	456	39.2

Means followed by the same letter are not significantly different at p = 0.05

WUE = Water use efficiency

WUE values obtained for all treatments are substantially lower as compared to the results obtained by other researchers (Onder *et al.*, 2005; Lim & Hyun, 2006; Lowery *et al.*, 2006). Onder *et al.* (2005) evaluated the WUE of potatoes under two irrigation regimes and obtained values that ranged from 66 to 114 kg ha^{-1} mm^{-1}. Similarly, Lowery *et al.* (2006) evaluated potato water use efficiency under drip and sprinkler irrigation systems, and obtained values ranging from 119 to 160 for drip irrigation and 50 to 100 kg ha^{-1} mm^{-1} for sprinkler irrigation. The low WUEs recorded for this experiment could probably be attributed to the overall low irrigation efficiency of furrow/flood irrigation, which is usually around 60%. Water conveyance and application losses for flood irrigation are substantially higher, compared with other irrigation systems, such as sprinkler or drip irrigation (Lowery *et al.,* 2006). Furthermore, yields were much lower than those typically obtained from areas with temperate climates, combined with optimal management practices (Cooper, 1988; Kooman *et al.,* 1996b). These authors argue that the low yielding potential of potatoes in the tropics and subtropics result from high temperatures and short day length conditions, to which most potato cultivars are not well adapted. The combined effects of low yields and high irrigation amounts finally culminated in the low WUEs recorded. However, high WUE on its own is not necessarily an indication of the best scheduling method. The findings of many research reports (Shimshi *et al.*, 1983; Ferreira & Carr, 2002; Yuan *et al.*, 2003) usually conclude that the less water applied, the higher the irrigation water use efficiency. Although the FTP treatment had a slightly higher WUE than other treatments in our study, its tuber yield was 24% lower than that of the NP treatment, for example. Therefore, any of the other three irrigation strategies would make better use of resources (solar radiation, fertilisers and land) compared to the FTP treatment.

Figure 4.5 illustrates the soil water deficits measured just before each irrigation event during the growing season. From this illustration, it is clear that the FTP treatment, which had the lowest seasonal water consumption (Table 4.2) and lowest final tuber yield (Table 4.1), also had the highest soil water deficits throughout the growing season.

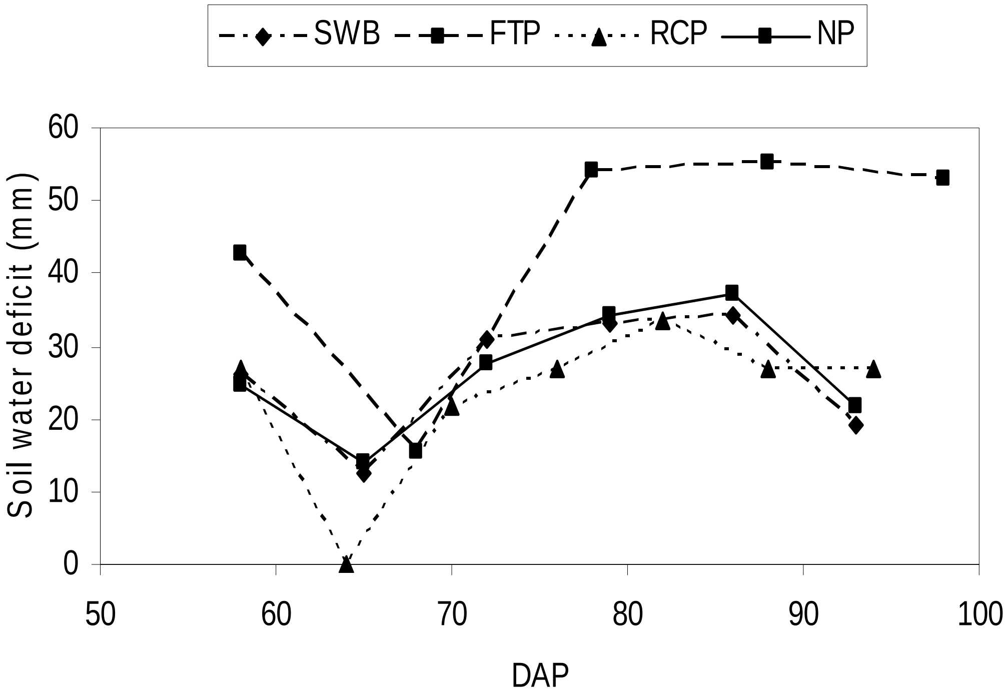

Figure 4.6 Soil water deficit measured before irrigation for four irrigation treatments: Soil Water Balance (SWB), farmers' traditional practice (FTP), research centre practice (RCP) and re-filling to field capacity as per the neutron probe reading (NP) treatments

The low soil water deficit recorded for the RCP at 64 DAP was due to a heavy rainfall event that occurred just after irrigating this particular treatment. Although soil water deficits for this treatment remained the lowest for the remainder of the growing season, it still had lower tuber yields than the SWB and NP treatments. The lower tuber yield recorded for RCP could probably be attributed to serious water stress earlier in the growing season, from which the crop could not fully recover. Although there is no soil water content data during the first part of the growing season to support this argument, the presence of early stress is confirmed by the lower LAI, LDM and CDM values recorded for the RCP earlier in the growing season.

4.4 Conclusions

The potato water regime experiment conducted at Debre-Zeit, Ethiopia, indicated that the traditional water application regime practised by farmers was not adequate for high potato production. The results revealed that fresh tuber yield and other yield attributes (LDM, CDM & FI) were significantly affected by the different irrigation scheduling methods. LDM and CDM were markedly reduced with the FTP and RCP treatments, with statistically significant ($p<0.05$) differences. Reduction in canopy size was mainly responsible for reduced interception of solar radiation or (FI), which resulted in reduced dry matter accumulation and, finally, lower tuber yields. Water use and WUE results revealed that the FTP scheduling method had slightly higher applied water productivity, followed by the NP method. However, WUE values of all treatments were similar, ranging from about 36 to 39 kg ha^{-1} mm^{-1}.

Since treatment differences in the WUE were small, it should not be the only parameter used to differentiate between scheduling methods, but tuber yield should also be considered. Although the FTP treatment had a slightly higher WUE than other treatments, its tuber yield was substantially lower than that of the NP and SWB treatments. Therefore, any of the other three irrigation strategies could be considered better than the FTP treatment. The FTP scheduling method resulted in significantly lower dry matter and tuber yields, indicating that water supply was not sufficient to maintain water requirements of the furrow- irrigated potato crop.

Hence, it is suggested that the current watering practice at the Godino Irrigation Scheme or (FTP) be replaced by a more efficient water management technique, based on thorough scheduling. From the results obtained, NP and SWB performed best, taking yield components and fresh tuber yields into account. However, the adoption of NP scheduling at the Godino scheme would require skilled NP users. Furthermore, this method is time-consuming and the equipment not affordable to individual farmers. Therefore, it is recommended that the SWB calendar scheduling method, which performed similarly to the NP method, be introduced to farmers at the Godino scheme. Extension staff at the adjacent Debre-Zeit Agricultural Research Centre could generate and supply farmers with site-specific SWB calendars for different soils, crops and planting dates commonly used by farmers on the scheme. This method is simple, but could have a substantial impact on the productivity of subsistence farmer irrigation schemes in Ethiopia.

CHAPTER 5

EVALUATION OF GROWTH PERFORMANCE AND DRY MATTER PARTITIONING OF FOUR PROCESSING POTATO CULTIVARS

5.1 Introduction

The potato (*Solanum tuberosum* L.) crop is a weather-sensitive crop with a wide variation among cultivars (Pashiardis, 1987). The environment is one of the major variables affecting crop production in general but, in particular, potato crops. Hence, knowledge of how it influences potato crop development, growth and yield is of great interest to researchers. Successful potato crop production requires efficient use of the climatic resources, namely solar radiation, temperature and water, among many others.

The growth rate of a potato crop, that is well supplied with water and nutrients and free from pests and diseases, is about proportional to its light absorption (Spitters, 1987; Van Delden, 2001). The total biomass production and accumulation of potato cultivars are dependent on the absorbed PAR, which is directly proportional to the plant canopy cover (Spitters, 1987; Vos & Groenwold, 1989; Van Delden, 2001). Spitters (1987) indicate that tuber yield is determined by the fraction of total biomass that is partitioned to the tuber. Potato cultivar variation in yield can thus be analysed in terms of differences in cumulative light absorption, the efficiency with which the absorbed radiation is used for DM, and the fraction of dry matter allocated to the desired plant organ (Pashiardis, 1987; Spitters, 1987; Van Delden, 2001). According to MacKerron (1987), cultivar differences in conversion efficiency have shown that, for most of the growing season, there is a linear relation between TDM and integral of intercepted solar radiation. Hence, the potential DM is manipulated using the conversion efficiency, which is the slope of the relationship. MacKerron (1987) further explained that the potential yield of tubers could be estimated from the average value of dry matter concentration, partitioned to both the top and tubers of the crop.

Biomass production in crops, including potatoes, is dependent on the amount of photosynthate available, which is directly proportional to the photosynthetic rate of the crop and its LAI (Meyer & Green, 1980; Tekalign & Hammes, 2005b). High LAI usually indicate that the crop can intercept more solar radiation for photosynthetic activity. Many researchers (Potters & Jones, 1977; Meyer & Green, 1980) report that the relationship between leaf area and biomass accumulation is linear. The most important factors that affect the rapid establishment of the crop canopy are genotype, seed environment, planting date and plant density, temperature and water stress conditions, and the availability of plant nutrients in the soil. Drought and high temperatures affect leaf area development and its persistence. The relationships between LAI and the proportion of radiation intercepted by the crop indicate that a LAI of four would intercept more than 80% of the incident radiation (Potters & Jones, 1977; Meyer & Green, 1980; Pashiardis, 1987).

Leaf radiation absorption is governed by the rate of leaf appearance, leaf expansion, leaf size, geometry and direction (Pashiardis, 1987). Pashiardis (1987) further explains that, in the absence of water stress, temperature is the major environmental factor influencing the development of leaf surface. Potato cultivars differ in the production of leaves at low temperatures in such a way that horizontal leaves intercept more light than erect leaves at low leaf area indices, and most cultivars differ considerably in this character (Pashiardis, 1987; Kooman & Rabbinge, 1996; Kooman *et al.,* 1996a). Generally, a temperature of below 7^{o}C and above 30^{o}C reduces the development rate of the potato crop (Kooman & Rabbinge, 1996; Kooman *et al.,* 1996b; Juzl & Stefl, 2002; Onder *et al.*, 2005).

Temperature and day length are among the major environmental factors that influence the development rate of potatoes and, consequently, the distribution of dry matter to various plant organs (Pashiardis, 1987; MacKerron & Jefferies, 1988; Kooman & Rabbinge, 1996). At early growth stages, most of the dry matter is distributed in a fixed proportion between leaves (80%) and stems (20%) (Van Heemist, 1986; Cadersa & Govinden, 2000; Jenkins & Mahmood, 2003), and from the onset of tuber initiation, the portion of dry matter partitioned to the tuber would constantly be at a maximum.

Dry matter production and allocation to the sink, the tuber, vary greatly in potato cultivars. Many researchers (Haverkort & Harris, 1987; Deblonde & Ledent, 2000) indicate that the poor adaptation of potato cultivars may be due to unfavourable allocation of assimilates in the plant. One of the reasons for failure of proportional assimilate allocation could be attributed to high temperatures, since, for some cultivars, a temperature of above 23^{o}C favours allocation of dry matter to the foliage at the cost of tuber growth (Haverkort & Harris, 1987; Jenkins & Mahmood, 2003). The variation in assimilate allocation in potatoes is related to maturity, (early or late,) because differences in life span of the crop in the field allow them to have extended time to produce and allocate more dry matter to the sink (Wolfe *et al.*, 1983; Van

Heemist 1986; Spitters, 1987). Hence, assimilate allocation is the result of genotype and climate interaction with appropriate cultural practices. Meyling & Bodlaender (1981) generalise that assimilate allocation is the combined result of genotype, growth and development, which are mutually interdependent and are difficult to analyse separately in an experiment.

With this background, the objective of this experiment was to evaluate two newly developed South African potato cultivars (Frodo and Darius) in comparison with two current commercial cultivars (Pentland Dell and Shepody) for their growth performance and dry matter partitioning to the sink, by efficient use of the microclimate of the specific growing location. Frodo was a new cultivar bred by the Agricultural Research Council (ARC), Roodeplaat, in South Africa and was not yet released during this experimentation. The result of this experiment has appraised the performance of this cultivar and hence, it was released in 2005 and licensed to McCain Foods (SA) (Pty) Ltd.

Darius was also developed by the ARC at Roodeplaat. It is characterised by medium maturity length and long-oval tuber shape with shallow eyes. The skin and flesh of this cultivar is white with a fairly high yield and good tuber size distribution. Darius has a high specific gravity (SG) and is generally used for french fries and crisping.

Pentland Dell was developed in the United Kingdom for its high yielding ability. Tubers are long and oval in shape, medium to large in size, white-skinned with cream flesh and shallow eyes (Van Niekerk, 1984). In South Africa, this cultivar is widely produced in the Gauteng, Limpopo, North West and Mpumalanga and Eastern regions. It is known to be excellent for boiling, wedges, baking, chipping and mashing (Van Niekerk, 1984). On the other hand, Shepody was developed in North America as a medium to high yielding cultivar (CSIDC, 2003). Plant type at full flower is upright with a good canopy and plant maturity at harvest has been rated as yellow before it finally dies completely. The tubers are characterised by medium to low SG compared to other potato cultivars. Tuber shape is mostly oblong with shallow eye depth. The skin colour is buff to white with a smooth to moderately smooth texture and the tuber flesh colour is white (Hutchinson *et al.*, 2001). The overall external tuber appearance was rated as poor to fair and the fry colour ranges from 00-3, where a rating of 3 is the maximum tolerance that processors accept under scarce supply situations (CSIDC, 2003). Shepody is known to be one of the high yielding cultivars with desirable processing quality in the areas where it was originally developed.

5.2 Materials and methods

Site description

The study was conducted from August 2003 to January 2004 at the Bronkhorstspruit McCain Experimental Station in South Africa. The station is located at a latitude of 25^{o} 44' 16" S, a longitude of 28^{o} 41' 03" E and an altitude of 1 490 m above sea level. The area receives an average rainfall of 709 mm per annum, with an average monthly maximum temperature of 26.4^{o}C and an average minimum temperature of 13.7^{o}C during the crop growth period. The seedbed preparation was performed following standard cultivation practices.

Field procedure and treatments

The four potato cultivars, Frodo, Pentland Dell, Darius and Shepody, were planted on 28 August 2003. All potato seeds were produced under the same conditions and stored at 4°C for about four months before planting. Each cultivar occupied six rows at a spacing of 0.9 m between rows and 0.3 m between plants. The experiment was arranged in a RCBD with three replicates. The experimental field was kept free of weeds, and no visible disease and insect pests were observed during the growing season. For other cultural practices, the station's standard methods were followed.

At planting, the crops received 80 kg ha^{-1} of nitrogen, 120 kg ha^{-1} of phosphorus and 160 kg ha^{-1} of potassium in a 2:3:4 (30) fertiliser blend. Three light doses, that added up to 140 kg ha^{-1} of nitrogen fertiliser in a form of limestone ammonium nitrate (28), were side-dressed 50-80 DAP, which gave an overall total of 220 kg ha^{-1} of nitrogen. No fertiliser deficiency and disease/pest symptoms were observed during the growth period of this crop.

Data recorded

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 before irrigation. Measurements were made in the middle of each plot, at 0.2 m soil depth increments down to 1 m. Sprinkler irrigation was used to replenish water deficit to field capacity for all plots according to the average soil water deficit recorded.

Crop growth parameters were measured weekly on all the plots from 35 DAP onwards. FI of PAR was measured weekly with a Decagon Sunfleck Ceptometer (Decagon, Pullman, Washington, USA) making one reference reading above and 10 readings beneath each canopy. Growth analyses were carried out weekly by harvesting plant material from 1 m^2 of ground surface at representative sites on each plot. Harvestable fresh matter was measured directly after sampling and dry matter of plant organs after drying in an oven at 60°C for four to five days. Four harvests were specifically considered to determine the proportion of dry matter partitioned to the different parts of the plant. The harvests were performed at 58 DAP (Harvest I), 72 DAP (Harvest II), 84 DAP (Harvest III) and 101 DAP (Harvest IV). Two records of percentage canopy cover were taken at 58 DAP (CC1) and 84 DAP (CC2). Leaf area was measured with an LI 3100 belt-driven leaf area meter (LiCor, Lincoln, Nebraska, USA) and LAI was calculated from the data. RD was estimated during the growing season from the WC measurement fluctuation in the profile. Phenological development was also monitored for each cultivar.

Weather data was collected using a Metos automatic weather station. Wind speed was measured by anemometer and solar radiation (Rs) with a photocell, which measures in the wavelength spectrum of 360 to 1 100 nm. Precipitation and irrigation were measured, using a tipping spoon rain gauge. The relative humidity (RH) sensor had a capacity of measuring RH from 10 to 95% RH.

Statistical analysis

Analysis of variance was performed using the SAS System for Windows, 2002 (the SAS Institute Inc., Cary, North Carolina, USA). Means were compared, using the

LSD test at the 95% probability level. Correlation between parameters was performed where applicable.

5.3 Results and discussion

Dry matter partitioning

Data on dry matter partitioning during the four consecutive harvests (Harvest I, II, III, and IV) are given in Tables 5.1, 5.2, 5.3 and 5.4 respectively. Dry matter partitioning to different plant organs, leaf (LDM), stem (SDM), tuber (HDM) and total (TDM) accumulation was determined for the four potato cultivars, namely Frodo, Pentland Dell, Darius and Shepody. At harvest I, the percentage of LDM and HDM partitioning was not significantly different among the cultivars, although Shepody had a comparably higher percentage of HDM (Table 5.1). This indicates that Shepody was already at the end of the vegetative growth stage and in transition to the tuber filling stage, while the rest of the cultivars were mainly partitioning dry matter to the canopy. This was substantiated by the fact that Shepody had the highest dry matter partitioned to the tubers (HDM), about 38% ($p>0.05$), compared to Darius, only about 10%.

Dry matter partitioning to the stem was significantly lower ($p<0.05$) for Shepody than for the remaining three cultivars that were still in the peak of vegetative development. Darius took a long time to emerge compared to the other cultivars and had less vegetative coverage during the harvest.

Table 5.1 Potato dry matter partitioning to leaves (LDM), stem (SDM), tuber/ harvestable (HDM), and total dry mass (TDM) for the four potato cultivars Harvest I (58 DAP)

Cultivars	LDM (%)	SDM (%)	HDM (%)	TDM kg m^{-2}
Frodo	58.95a	23.30a	17.75a	0.82ab
Pentland Dell	65.89a	20.09a	14.02a	0.84ab
Darius	65.88a	24.15a	9.96a	0.60b
Shepody	49.58a	11.98b	38.44b	1.65a
SEM	4.22	1.92	4.83	0.16
C V (%)	23.70	16.84	70.52	44.87

Means with the same letter are not significantly different

The TDM accumulation data revealed that Shepody produced significantly higher TDM ($p<0.05$) compared to Darius that had the lowest TDM accumulation (Table 5.1). At the first harvest, cultivars Frodo and Pentland Dell performed similarly and were second to the best performing cultivar (Table 5.1). Significantly higher tuber dry matter accumulation of Shepody during the first harvest indicated that it was an early maturing cultivar that had already advanced to the tuber bulking stage, while others were still in the vegetative stage.

During harvest II, cultivars Frodo and Darius were still allocating dry matter to leaves (Table 5.2) compared to the other two cultivars, which showed significantly lower partitioning to the leaves ($p<0.05$). On the other hand, dry matter partitioning to stem was still high for all cultivars, except for cultivar Frodo, which had significantly lower SDM values ($p<0.05$). The dry matter accumulation into the tuber was about 11% higher for Shepody, as compared to Darius, which indicated that Darius was still diverting a major quantity of assimilates to the production of new leaves and stems. At this harvest, Shepody again had the highest TDM accumulation ($p<0.05$), while Frodo still had the least (Table 5.2).

Table 5.2 Potato dry matter partitioning to leaves (LDM), stem (SDM), tuber/ harvestable (HDM) and total dry mass (TDM) for the four potato cultivars Harvest II (72 DAP)

Cultivars	LDM (%)	SDM (%)	HDM (%)	TDM kg m^{-2}
Frodo	37.70a	18.44b	43.86a	1.08b
Pentland Dell	12.85b	43.57a	43.57a	1.28ab
Darius	27.40a	36.30a	36.30a	1.15b
Shepody	6.22b	46.89a	46.89a	1.84a
SEM	4.04	3.59	2.25	0.11
C V (%)	26.09	15.83	16.94	23.55

Means with the same letter are not significantly different

The percentage of dry matter partitioned to stem did not vary significantly among cultivars during harvest III (Table 5.3), although the highest dry matter accumulation in the stem was observed for Shepody, compared to Frodo, which had the lowest accumulation. During this growth period, the proportion of dry matter translocated to leaf was significantly higher for Frodo and the lowest for Shepody ($p<0.05$). Once again, this indicated that Shepody was already undergoing leaf senescence, while stems and tubers remained the dominant sinks for dry matter allocation. Table 5.3 also reveals that the percentage of dry matter partitioned to tuber was significantly higher for Pentland Dell and Shepody ($p<0.05$). During this harvesting period, Frodo had the lowest proportion of dry matter translocated to tubers. Once again, Shepody had the highest ($p<0.05$) TDM accumulation and it was the lowest for Pentland Dell. Tubers had accumulated the highest proportion of assimilates during this time for all cultivars and the leaves accumulated the minimum share, followed by stems (except for Frodo).

Table 5.3 Potato dry matter partitioning to leaves (LDM), stem (SDM), tuber/ harvestable (HDM) and total dry mass (TDM) for the four potato cultivars Harvest III (84 DAP)

Cultivars	LDM (%)	SDM (%)	HDM (%)	TDM kg m^{-2}
Frodo	28.59a	28.86a	42.54b	1.38b
Pentland Dell	14.32bc	31.00a	54.68a	1.18b
Darius	18.47b	34.65a	46.88ab	1.47ab
Shepody	5.55c	40.40a	54.03a	1.78a
SEM	2.73	4.46	4.60	0.08
C V (%)	27.70	25.93	10.66	12.09

Means with the same letter are not significantly different

At harvest IV, most cultivars were already at the stage of senescing and Shepody had already completely senesced and had to be left out of the comparison. In general, dry matter partitioning to different plant parts was uniformly consistent among cultivars for all the parameters considered. Translocation of assimilates was lower for leaves and stems, and the highest for tubers. Frodo had the highest dry matter accumulation compared to remaining two cultivars, Pentland Dell and Darius (Table 5.4), where no significant differences were evident.

Table 5.4 Potato dry matter partitioning to leaves (LDM), stem (SDM), tuber/ harvestable (HDM) and total dry mass (TDM) for the four potato cultivars Harvest IV (101 DAP)

Cultivars	LDM (%)	SDM (%)	HDM (%)	TDM kg m^{-2}
Frodo	15.12a	13.46a	71.42a	1.89a
Pentland Dell	15.41a	12.29a	72.31a	1.35a
Darius	15.40a	13.99a	70.61a	1.46a
Shepody	-	-	-	-
SEM	1.76	0.95	2.52	0.12
C V (%)	15.28	15.94	5.37	20.51

Means with the same letter are not significantly different

These findings are in agreement with the results of Spitters (1987), who concluded that potato cultivars differed greatly in the proportion of dry matter allocation to the tuber over time. Spitters (1987) grouped potato cultivars into three categories with regard to the growth, development and dry matter allocation to the tuber. Group one were the cultivars in which tuber filling stars early and harvest index increases rapidly with time and, after the onset of tuber filling, assimilates were largely used for tuber growth. The second group was the cultivars in which tuber filling also started early, but harvest index increased less rapidly with time and a substantial fraction of current assimilates were still partitioned to the haulm growth. The third group was the cultivars in which tuber filling commenced later and showed a gradual increase in harvest index, with a continuous diversion of a major fraction of current assimilates to the production of new leaves and stem growth.

Number of stems, canopy cover and yield

Data on the number of stems, canopy cover, dry matter and fresh potato tuber yield, as well as average LAI is presented in Tables 5.5 and 5.6. Table 5.5 reveals average stem number and the percent canopy cover for two records, CC1 (58 DAP) and CC2 (84 DAP), for the four potato cultivars under comparison. From the results, Shepody was observed to be initially (at 58 DAP) the most vigorous potato cultivar, followed by cv. Frodo. The percentage canopy cover of these cultivars during CC1 was significantly higher relative to Pentland Dell and Darius ($p<0.05$). However, at the second canopy measurement date, Shepody had the lowest coverage, 8%, as compared to Frodo with 72% and Darius with about 67% canopy cover. This confirmed that for Shepody leaf senescence commenced very early, compared to the other cultivars (Table 5.5). Shepody had the highest average number of stems, which was significantly different from P. Dell & Darius at the 95% probability level. In general, Shepody is known as an early cultivar with more excessive vegetative growth and is less efficient in dry matter partitioning to the tuber. Many researchers (Pashiardis, 1987; Spitters, 1987; Kooman & Rabbinge, 1996; Kooman *et al.*, 1996a) agree that canopy cover is directly proportional to LAI as it enables crops to intercept adequate PAR and finally achieve a high biomass.

Table 5.5 Average stem number and percent canopy covers for the first (CC1) and the second (CC2) measurements for the four potato cultivars compared

Cultivars	Stem number (m^2)	CC1 (58 DAP) (%)	CC2 (84 DAP) (%)
Frodo	8.00a	69.39a	71.50a
Pentland Dell	5.17b	56.92b	49.28b
Darius	4.33b	47.55b	66.72a
Shepody	8.83a	79.11a	8.25c
SEM	0.71	4.230	7.788
C V (%)	23.56	6.80	12.13

Means with the same letter are not significantly different

From the potato cultivars compared, Shepody had produced the highest seasonal average LDM, which is significantly different ($p<0.05$) from Pentland Dell and Darius (Table 5.6). Shepody also produced the highest seasonal average CDM, though the difference is significant ($p<0.05$) only from Darius (Table 5.6). On the other hand, the fresh potato tuber yield record revealed that Shepody produced significantly lower tuber yield ($p<0.05$) as compared to the rest of the potato cultivars (Table 5.6). Of the four cultivars evaluated, Frodo significantly out-yielded the rest, followed by Pentland Dell and Darius with more or less similar dry matter yields. Shepody once again produced significantly lower HDM yield ($p<0.05$). Table 5.6 again revealed that Shepody produced the highest seasonal average LAI compared to the rest of the cultivars and the value is significantly higher than that of Pentland Dell and Darius ($p<0.05$).

Table 5.6 Comparison of average leaf dry mass (LDM), average canopy dry mass (CDM), fresh potato tuber yield (FTY) at final harvest, tuber/harvestable dry matter (HDM) at final harvest and average leaf area index (LAI) for the four potato cultivars compared

Varieties	LDM kg m^{-2}	CDM kg m^{-2}	FTY ton ha^{-1}	HDM kg m^2	LAI m^2 m^{-2}
Frodo	0.11ab	0.18ab	52.23a	10.45a	1.86ab
Pentland Dell	0.10bc	0.16ab	43.86a	8.59b	1.25bc
Darius	0.07c	0.11b	40.84a	8.41b	1.11c
Shepody	0.15a	0.23a	25.07b	4.51c	2.31a
SEM	0.01	0.01	3.27	0.65	0.17
CV. %	17.53	15.76	10.34	9.96	16.15

Means with the same letter are not significantly different

This experiment clearly shows that the cultivar with the highest CDM and high leaf area index, Shepody, eventually had the lowest tuber yield, which indicates that this cultivar is less efficient in dry matter translocation to its end product, the tuber. Shepody is a high-yielding cultivar in North America, where it was originally developed. In South Africa, however, it is a lower yielding cultivar, compared to most commercial potato cultivars. This could be attributed to the high temperature and long days in South Africa. The advantage of this cultivar is that it is an early maturing cultivar with the capacity of possessing high tuber SG to fill the market gap in case of scarcity. This result, however, agrees with the finding of Pashiardis (1987) who concluded that yield is associated more with the duration of potato growth period and LAD than with its growth rate. This is further confirmed by Kooman and Rabbinge (1996), who conclude that DM is not only dependent on new leaf production but also on the longevity of leaves. Leaf longevity is cultivar-dependent and systematically shorter in early cultivars than in late cultivars. Therefore, Frodo was found to be a late-maturing potato cultivar that allows its leaves to take more time collecting dry matter and partitioning significantly more to the tuber as compared to other cultivars.

Leaf area index (LAI), leaf dry mass (LDM) and canopy dry mass (CDM)

Figures 5.1 to 5.3 present data on the LAI, LDM and CDM, or the above-ground plant part, during the growing period. The LAI is one of the physical parameters indicating performance of crop growth and partitioning of assimilates. LAI of the four tested potato cultivars uniformly increased until about 80 DAP (Fig. 5.1). After about 80 DAP, Frodo and Darius were still actively growing, with increasing LAI, while Shepody's LAI, in particular, dropped sharply and completely senesced by 106 DAP (Fig. 5.1). The LAI for Pentland Dell also gradually declined from about 80 DAP to its senescence at about 118 DAP. The long duration for which a potato crop maintains active leaves, indicating the length of time foliage remains photosynthetically active on the plant, is very important in tuber dry matter accumulation (Lahlou *et al.,* 2003). Higher values of LAI were observed at about 100 DAP for Frodo, followed by Darius. The duration of active leaf growth mainly determines potato yield and is a major limiting factor with early-maturing cultivars (Lahlou *et al.,* 2003). Other research also confirms that tuber yield might be limited by insufficient maximum LAI values and/or LAD (Potter & Jones, 1977; Jefferies & MacKerron, 1993; Lahlou *et al.,* 2003). Potter & Jones (1977) explain that the rate of leaf area expansion has a greater influence on DM production than the net assimilation rate. The LAI data of Shepody indicates that it reached a maximum value between 70 and 80 DAP, whereafter it declined sharply. As a result of this growth characteristic, the crop did not have enough time to intercept adequate solar radiation for sufficient photosynthesis and dry matter accumulation in the tuber.

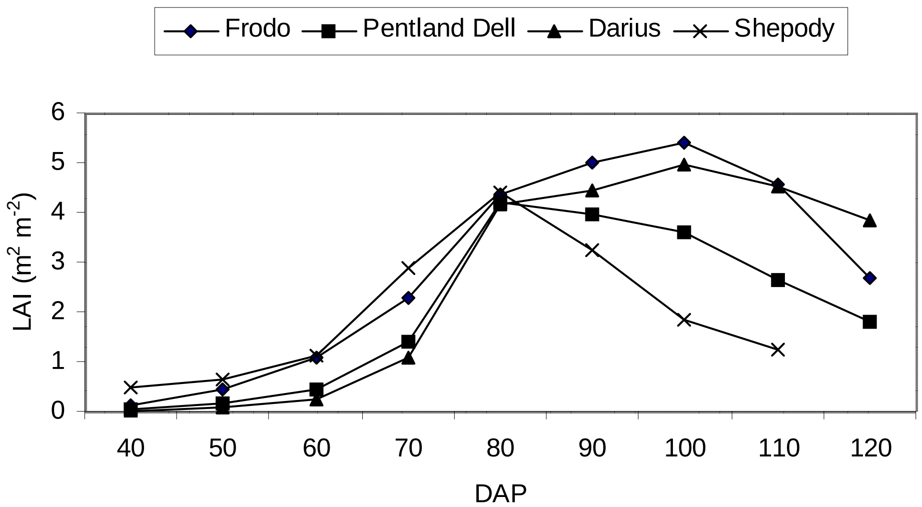

Figure 5.1 Leaf area index (LAI) of four potato cultivars during the days after planting (DAP)

This result, once again, is in agreement with that of Allen and Scott (1980), who drew the relationship between LAI and the proportion of radiation intercepted by the crop, indicating that a LAI of 4 and above intercepts more than 80% of the incident radiation for maximum photosynthetic activity and adequate dry matter partitioning to the tuber.

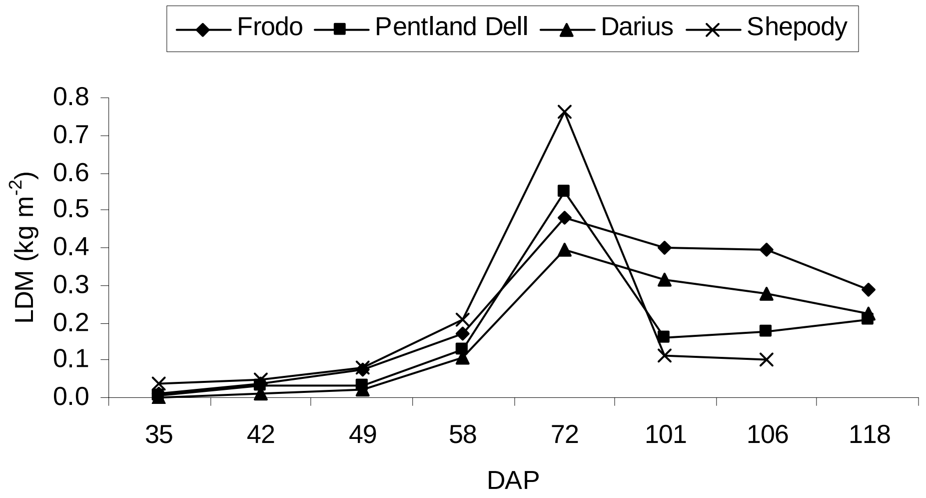

Figure 5.2 Leaf dry mass (LDM) of four potato cultivars during the days after planting (DAP)

Leaf dry matter (LDM) and CDM both followed the same trend as for LAI (Fig. 5.2 & 5.3). The LDM (Fig. 5.2) and CDM (Fig. 5.3) attained maximum values between 70 and 100 DAP for all cultivars and gradually declined to the same point at 118 DAP, except for Shepody, which died much earlier. This confirms the conclusion of many researchers (Allen & Scott, 1980; Lahlou *et al.*, 2003) that potato plant growth and DM are affected by the LAI and its duration.

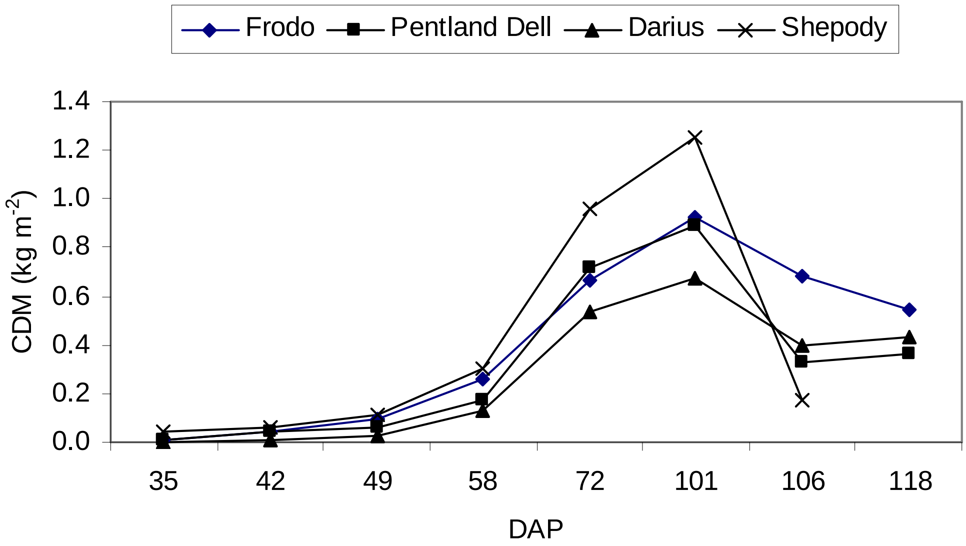

Figure 5.3 Canopy dry mass (CDM) of four potato cultivars during the days after planting (DAP)

Generally, Shepody produced high overall above-ground dry matter within a short growth period. This growth characteristic does not favour DM production and its allocation. Many researchers (Potter & Jones, 1977; Allen & Scott, 1980; Jefferies & MacKerron, 1993; Lahlou *et al.*, 2003) agree that long LAD is essential for high DM and high final yield.

5.4 Conclusions

The four potato cultivars were compared for their DM production and partitioning to the different plant parts, including the tubers. The main factor determining dry matter production is the length of the growth period. The results reveal that all cultivars performed differently at different harvests, even though Shepody had consistently higher TDM accumulation, with the most important contribution from the LDM. In addition, Shepody was found to be an early cultivar, performing all the growth activities and dry matter accumulation in a short period of time, compared to the remaining cultivars. Such a growth character, however, is not favourable for high tuber yield, since dry matter partitioning to tuber requires prolonged vegetative growth and high dry matter allocation efficiency, which is genotype-specific. The earliness of Shepody could be advantageous in rain-fed agriculture, where the rainfall duration is limited, but not under adequate irrigation, where maximum yield is expected. Another advantage is that earlier production enables processing factories to open their season earlier and get better use of their capital investment. This research finding reveals, however, that Frodo is the highest producer of fresh tuber yield, followed by Pentland Dell and Darius, which were significantly different from Shepody. The high average value of LAI for Shepody indicates that it is more efficient in translocation of dry matter to its canopy, as opposed to the ultimate goal of attaining high tuber yield. From the results, Frodo had effectively allocated most dry matter to the tubers, relative to others, which is the ultimate goal of potato crop production. From the tuber processing quality tests (data presented in Chapter 6), Frodo tubers exhibited good quality performance with minimum external and internal defects compared to the remaining cultivars. Its slow-growing nature and efficiency of partitioning dry matter to its tubers make Frodo a high-yielding cultivar with appropriate tuber characteristics. Hence, this newly developed potato cultivar is very suitable for the intended commercial production in South Africa.

CHAPTER 6

EVALUATION OF TUBER-PROCESSING QUALITY OF FOUR POTATO CULTIVARS

6.1 Introduction

The production of high-quality potatoes depends on the cumulative effect of various factors, including the genetic make-up of cultivars, the climate and the physical and biological properties of the soil (Brown, 1993). In addition, the external and internal tuber characteristics also affect the processing quality. According to David *et al.* (1983), a high-quality potato tuber should be turgid, well shaped, uniform and brightly coloured. These authors also refer to some external tuber characteristics for standardised quality grades, including being free from adhering soil, mechanical damage, greening, sprouts, disease and physiological defects. Quality traits important for cultivars used in potato chip manufacturing include high dry matter (specific gravity), low sugar levels and being free from defects (Hayes & Thill, 2002). The same authors report that the development of brown colour upon frying is the result of reactions between acids and sugars having a particular chemical structure or amino acids and the reducing sugars (glucose and fructose). In addition, though not a reducing sugar, sucrose is also an important indicator of processing quality because it can break down into glucose and fructose during cold storage, thus contributing to the development of brown colour during the frying process (Gary & Hughes, 1978). Standard limits for reducing sugars for chipping quality is less than 0.2% of fresh tuber mass. The concentration of reducing sugars above this level results in unacceptably dark fries (Cottrell *et al.*, 1995). The lower the content of reducing sugars, the lighter the chip colour.

Greater amounts of reducing sugars accumulate when tubers are stored at temperatures below 5^{o}C, which is commonly known as low-temperature sweetening (Cottrell *et al*., 1995). Cultivars that are resistant to low-temperature sweetening usually have lower activities of starch-degrading enzymes than those sweetening under low temperatures. However, sensitivity to low-temperature sweetening could also be related to starch granule degradation by endogenous enzymes (Cottrell *et al*., 1995).

Specific gravity of potatoes is an important determinant of harvest quality. This attribute of a tuber is an indicator of maturation that the industry uses as a reference to judge fry quality, baking characteristics and storability. More importantly, specific gravity measurements reflect environmental factors and cultural management procedures during the production season.

The specific gravity of tubers is also an important quality criterion for processing. It is used as an estimate of the solids or dry matter content of tubers. The higher the dry matter content, the lower the water content and the higher the specific gravity. Processors and consumers like to recognise the ideal french fry as lighter in colour, crisp on the outside and fluffy or mealy on the inside with a minimum of oiliness.

Specific gravity standards range from less than 1.060 (very low) to greater than 1.089 (very high) for quality chips and french fries (Mosley & Chase, 1993). The same authors further explain that specific gravity values between 1.060-1.069 are regarded as low, 1.070-1.079 as medium and 1.080-1.089 as high. Specific gravity can be influenced by several physiological processes of which respiration, transpiration, photosynthesis and water absorption are the major ones. Temperature and solar radiation favours the continuity of photosynthesis for production of carbohydrates for faster tuber growth. The production of a high yield of high specific gravity is directly related to the length of the growing season (Hudson, 1975; Baritelle & Hyde, 2003). Early maturing cultivars typically have short storage dormancy and are usually processed at harvest or shortly afterwards. Cultivars that are relatively late maturing, have long storage dormancies and can be processed for several months. In addition, specific gravity of potatoes is highly dependent on fertilisation and optimum soil water content. Excess nitrogen or high vegetative proportion can lower specific gravity (Hegney, 2001). The same author also indicates that, although potatoes are more sensitive to shortage of chloride than many crops, some works have shown an association between chloride application and a decrease in specific gravity. It has been observed that excess or insufficient soil water, particularly when accompanied by a high temperature, can lower specific gravity (Baritelle & Hyde, 2003; Stark *et al*., 2003). On the other hand, these authors indicate that optimum soil water, as tubers approach maturity, can increase specific gravity.

In general, late maturing (frozen processing) cultivars are usually rather high in starch (high dry matter, high specific gravity) and low in reducing sugars. Tubers with dry matter ranging from 20-25% are preferable for quality chipping (Mosley & Chase, 1993). Tubers with less than about 18% dry matter are seldom used for frozen processing or chips because of their poor texture (Mosley & Chase, 1993). Approximately two-thirds of the water in french fries, using tubers with high water content, is replaced by oil during frying (Mosley & Chase, 1993). Therefore, cultivars with high water content or low dry matter produce oily and soggy (wet and soft) french fries, as more water has to be removed during processing (Mosley & Chase, 1993).

Cultivar is not the only factor responsible for reduced external and internal tuber quality. Proper water management during the growing period is crucial for high yield and high chipping standard of tubers. Research has shown that next to genetic variation, water is one of the most detrimental limiting factors to potato growth, yield and processing quality. Potatoes are particularly sensitive to water stress during tuber initiation and early tuber development (Steyn *et al.*, 1992). Water deficit during this period can substantially reduce quality tubers by increasing the proportion of rough and malformed tubers (Shock *et al.*, 1998). Early-season water stress can also reduce specific gravity and increase the proportion of translucent ends (Tourneux *et al.*, 2003; Bradley & Stark, 2005). Low soil water during the crop growth can result in tuber vascular discolouration, especially when the crop is close to maturity. In addition, rapid death of vines due to frost, mechanical destruction and stress from high temperatures can also result in tuber internal growth defects, including vascular discolouration (Pavlista, 2002). Other forms of internal growth defects, like brown centre and hollow heart, substantially reduce the processing quality of tubers. These disorders are mostly associated with the abrupt change of growth conditions during the season (Hochmuth *et al.*, 2001). Excessively rapid tuber growth after cool temperatures and soil water stress aggravates the formation of brown centres and hollow hearts (Hochmuth *et al.*, 2001). On the other hand, plants exposed to cool soil temperatures of less than 12 ^{o}C and high soil water of greater than 80% plant available water during tuber initiation and a few weeks thereafter enhances brown centres (Hochmuth *et al.*, 2001). McCann and Stark (1989) also report an association of stem-end hollow heart with potassium deficiency. Finally, the physiological disorders of tubers resulting from either a water deficit or an excess of water is a major concern, resulting in tuber-processing quality decline. The extent of quality deterioration, on the other hand, depends greatly on inherent cultivar variation.

Background information of Pentland Dell and Shepody cultivars are dealt with in Chapter 5.1.

6.2 Materials and methods

Site description, field procedures and treatments are explained in detail in Chapter 5.2.

External and internal tuber characteristics

Specific gravity and crisp fry colour were determined for all cultivars from tuber samples collected from each plot. For specific gravity (SG) determination, tubers were weighed in air (Ma) and water (Mw). The SG was calculated by the formula SG = Ma/(Ma-Mw) (USDA, 1997). The reading obtained from each specific gravity test is corrected for temperature variations according to the standards provided by the USDA (1997). Reducing sugars were determined according to USDA (1997) standards for grades of potatoes for chipping quality. Tuber form index (TFI) was evaluated for tubers categorised as large, medium and small. Tubers are categorised as large when the diameter is greater than 75 mm, medium when it is between 55 and 75 mm, and small when it is less than 55 mm. For each category, length, width and mass of tubers were measured and a TFI was computed using the formula:

$$\text{TFI} = \text{Length (large) / Width (large)} \qquad (6.1)$$

The scoring methods used and their respective values for external tuber characteristics are given in Table 6.1, and for internal tuber characteristics in Table 6.2.

Table 6.1 External tuber characteristics evaluated for the four potato cultivars under comparison (USDA, 1997)

Parameters	**Scoring methods used and their relative values**
Secondary growth	Scored from 1 to 5, where 1 = no tubers with secondary growth; 2 = less than 10% of the tubers had secondary growth; 3 = 10–30% of the tubers had secondary growth; 4 = 30–60% of the tubers had secondary growth; and 5 = more than 60% of the tubers had secondary growth
Malformation	Tuber malformation scored from 1 to 5, where 1 indicates tubers with no malformation; 2 = less than 10%; 3 = 10–30% tubers, 4 = 30–60% tubers and 5 = more than 60% tubers were malformed
Mechanical damage	Tuber mechanical damage scored from 1 to 5, where 1 indicates no visible damage on the tuber; 2 = less than 10% tubers; 3 = 10–30% tubers; 4 = 30–60% tubers and 5 = more than 60% tubers exhibiting visible mechanical damage
Growth cracks	Growth cracks scored from 1 to 5, where 1 indicates tubers without growth cracks; 2 = less than 10% tubers; 3 = 10–30% tubers, 4 = 30–60% tubers and 5 = more than 60% of the tubers exhibiting growth cracks
Stolon indent	Appearance and depth of stolon indent scored from 1 to 3, where 1 indicates the appearance of stolon indents superficially; 2 = indents with medium depth; and 3 = deep indents
Eye depth	Tuber eye depths scored from 1 to 3, where 1 indicates superficial depth; 2 = medium depth; and 3 = deep tuber eyes.
Skin colour	Tuber skin colour was identified and each colour represented by numbers from 1 to 5, where 1 represent white; 2 = yellow; 3 = white with markings; 4 = red; and 5 = russet

Table 6.2 Internal tuber characteristics used for evaluating the four potato cultivars under comparison (USDA, 1997)

Parameters	Scoring methods and their relative values
Hollow heart	Tubers with hollow heart were counted and expressed in percentage.
Brown spot	Tubers with brown spot were counted and expressed in percentage.
Vascular discolouration	Tubers with vascular discolouration counted and expressed in percentage.
Dry rot	Dry rot scored from 1 to 5, where 1 represents no tubers with dry rot; 2 = less than 10% tubers; 3 = 10-30% tubers; 4 = 30–60% tubers; and 5 = more than 60% tubers characterized with dry rot
Common scab (area)	The presence and area of common scab was scored from 1 to 5, where 1 represents tubers with no symptoms of common scab; 2 = 1–25%; 3 = 25–50%; 4 = 50–75%; and 5 = 75–100% of surface with symptoms of common scab.
Eelworm (root knot)	Symptoms of eelworm scored from 1 to 5, where 1 represents tubers with no symptoms of eelworm; 2 = 1–25%; 3 = 25–50%; 4 = 50–75%; and 5 = 75–100% of surface with symptoms of eelworm
Flesh colour	Tuber flesh colours represented from 1 to 4, where 1 = white; 2 = cream; 3 = light yellow; and 4 = intense yellow

Statistical analysis

An analysis of variance was performed using the SAS System for Windows, 2002 (SAS Institute Inc., Cary, NC, USA). Means were compared using the least significant difference (LSD) test at a 95% probability level. Correlation between parameters was performed where applicable.

6.3 Results and discussion

In potatoes, specific gravity plays an important role in determining crop maturity, harvest quality and possibly longer periods of storability. In practice, this attribute is the indicator of maturation that the industry uses to judge fry quality, bagging characteristics and storability (Shetty, 2005). From the cultivars compared in the experiment, Shepody was significantly inferior to the others in specific gravity and it is regarded as low (Fig. 6.1).

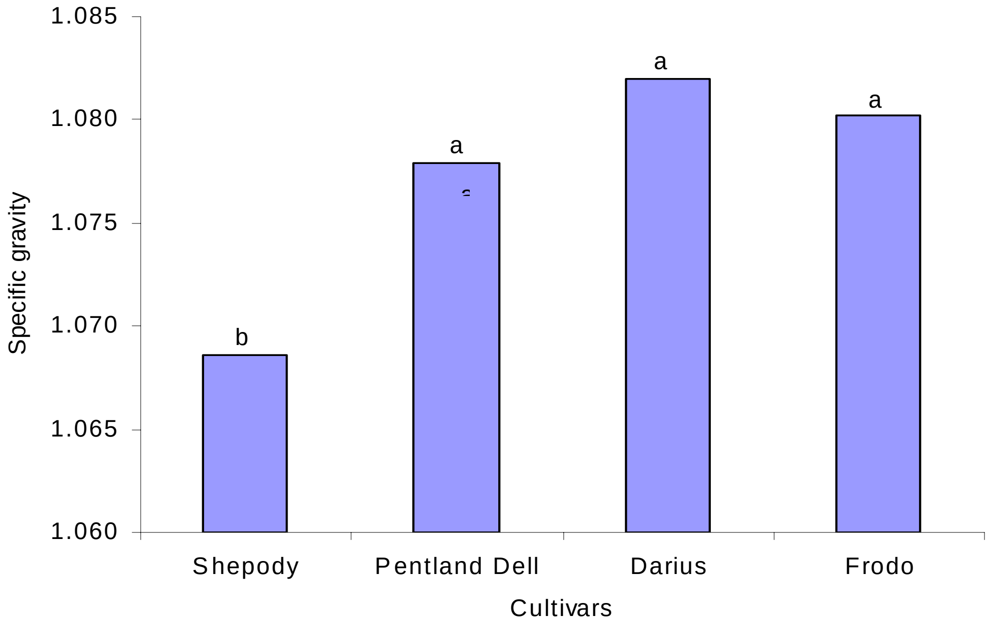

Figure 6.1 Tuber specific gravity of the four potato cultivars under comparison

The specific gravity of early-maturing cultivars is reported to be lower than those of late-maturing cultivars (Belanger *et al.*, 2002). Shepody is an early-maturing cultivar compared to Frodo, Pentland Dell and Darius, and this might partially explain its lower specific gravity in this study. The low specific gravity of this cultivar indicates that its dry matter percentage is also low. This cultivar is not encouraged to be used for chips and fries, as it becomes soggy (wet and soft) due to its low texture. On the other hand, Shepody is suitable for pan frying, salads, boiling and canning. From the specific gravity result, Pentland Dell is regarded as medium with a dry matter of about 20%. It is expected to bear a waxy texture after frying, but it is more ideal for boiling or mashing and would result into fair to medium chipping and canning qualities.

Frodo and Darius are late maturing cultivars with a high specific gravity that correlate to a high dry matter content of not less than 22%. These cultivars should result in a good mealy and dry texture chip when processed and are suitable for baking, chips and storage for several months, without producing reducing sugars when processed.

Specific gravity is not only a cultivar characteristic; the movement of water into and out of the tubers during the growing period also governs it. When the rate of transpiration exceeds water uptake, vines draw water from the tubers, causing them to decrease in mass and shrink, thereby increasing specific gravity. However, when the rate of water absorption by the roots exceeds water loss by transpiration, excess water can be stored in the tuber, leading to tuber expansion and increase in mass and therefore a decrease in specific gravity. Specific gravity is directly proportional to dry matter yield (Belanger *et al.*, 2002).

Reducing sugar content of tubers is the major factor influencing fry colour. According to Cottrell *et al.* (1995), fry colour depends mainly on the concentration of the reducing sugars (glucose and fructose) in the tubers, prior to processing. A higher concentration of reducing sugars in fresh tubers causes chips to become unacceptably dark when fried. Results of this experiment revealed that, although Pentland Dell and Shepody exhibited high reducing sugar levels that would result into high fry colour, they were still within the acceptable range of USDA standards (Fig. 6.2). Hence, as these cultivars are stored for longer periods, they will produce more reducing sugars when processed, and they should preferably be used at harvest or shortly afterwards. On the other hand, the new cultivars, Frodo and Darius, contain less than 0.1% (Fig. 6.2) reducing sugars that should result in bright fry colour, which indicates that the two cultivars well meet the required quality standards for processing french fries and crisps.

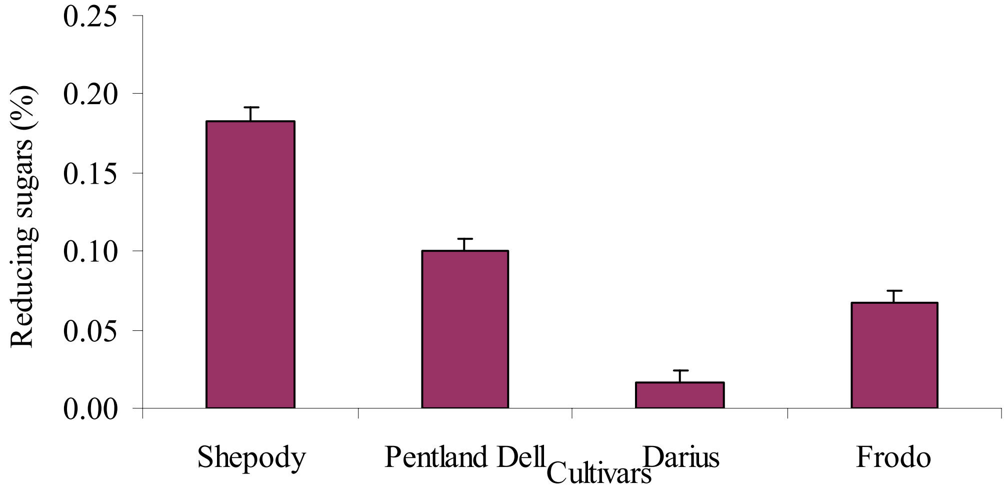

Figure 6.2 Reducing sugars (%) of USDA standard of the four potato cultivars under comparison

Pentland Dell and Shepody had acceptable reducing sugars that would result in high fry colour in the areas where they were developed. Since reducing sugars are influenced by many factors other than cultivar characteristics, such as environment, cultural practice, soil and plant nutrient management (Stark *et al.*, 2003), one of these factors could have influenced these cultivars to accumulate high reducing sugars in South Africa. These authors indicate that, when reducing sugar levels are too high during harvest, it is still possible to reduce to acceptable levels through manipulation of early storage temperatures.

An analysis of the TFI revealed that Frodo possesses significantly higher TFI for large and small tuber sizes, while Darius had consistently lower TFI values for all the three tuber sizes (Table 6.3). Pentland Dell and Shepody had similar TFI values for all the tuber sizes. This result implies that Frodo has longer tubers that are more suitable for fries, followed by both Pentland Dell and Shepody. Frodo is a newly developed South African cultivar, with superior tuber characteristics for fries. On the other hand, Darius was observed to have significantly lower TFI values for all the three tuber sizes, making them less suitable for fries.

Table 6.3 Average tuber form index (TFI) for large, medium and small-sized tubers of the four cultivars compared

Cultivars	TFI (large)	TFI (medium)	TFI (small)
Frodo	1.74a	1.55a	1.44a
Pentland Dell	1.65b	1.53a	1.33b
Shepody	1.64b	1.58a	1.34b
Darius	1.47c	1.41b	1.20c
LSD (0.05)	0.085	0.085	0.075
CV(%)	2.8	2.1	2.9

Means in the same column with the same letter are not significantly different.

The tuber size distribution into large, medium and small tubers indicates that Pentland Dell possessed significantly less large sized tubers (Table 6.4). For medium tuber sizes, however, the difference between cultivars was not significant. On the other hand, the small tuber size distribution for Frodo is significantly higher than that of Shepody and Darius. The total fresh tuber yield results also indicated that Shepody produced the lowest ($p<0.05$) total tuber yield compared to the other three cultivars (Table 6.4).

Table 6.4 Tuber size distributions for large, medium and small tubes, and total tuber yield of the four cultivars compared

Cultivars	Large (ton ha^{-1})	Medium (ton ha^{-1})	Small (ton ha^{-1})	*Total tuber Yield (ton ha^{-1})
Frodo	11.98a	20.45a	21.24a	52.23a
Pentland Dell	3.94b	24.79a	13.30ab	43.81a
Shepody	8.38a	18.23a	3.81b	25.07b
Darius	9.58a	25.39a	6.70b	40.84a
LSD (0.05)	4.20	10.14	9.02	11.40
CV%	26.7	23.5	45.1	10.34

Means in the same column with the same letter are not significantly different

* After Geremew, E.B., Steyn, J.M. and Annandale, J.G., 2007. *NZ. J. Crop Hort. Sci*, 35, 385-393.

Table 6.5 summarises the external and internal tuber characteristics as part of the quality indicators. From the results, all four cultivars had the same performance with regard to secondary growth, resistance to mechanical damage and growth cracks. Similarly, all cultivars were found to be free of tuber malformation except Shepody, which had less than 10% malformed tubers (Table 6.5). Cultivars Frodo and Darius were characterised by medium depth of stolon indent, while the remaining cultivars had superficial stolon indents. Frodo and Shepody had medium eye depths and the remaining two cultivars had superficial eye depths. In addition, Shepody and Darius possessed a white skin colour, whereas Pentland Dell and Frodo were yellow (Table 6.5).

Table 6.5 External and internal quality characteristics of the four potato cultivars under comparison

Cultivar Parameters (*)	Frodo	Pentland Dell	Darius	Shepody
External characteristics				
Secondary growth (1-5)	1	1	1	1
Malformation (1-5)	1	1	1	2
Mechanical damage (1-5)	2	2	2	2
Growth cracks (1-5)	1	1	1	1
Stolon indent (1-3)	2	1	2	1
Eye depth (1-3)	2	1	1	2
Skin colour (1-5)	3	3	1	1
Internal characteristics				
Dry rot (1-5)	2	2	2	1
Common scab area (1-5)	1	1	1	1
Eelworm (Root knot) (1-5)	1	1	1	1
Flesh colour (1-4)	1	1	1	1

1 = Superior, 5 = Inferior

(*) For details, refer to Tables 6.1 and 6.2

Internal characteristics of tubers for all the cultivars were also evaluated as standard criterion of quality assessment (Table 6.5, Fig. 6.3). The assessment revealed that cultivars Frodo, Pentland Dell and Darius contained less than 10% tubers affected by dry rot, while Shepody was free (Table 6.5). Furthermore, the result indicated that none of the cultivars showed any symptoms of common scab and eelworm and all of them had a preferential white flesh colour.

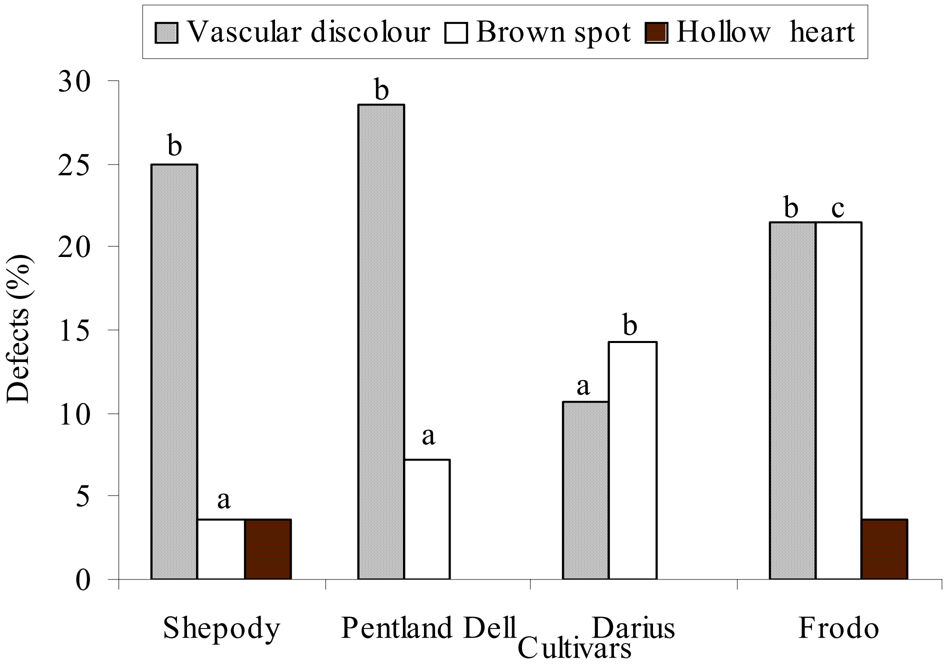

Figure 6.3 Vascular discolouration (%), brown spot (%), and hollow heart (%) recorded for the four potato cultivars under comparison

With regard to vascular discolouration, Pentland Dell had the highest incidence, close to 30%, followed by Shepody with 25% and Frodo with 20%. Darius had a relatively low percentage of vascular discolourations, about 10% (Fig. 6.3). On the other hand, Frodo showed the highest percentage of brown spot, about 20%, followed by Darius and Pentland Dell, while Shepody had the lowest percentage, less than 5% (Fig. 6.3). Furthermore, Pentland Dell and Darius were not characterised with hollow heart, while Frodo and Shepody were found to have a small percentage of hollow heart (<5%) (Fig. 6.3).

Generally, the cultivars investigated in this experiment were within acceptable low levels of tuber defects, with Frodo and Darius appearing to be good performers in most internal and external characteristics. Vascular discolouration, brown spot and hollow heart detects are results of improper management of the crop during the growing period. Proper management, such as water, and plant nutrient supply, and selection of the ideal climate for different cultivars, reduces the onset of tuber deformities and results in acceptable processing qualities.

6.4 Conclusions

Potato cultivars vary widely in internal and external tuber characteristics. Of the four cultivars tested for internal and external tuber characteristics and desirable processing quality, most adhered to acceptable quality standards. However, Pentland Dell and Shepody were found to have high proportions of vascular discolouration, between 25 and 30%, followed by Frodo with about 20%. Darius showed a low level of vascular discolouration, about 10%. Furthermore, Frodo contained a relatively high percentage of brown spots, about 20%, followed by Darius.

The current management level, mainly the water management, needs to be improved substantially in order to reduce the overall deformities. Specific gravity and dry matter percentage for Shepody is far below the USDA standard for chipping quality, while Pentland Dell is in an average position. Frodo and Darius had high specific gravity and low reducing sugars, which are the ideal characteristics for longer storage and quality frozen fries. Frodo possesses significantly higher TFI in all the size classes, while Darius possesses the least. Shepody seems to have relatively higher tuber malformation and deeper eye depths, but it is the least vulnerable cultivar to dry rot. In general, internal and external tuber characteristic results have followed the trend of the tuber fresh yield, with Shepody found to be significantly inferior to the remaining three cultivars. Hence, the experiment revealed that Frodo and Darius were within the acceptable range in terms of desirable tuber characteristics for processing as fries. On the other hand, Shepody and Pentland Dell had high reducing sugars, that could result in darker fry colours, though values are barely within the limits of the USDA standard. These results indicate that Frodo and Darius are more suitable for good mealy and dry texture fries due to high specific gravity and low reducing sugars, with characteristics that allow for long storability and frozen fries. On the other hand, Shepody, with low specific gravity, and Pentland Dell, with medium specific gravity, and both marginally within the standard ranges of reducing sugars, are rather to be used for pan frying, salads, boiling and canning and less for chipping and frying. Long storage of these cultivars will result in more reducing sugars being produced and an undesirable dark fry colour.

CHAPTER 7

GROWTH AND YIELD RESPONSE OF ONIONS (*ALLIUM CEPA* L.) TO WATER STRESS AT DIFFERENT GROWTH STAGES

7.1 Introduction

Onions are a shallow rooted crop that is sensitive to water stress conditions. The root depth of most onion cultivars extend down to 0.7 m soil depth. Most water and nutrient uptake occurs from the top 0.3 m of soil (Drinkwater & Janes, 1955; Voss & Mayberry, 1997). Onions, therefore, require frequent light irrigations throughout the season.

To achieve large bulb size and high bulb mass, water deficits should be avoided, especially during the yield formation period (bulb enlargement) (Kadayifci *et al.*, 2005). Nevertheless, crop cultivars vary widely in water use, mainly during times of water shortage. Some cultivars close their stomata to reduce transpiration during soil water deficit, which in most cases is associated with yield reduction. Stomatal closure limits the mass of CO_2 that enters stomata, which further limits photosynthesis and, therefore, also limits dry matter production (Al-Jamal *et al.*, 2000). Dry matter production of a crop depends on water uptake and its water use efficiency (Black & Ong, 2000).

Previous researchers (Shock *et al.*, 2004) have demonstrated the sensitivity of onions to small water deficits and the need to maintain high soil water potential for optimum yield and economic return. If water is withheld, young plants continue to grow until all available soil water within reach of the shallow root system is fully depleted. When this happens, the root hairs begin to die, the plants respond by wilting and, if drought conditions persist, the plants cease to grow. Absorption of soil water and nutrients for plant growth takes place through the outermost cells of the root hairs. Therefore, water stressed plants have to re-establish functioning root hairs before normal growth can resume. Onions show little capacity for reducing leaf water potential by osmotic adjustment to compensate for reduced water availability. Stressed onions usually result in stunted growth and bulb doubling or splitting and are usually higher in pungency (Voss & Mayberry, 1997).

There are four phenological growth stages in onions: from sowing to transplanting, the vegetative stage, yield formation or bulb enlargement, and the ripening or bulb maturity period that makes a total growth period of 130-175 days, depending on cultivar and climatic conditions (FAO, 2002). Knowledge of the crop growth phenology helps to save irrigation water under limited water supply conditions. Some researchers claim that small water savings can be made during the vegetative period, while others report towards the end of the ripening period, depending on the cultivar and soil water holding capacity (Kalb & Shanmugasundaram, 2001). Others report that bulb formation and enlargement periods are most sensitive to water stress (Singh & Alderfer, 1966). Onion plants stressed prior to bulb formation, result in reduced bulb sizes that are not acceptable for market grades. Those plants stressed after bulb formation are prone to re-growth problems, such as thick necks and scallions, which reduce marketable grade and increase storage problems (Casey & Garrison, 2003). In addition, internal bulb defects, such as multiple centres and translucent scales, can develop even after short duration stresses (Shock *et al.*, 1998; Shock *et al.*, 2004). This indicates that duration of water stress determines the degree of yield and grade loss. Singh and Alderfer (1966) observed that soil water stress at any growth stage leads to reduction in marketable yield at varying levels. They further observed that, with regard to yield reduction, onions are more sensitive to water stress during bulb enlargement than during the vegetative stage. On the other hand, Pelter *et al.*, (2004) reported that a three week stress at the early growth stage reduce onion yield more than when the same duration of stress is imposed at the end of the growing season. Further studies by Van Eeden and Myburgh (1971) revealed that stress imposed between 84-103 days after transplanting reduced total onion yield by 15%, compared to yield with no water stress. Van Eeden and Myburgh (1971) recommend that, when high yield of good quality is sought, it is advisable to irrigate onions before about half of the water in the root zone has been used. However, irrigation should be discontinued as the crop approaches maturity to allow tops to desiccate and to prevent a second flush of root growth. For a seed crop, however, the flowering period is very sensitive to water deficit (Kalb & Shanmugasundaram, 2001), while, during the vegetative growth period, the crop appears to be relatively less sensitive. In general, for high yield of good quality, the crop needs a controlled and frequent supply of water throughout the growing period, while over-irrigation leads to reduced growth (Ehler, 2005). The objective of this experiment, therefore, was to determine the critical growth stage of onions (cv. Texas Grano) to water stress applied at different growth stages and generate crop growth parameters for SWB modelling (the latter is dealt with in Chapter 8).

7.2 Materials and methods

The experiment was established at the Hatfield experimental station of the University of Pretoria in South Africa. The site is situated at 25^{o} 45' S and 28^{o} 16' E, at an altitude of 1 327 m. The area receives an average rainfall of 670 mm per annum, with the peak rainy season between October and March (Annandale et al., 1999). The soil was thoroughly prepared to ensure a suitable seedbed. Onion seedlings, cv. Texas Grano, of about 35 days old were planted on 15 May 2004. Plant spacing was 0.3 m between rows and 0.1 m between plants within rows. The experiment was arranged in a strip plot design with four replications. Other cultural practices were conducted according to the station's standard practices.

During transplanting, the crop received 47 kg ha^{-1} of N, 70 kg ha^{-1} of P and 47 kg ha^{-1} of K as a basal dressing. Top dressing of 43 kg ha^{-1} N, 20 kg ha^{-1} of P and 113 kg ha^{-1} of K was given 60 days after transplant (DATP), giving a total of 90 kg ha^{-1} nitrogen and phosphorus, and 160 kg ha^{-1} potassium.

Irrigation treatments applied were:

1. Replenishing the soil water deficit to field capacity after weekly neutron water meter measurements (NNN);
2. Stress during the vegetative growth stage, between 35-70 DATP (SNN), and replenishing soil water deficit to field capacity on a weekly basis for the rest of the growing season.
3. Stress during the bulb enlargement stage, between 70-110 DATP (NSN), and replenish soil water deficit to field capacity on a weekly basis for the rest of the growing season.
4. Stress during bulb maturity stage, between 110-145 DATP (NNS), and replenish soil water deficit to field capacity on a weekly basis for the rest of the growing season.

Where DATP denotes the days after transplant, N stands for non-stressed and S for stressed at a certain growth stage.

Soil water content (WC) was measured using a neutron water meter Model 503 DR CPN Hydroprobe (Campbell Pacific Nuclear, California, USA). The neutron water meter was calibrated for the site and weekly readings were taken before irrigation. Measurements were taken in the middle of each plot at 0.2 m depth increments, down to 0.8 m. Rainfall during the experimental period was recorded by a rain gauge installed at the weather station near the experimental field. Drip irrigation was used to irrigate each plot every week to refill the soil water content to field capacity, except for the stress treatment. The spacing between dripper lines was 0.5 m while the spacing between drippers in a line was 0.3 m. The drippers were pressure-compensated with a delivery rate of 2.2 l hr^{-1} at a pressure range of 100-150 kPa. Water use (ET) in mm and WUE (kg ha^{-1} mm^{-1}) were calculated using bulb yield at final harvest and the total seasonal irrigation water applied (mm) during the growing season. ET was calculated using eq 7.1, while eq 7.2 was used to calculate WUE.

$$ET\ (mm) = I + P - Dr - \Delta S - R \qquad (7.1)$$

Where

I = irrigation in mm, P = precipitation in mm, Dr = drainage in mm (assumed to be zero), ΔS = change in soil water storage in mm, and R = runoff in mm (assumed to be negligible)

$$WUE\ (kg\ ha^{-1}\ mm^{-1}) = BY/ET \qquad (7.2)$$

Where, BY = bulb yield in kg ha^{-1}

Fractional interception (FI) of PAR was measured every 14 days with a Decagon Sunfleck Ceptometer (Decagon, Pullman, Washington, USA), making one reference reading above and 10 readings beneath each canopy. Growth analyses were carried out every 14 days by harvesting above-ground plant material and bulbs from 1 m^2 of ground surface from each plot. Harvestable fresh mass was measured directly after sampling and dry mass of plant organs after drying it in an oven at 60°C for four to five days. Leaf area was measured destructively with an LI 3100 belt-driven leaf area meter (LiCor, Lincoln, Nebraska, USA) and LAI calculated from the data. Leaf area duration (LAD) is obtainable from LAI with respect to time or DATP, and expressed as:

$$LAD = ((LAI_2 + LAI_1)/2) * (t_2 - t_1) \quad (7.3)$$

LAD is expressed as $m^2\ m^{-2}$ days

Root depth was not measured during the growing season, but estimated from the depth of water extraction from the soil profile.

7.3 Results and discussion

Onions' critical growth stage to water stress was evaluated during the cool season of 2004, where stresses were applied at intervals of 35 days after which normal water management continued. The NNN treatment was not water stressed and used as a control for comparison. Results of the SWD indicated that, for the non-stressed treatment, the level of SWD between irrigation intervals of seven days remained less than 20 mm during the early growth period but increased to more than 40 mm during the later growth stages (Fig. 7.1). The low SWD at the beginning of the growth period was due to the cool time of the season with low daily ETo and low LAI. The first water stress was applied to SNN treatment for 35 days in the vegetative growth stage (Fig. 7.2). The cumulative SWD during this period was about 86 mm, after which normal irrigation was resumed until the final harvest. The next growth stage at which water stress was applied was the bulb enlargement stage, where irrigation was withheld between 70 and 110 DATP (Fig 7.3). During this stress period, cumulative SWD peaked at to more than 80 mm.

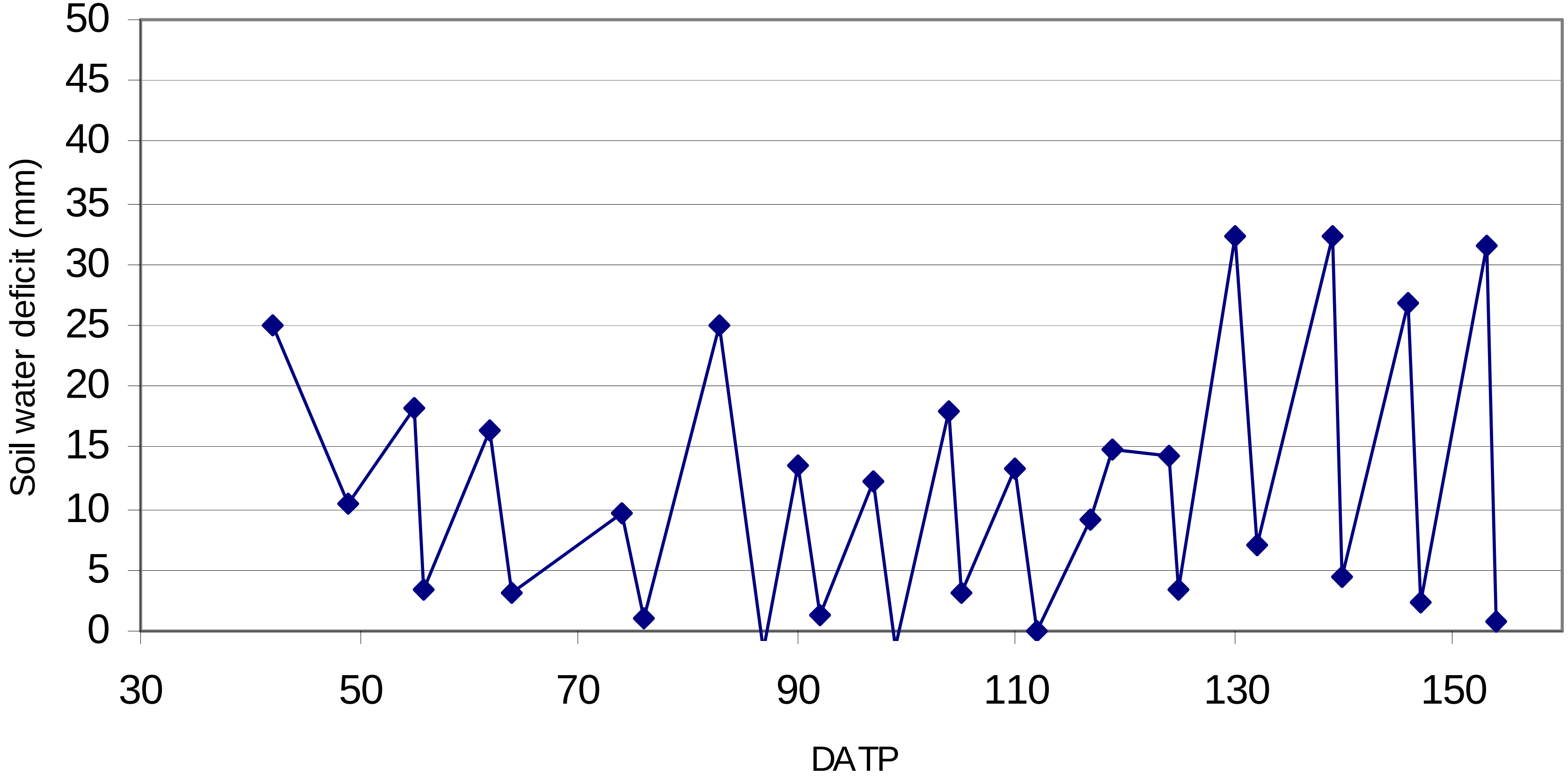

Figure 7.1 Soil water deficit (SWD) (mm) of onions, non-stressed treatment (NNN)

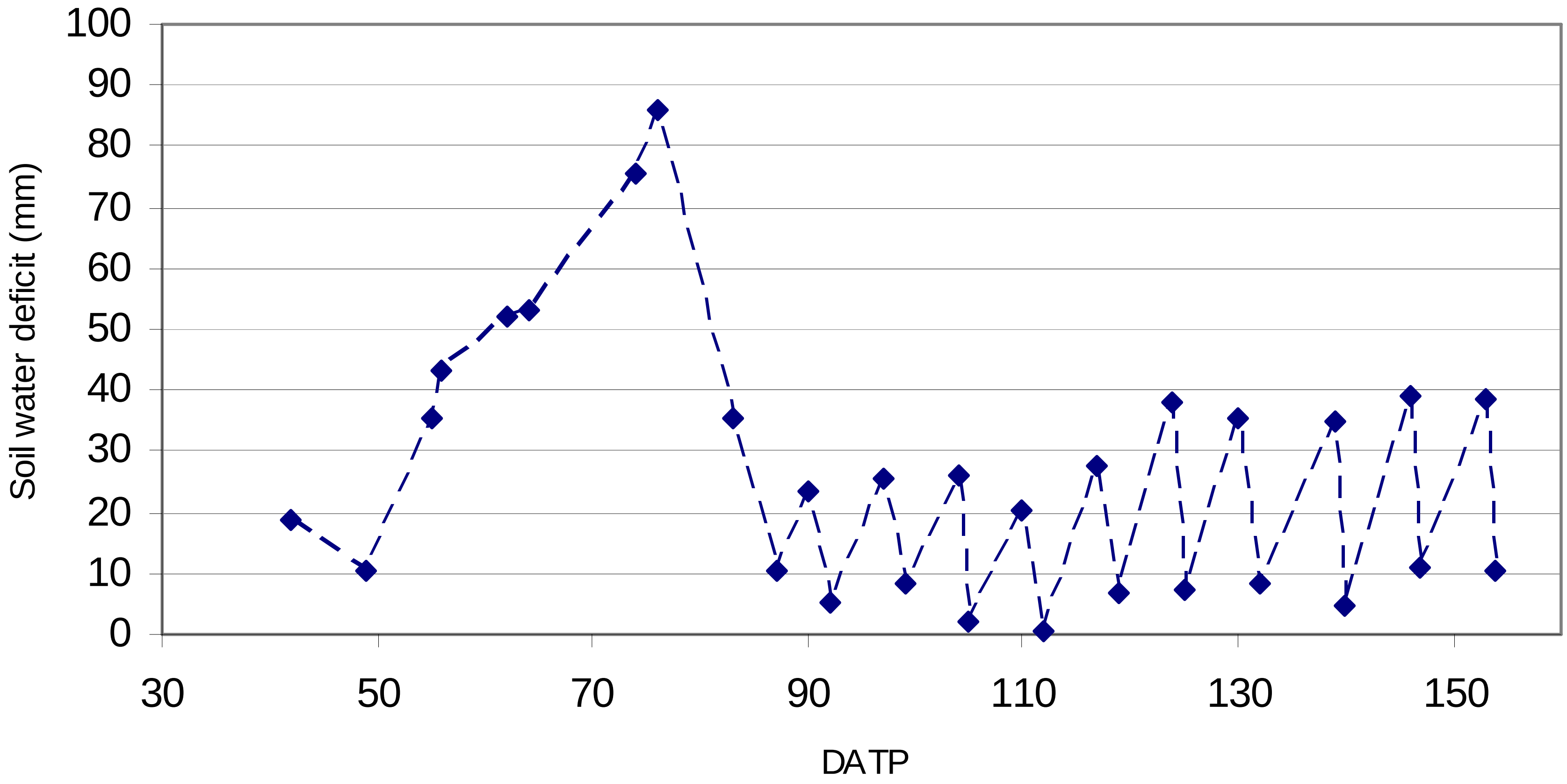

Figure 7.2 Soil water deficit (SWD) (mm) of onions, water stressed at vegetative growth stage (35-70 DATP) (SNN)

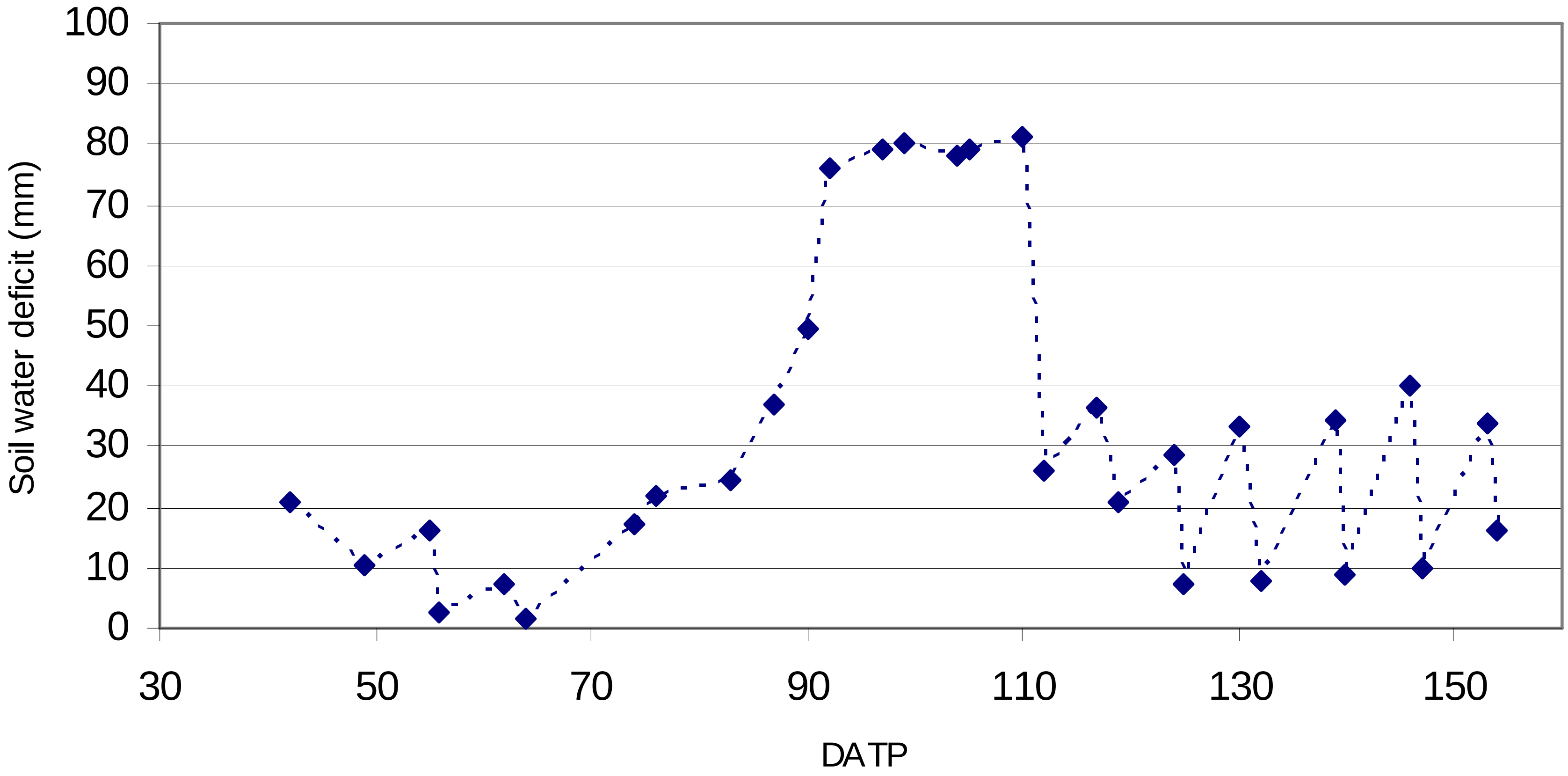

Figure 7.3 Soil water deficit (SWD) (mm) of onions, water stressed at bulb elongation (70-110 DATP) (NSN)

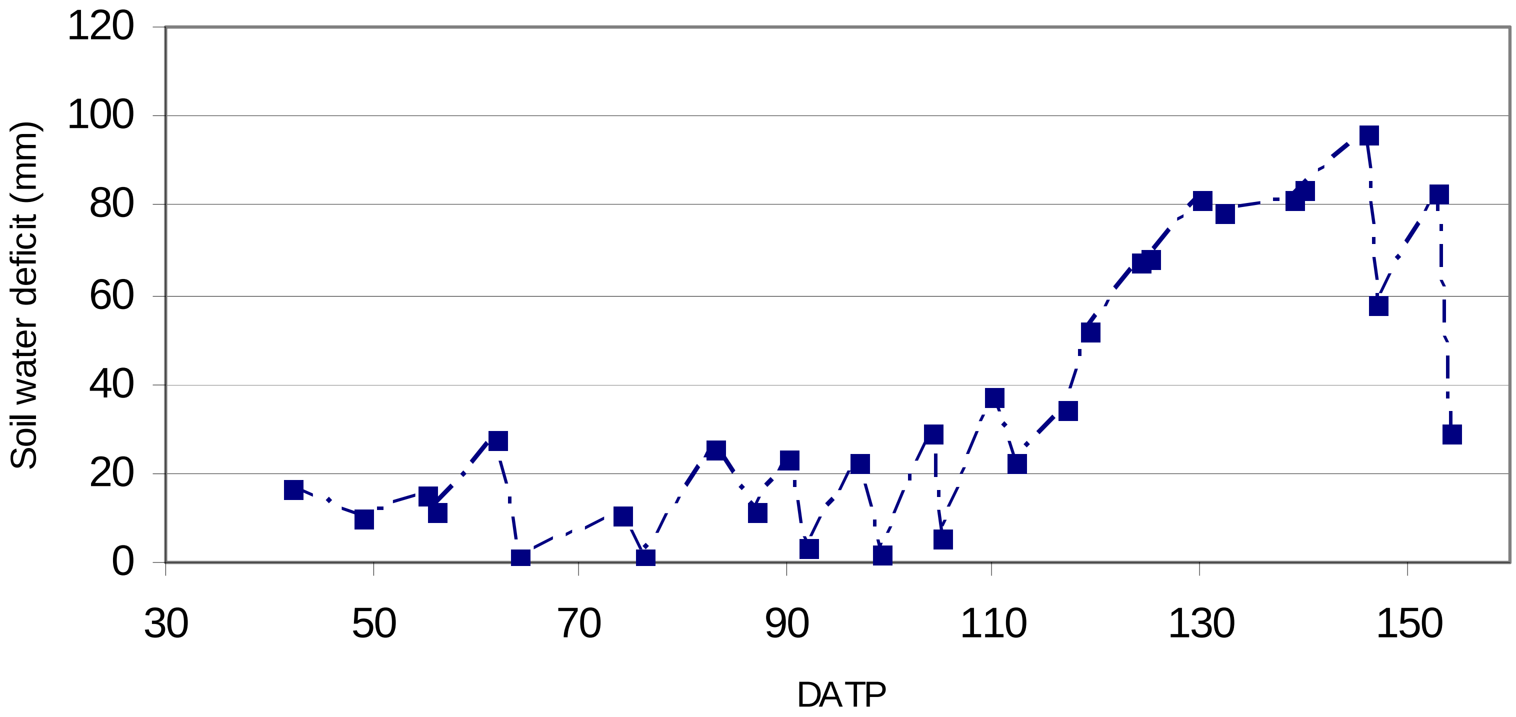

Figure 7.4 Soil water deficit (SWD) (mm) of onions water stressed at bulb maturity (110-145 DATP) (NNS)

Figure 7.3 shows a stabilised cumulative SWD at the peak of the graph, which is due to several small rainfall events that covered more or less the daily evaporative demand of the crop. The last growth stage at which water stress was applied, was the bulb maturity stage, between 110 and 145 DATP. The cumulative SWD during this stress period peaked at nearly 100 mm (Fig. 7.4). From the graph, it can be seen that, at the peak of the cumulative deficit, there are a number of occasions when the deficit, dropped suddenly, which, once again, indicates the prevalence of small rainfall events that relieved the deficit.

Figures 7.1-7.4 show the SWD during water stress applied at different growth phenological stages. The highest cumulative SWD was observed when water stress was applied during the bulb maturity stage of the crop. During this growth stage, even though several small rain showers occurred, the level of deficit was big enough to hamper the growth of the onions significantly, which shows that this stage is most critically influenced by soil water stress, followed by stress at bulb elongation. These findings support the result of Pelter *et al.* (2004), who stated that onions are sensitive to even a slight water stress, depending on growth stage, cultivars and climatic conditions. The water stress applied during vegetative growth stage did not affect the crop significantly (from the yield data). This was due to the fact that water stress was applied during the early growth stage, so that the crop still had enough time for recovery. The other reason could be due to the cool period of the season resulting in relatively low evaporative demand.

In time, onions that are water stressed at different growth stages, show a different growth trend in response to the stress. To evaluate the growth variation with regard to the time aspect, three harvests, were considered and subjected to statistical analysis. The three harvests considered were at 124, 138 and 152 DATP. The response of LDM, bulb dry matter (BDM), TDM, LAI and FI of PAR, are provided in Table 7.1 for 124 DATP; in Table 7.2 for 138 DATP; and in Table 7.3 for 152 DATP.

The highest LDM was obtained from the control treatment (NNN) where no water-stress was induced. The LDM obtained from this treatment was not significantly different from the SNN treatment, where water-stress was induced during the vegetative stage between 35 and 70 days after transplanting. Water-stress during bulb enlargement (70-110 DATP) and bulb maturity (110-145 DATP) significantly ($p<0.05$) affected the LDM accumulation (Table 7.1). At the harvest of 124 DATP, BDM and TDM were significantly affected ($p<0.05$) by water stress during bulb enlargement and maturity (Table 7.1). Table 7.1 further reveals that water-stress in onions at any growth stage result in LAI and FI reduction, although the level of decline varies among treatments.

Table 7.1 Leaf dry matter (LDM), bulb dry matter (BDM), total dry matter (TDM), leaf area index (LAI) and fractional interception (FI) of onions at 124 days after transplant (DATP) for four water regimes

Treatments	*LDM (kg m^{-2})*	*BDM (kg m^{-2})*	*TDM (kg m^{-2})*	*LAI (m^2 m^{-2})*	*FI*
NNN	0.28a	0.23a	0.51a	1.41a	0.43a
SNN	0.26a	0.21ab	0.47a	1.08b	0.34b
NSN	0.10b	0.07c	0.17c	0.48d	0.29b
NNS	0.15b	0.18b	0.33b	0.83c	0.34b
SEM	0.02	0.01	0.01	0.01	0.01
CV.%	16.2	9.7	14.1	11.6	12.8

The effect of water stress on LDM accumulation did not change during the second harvest (138 DATP), where NSN and NNS treatments were still significantly affected as compared to the control treatment (Table 7.2). During this harvest, the LDM and LAI performed similarly, where NNN and SNN treatments had similar yields, whilst the NSN and NNS treatments resulted in significantly lower LDM and LAI values. On the other hand, the BDM and TDM were affected in a similar way (Table 7.2), where water stress applied at any growth stage induced a significant effect on both parameters. Table 7.2 further reveals that water stress during this stage (138 DATP) had a major effect on the BDM, which was the major component of TDM. The FI was not negatively influenced by water stress during this harvest, which could be due to a lack in uniformity during sampling.

Table 7.2 Leaf dry matter (LDM), bulb dry matter (BDM), total dry matter (TDM), leaf area index (LAI) and fractional interception (FI) of onion at 138 days after transplant (DATP) for four water regimes

Treatments	*LDM* *(kg m^{-2})*	*BDM* *(kg m^{-2})*	*TDM* *(kg m^{-2})*	*LAI* *(m^2 m^{-2})*	*FI* -
NNN	0.38a	0.44a	0.82a	1.93a	0.53a
SNN	0.37a	0.35b	0.71b	1.84a	0.51a
NSN	0.18b	0.12d	0.30d	1.06b	0.43a
NNS	0.19b	0.21c	0.40c	0.79b	0.49a
SEM	0.01	0.01	0.01	0.01	0.01
CV.%	7.1	5.4	8.4	14.2	14.8

Water stress applied at different growth stages of onions did not influence the tested parameters differently during the third harvest at 152 DATP (Table 7.3). The treatment stressed during the vegetative growth stage, 35-70 DATP, was not significantly different from the non-stressed treatment (Table 7.3) for LDM, BDM, TDM, LAI and FI, while the remaining treatments, NSN and NNS, were significantly inferior to others in all the measured parameters.

Table 7.3 Leaf dry matter (LDM), bulb dry matter (BDM), total dry matter (TDM), leaf area index (LAI) and fractional interception (FI) of onions at 152 days after transplant (DATP) for four water regimes

Treatments	*LDM* *(kg m^{-2})*	*BDM* *(kg m^{-2})*	*TDM* *(kg m^{-2})*	*LAI* *(m^2 m^{-2})*	*FI* -
NNN	0.39a	0.61a	1.00a	1.76a	0.46a
SNN	0.37a	0.60a	0.97a	1.68a	0.41ab
NSN	0.21b	0.28b	0.49b	1.02b	0.36bc
NNS	0.15c	0.27b	0.42b	1.01b	0.31c
SEM	0.01	0.01	0.01	0.01	0.01
CV.%	9.9	8.4	14.7	10.2	12.7

Many researchers disagree on the critical growth stages of onions to water stress. Al-Jamal *et al.* (2000) and Al-Kaisi & Broner (2005) report that water stress at any growth stage of onions result in dry matter and fresh yield reduction. The degree of reduction, however, varies depending on the cultivar and climate, while others (Pelter *et al.,* 2004) agree that onions are more sensitive to water stress during bulb elongation than during the vegetative stage. They also found that soil water stress at any growth stage decreased the yield of onions, but the greatest decrease was observed when irrigation was withheld between 5-7 leaf stages, which is about 70 DATP and beyond. Pelter *et al.* (2004) further report that soil water stress caused by withholding irrigation for longer periods at both 3 and 7-leaf growth stages, severely reduced onion bulb yield. Similarly, Al-Kaisi and Broner (2005) concluded that the most critical growth period of onions to water stress is the bulb formation and development stage, which is the growth stage beyond 70 DATP. From this experiment, it can be concluded that from the three growth stages when water stress was applied, the bulb development (70-110 DATP) and bulb maturity (110-145 DATP) stages were found to be most critical to growth and yield reduction. When the crop is water stressed during the vegetative growth stage (35-70 DATP) growth and yield reduction was not significant. This could perhaps be due to the cool period of the season, (low ET) and the crop having a long remaining period for compensatory growth, with the minimum yield loss.

The influence of water stress, applied at different growth stages of onions, on leaf growth and development was observed from the leaf area measurements, from which LAI was calculated. The LAI increment over the growing period followed a similar trend to the dry matter yield. The canopy growth for all treatments was not different until about 82 DATP, whereafter treatment differences occurred (Fig. 7.5).

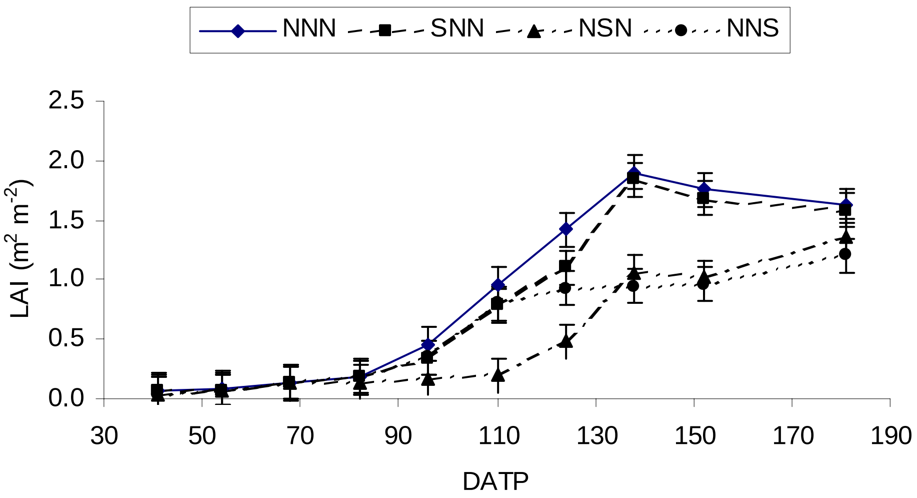

Figure 7.5 Onion leaf area index (LAI) for four water-stress treatments applied at different days after transplanting (DATP): Non-stressed (NNN), vegetative stage (SNN), stressed at bulb development (NSN) and stressed at bulb maturity (NNS)

Even though the control treatment (NNN) produced the highest LAI throughout the growth period, the SNN performed similarly and both reached the highest peak values at 138 DATP. On the other hand, LAI for the NSN treatment started to decline from about 82 up to 110 DATP, when irrigation was resumed. From this point (110 DATP), irrigation was ceased for NNS, where after the LAI started to decline until it converged to the same point as for the NSN treatment on 138 DATP. These two treatments performed poorly as compared to the other two treatments, until final harvest. This finding confirms that leaf growth and development are one of the crop parameters most severely affected by soil water stress during active crop growth. Liptay *et al.* (1998) report that even moderate water stress results in a reduction in plant leaf area and LAI. This result also agrees with the findings of Kuchenbuch *et al.*

(1986), who concluded that an increase in soil water stress resulted in a linear decrease in onion shoot growth and LAI. The trend of specific leaf area (SLA) during the growing season did not vary for all treatments. The SLA followed a decreasing trend, from more than 12 to around 4 m^2 kg^{-1} for all treatments, with increasing DATP (Fig. 7.6).

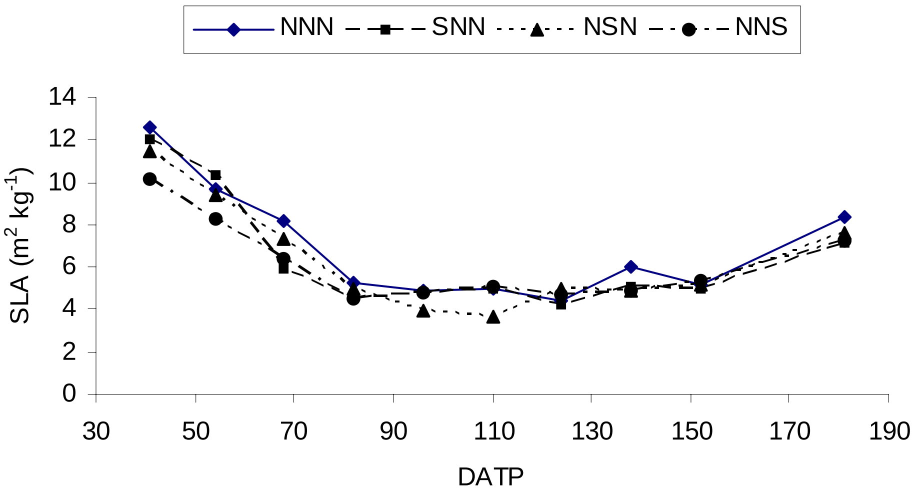

Figure 7.6 Onion specific leaf area (SLA) for four water stress treatments applied at different days after transplanting (DATP): Non-stressed (NNN), stressed at vegetative stage (SNN), stressed at bulb development (NSN) and stressed at bulb maturity (NNS)

The effect of water stress applied at different growth stages also manifested differently on the LAD that accounts for the elapsed duration of photosynthetic activities. The development of LAD for the non-stressed treatment was smooth until 150 DATP, when it reached its peak and decreased smoothly until final harvest (Fig. 7.7). The LAD showed a sharp increment at 82 and 96 DATP for the NNN treatment until its maximum development at 150 DATP. For the SNN treatment, however, even though there was a gradual increment seen at 82 and 96 DATP, a sharp increment was observed at 124 DATP, until its maximum growth at 150 DATP (Fig. 7.7). The NSN treatment had a slow growth between 96 and 124 DATP, where after showed a sharp increase until 150 DATP (Fig. 7.7), and again showed a decreasing growth trend until the final harvest. On the other hand, treatment NNS showed a sharp growth trend between 96 and 124 DATP and followed by a decreasing growth trend until final harvest. These two treatments were harvested while their LAD was actively increasing after relieved from the water stress.

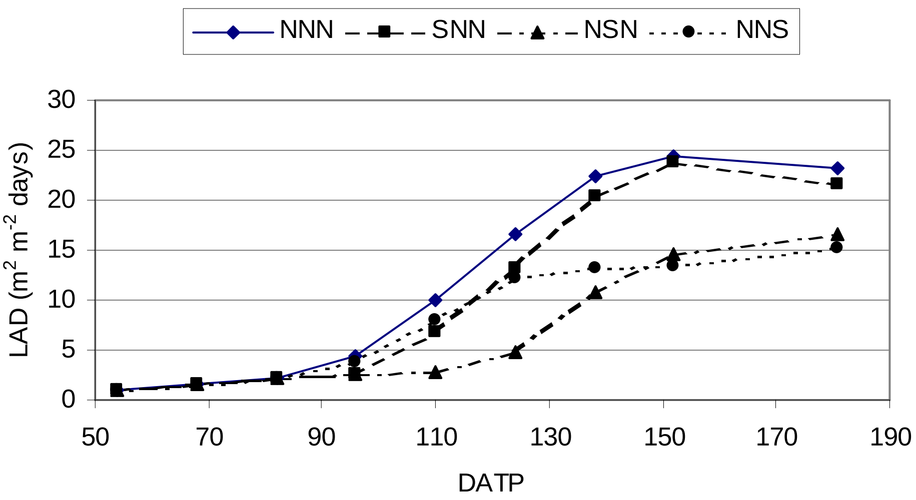

Figure 7.7 Onion leaf area duration (LAD) for four water stress treatments applied at different days after transplanting (DATP): Non-stressed (NNN), stressed at vegetative stage (SNN), stressed at bulb development (NSN) and stressed at bulb maturity (NNS)

Fig. 7.8 presents the relationships between LAD and TDM. Treatments NNN and SNN were found to have stronger relationships with the coefficients of determination (r^2) of 0.97 and 0.99, compared to NSN with r^2 of 0.95 and NNS with r^2 of 0.93 (Fig. 7.8). Figure 7.8 shows good relationships between LAD and TDM. Thus yield is directly correlated with size and duration of canopy to maintain good canopy cover and ensure high TDM and bulb yield.

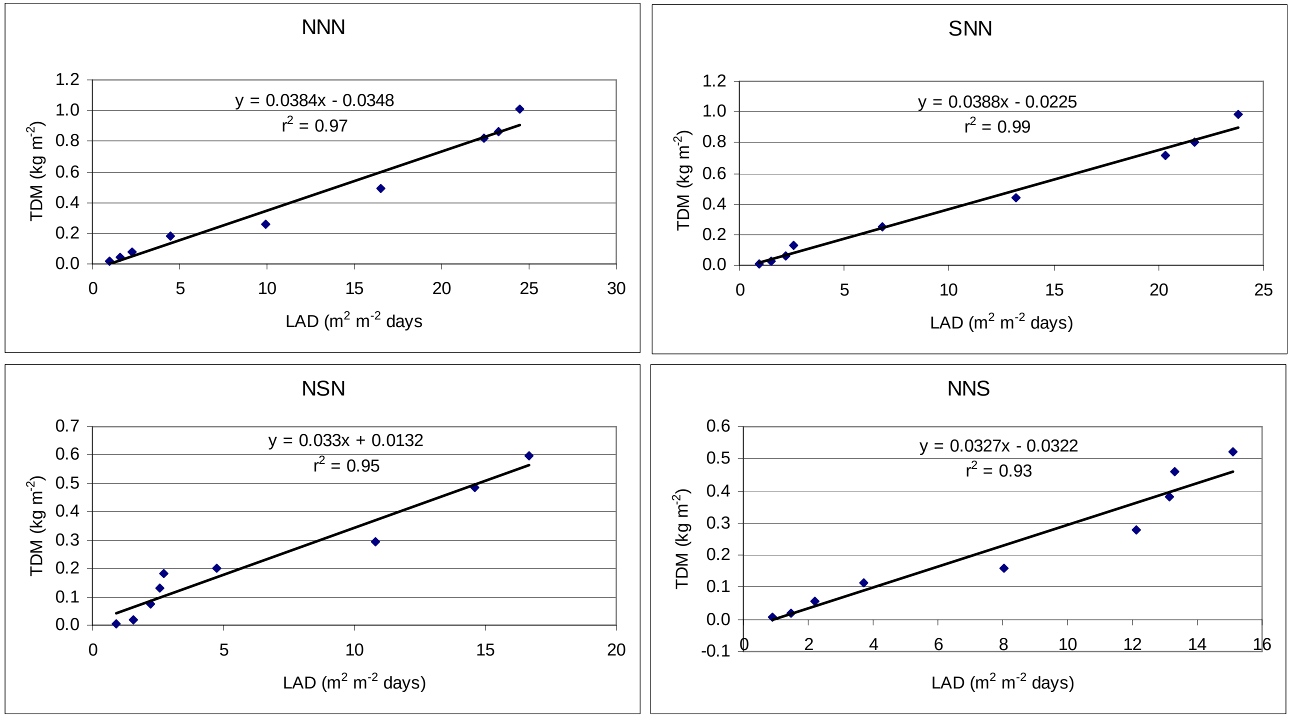

Fig. 7.8 Relationship between leaf area duration (LAD) and total dry matter (TDM) for treatments non-water stressed (NNN), water stressed during vegetative growth stage (SNN), water stressed during bulb development stage (NSN) and water stressed during bulb maturity stage (NNS) of onion.

The TDM increment during the growing season was also recorded to assess the effects of water stress induced at the different growth stages of onions. TDM did not differ until about 96 DATP, whereafter the NSN treatment started to decline (Fig. 7.9). On the other hand, TDM for NNS treatment started to decline from 124 DATP until it converged to a point with a reviving NSN on about 138 DATP. LAI of these treatments continued to increase slow by until the final harvest, as opposed to the NNN and SNN treatments that had significantly higher TDM values. This finding, once again, is in line with the results obtained by Martin (2004), who concluded that water stress imposed on onions during bulb maturity and ripening, significantly reduce TDM and bulb yield.

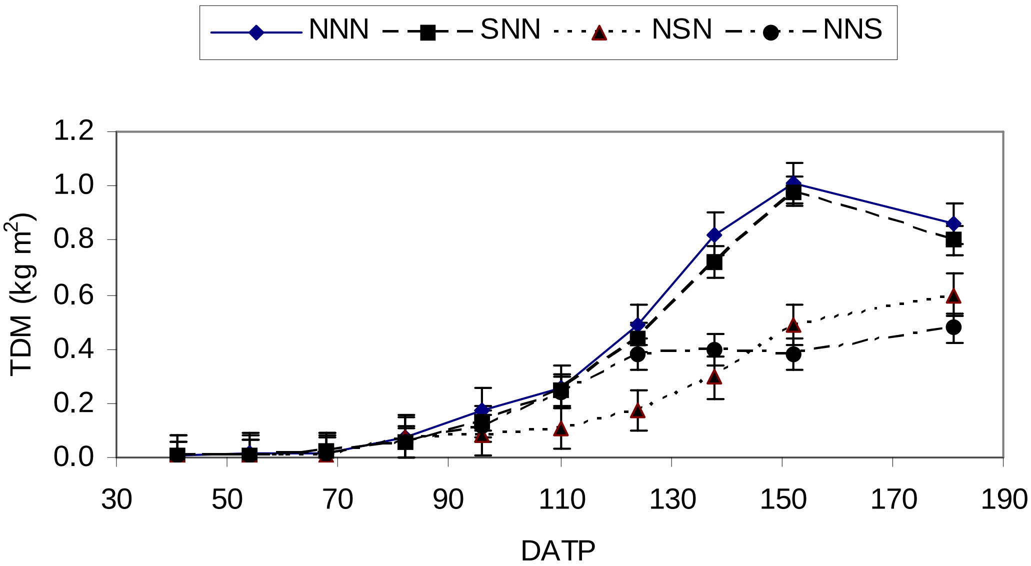

Figure 7.9 Onion total dry matter (TDM) yield for four water stress treatments applied at different days after transplanting (DATP): Non-stressed (NNN), stressed at vegetative stage (SNN), stressed at bulb development (NSN) and stressed at bulb maturity (NNS)

Fractional interception of the PAR followed the same increasing trend for all treatments until 82 DATP (Fig. 7.10). Even though not much variation was observed, FI for SNN was the lowest until 110 DATP, and reached its peak at 138 DATP. The FI response can be grouped into two, NNN and SNN treatments performed similarly with higher values, while NSN and NNS treatments produced similarly lower FI values. FI values reached peak values at 138 DATP and thereafter declined until harvest.

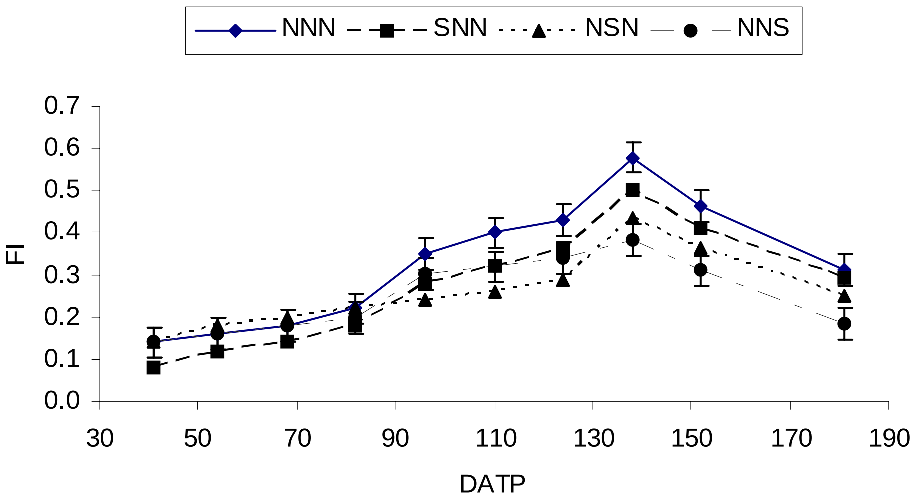

Figure 7.10 Fractional interception (FI) of photosynthetically active radiation (PAR) for four water stress treatments applied at different days after transplanting (DATP) of onions: Non-stressed (NNN), stressed at vegetative stage (SNN), stressed at bulb development (NSN) and stressed at bulb maturity (NNS)

The growth and development data of onions water stressed at different growth stages, revealed that the non-stressed (NNN) treatment produced the highest yield for all parameters evaluated, while the NNS treatment performed the poorest. For most parameters evaluated, NNN and SNN treatments performed similarly, but significantly better than the remaining treatments (NSN and NNS), with no significant difference between them. These results reveal that the most critical growth stages of onions to water stress are during bulb enlargement and bulb maturity (70-110 and 110-145 DATP), with the latter stage being the most critical. The experiment also indicated that water stress during the early growth stage (35-70 DATP) helped the crop to harden or develop good root growth that allowed compensatory growth with acceptable yield loss ($p>0.05$).

Table 7.4 reveals the water use and WUE data of onions as influenced by water stress applied at different growth stages. The highest irrigation amount, 537 mm, was applied by the non-stressed treatment, while the lowest amount, 440 mm, was used when water stress was applied during the vegetative growth stage (Table 7.4). Withholding irrigation water during the vegetative growth stage (35-70 DATP) saved 97 mm of water, which is about 18% with a yield reduction of about 6%. Similarly, the SNN treatment provided the highest WUE of 150 kg ha^{-1} mm^{-1}, followed by the NNN with 131 kg ha^{-1} mm^{-1} (Table 7.4). The remaining two treatments resulted in substantially lower WUE of 111 kg ha^{-1} mm^{-1} for NSN and 98 kg ha^{-1} mm^{-1} for NNS, which indicate that these treatments were severely affected by the water stress applied during their respective growth periods. The result, once again, confirms that stress at bulb enlargement and bulb maturity reduces the growth and yield of onions significantly.

Table 7.4 Onion water use and irrigation water use efficiency (WUE) for four water stress treatments applied at different days after transplanting (DATP): Non-stressed (NNN), stressed at vegetative stage (SNN), stressed at bulb development (NSN) and stressed at bulb maturity (NNS).

Treatment	FBY kg ha^{-1}	Total water applied (mm)	WUE kg ha^{-1} mm^{-1}
NNN	70200a	532	131
SNN	65870a	440	150
NSN	49470b	446	111
NNS	43260c	441	98
CV. (%)	24.67		

Means with the same letter are not significantly different.

FBY = Fresh bulb yield

The NNS treatment had the lowest yield, which, therefore, resulted in the lowest WUE. The SWD measurements during the stress period also substantiated the results obtained from the growth performance and both dry matter and fresh bulb yields. The treatment stressed during the early growth stage had ample time to recover lost vegetative growth after the stress and yield loss was consequently not severe ($p>0.05$). This result agrees with the finding of Kalb and Shanmugasundaram (2001) who concluded that, during the vegetative growth period, the crop appears to be relatively less sensitive to water deficits. On the other hand, the treatment stressed between 110 and 145 DATP (NNS) was in a stage where maximum dry matter was to be partitioned to the bulb and minimum to the shoot (Shock *et al*., 2004). This, coupled with the short period between stress relieve and harvesting, did not allow the crop to undergo compensatory growth.

7.4 Conclusions

Onions are sensitive to soil water stress, depending on the growth stage at which stress is applied and the level of drought tolerance of cultivars. The water stress experiment conducted on onions revealed that water stress induced at any growth stage affected the LDM, BDM, TDM, LAI, FI and fresh bulb yield, but the extent varied depending on the growth stage during which the stress was applied. Water stress applied during the vegetative growth stage (35-70 DATP) did not result in a significant reduction of plant growth and yield. On the other hand, water stress induced during the growth stages, between 70 and 110 DATP and between 110 and 145 DATP, significantly reduced the LDM, BDM and TDM yields. Water stress during these growth stages also significantly affected the bulb fresh yield, LAI and FI of PAR. However, the SLA was not affected by water stress applied at any growth stage and showed a decreasing trend for all treatments over time. With NNN and SNN treatments, the LAD consistently developed until it reached its highest peak and then gradually declined until harvest. On the other hand, with NSN and NNS treatments, the LAD was observed to intermittently increase and decrease up to the final harvest. The data on irrigation water management revealed that the highest water amount was used by the non-stressed treatment, while SNN treatment consumed the lowest water amount. On the other hand, the highest WUE was obtained from the SNN, with water saving of about 18%, which resulted in about 6% bulb yield reduction. The remaining two treatments, the NSN and NNS, resulted in very low irrigation water use efficiency. From this experiment, it could be concluded that the yield and yield components of onion (cv. Texas Grano) is most severely affected when water stress was induced during bulb maturity stage (110-145 DATP), followed by the bulb enlargement stage. On the other hand, when water stress is induced during the vegetative growth stage (35-70 DATP), the highest WUE could be obtained with an acceptable yield reduction.

CHAPTER 8

CALIBRATION AND VALIDATION OF THE SWB MODEL FOR POTATOES (*SOLANUM TUBEROSUM* L.) AND ONIONS (*ALLIUM CEPA* L.)

8.1 Introduction

Crop growth modelling is the dynamic simulation of crop growth by numerical integration of constituent processes with the aid of computers (Wajid & Hussain, 2005). It also involves the development of biological life cycles that can be described as a series of stages from germination to maturity (Matthews, 2004; Wajid & Hussain, 2005). Crop models have been used to quantify the yield gap between actual and climatic potential yields of different field crops (Montesinos *et al.*, 2001). It can also be used to evaluate possible causes for change in yield over time in a given region and yield forecasting prior to harvest. In addition, models are also used as a research tool to evaluate optimum management of cultural practices, fertiliser and water use (Mason *et al.,* 1980; Wajid & Hussain, 2005). The simulation approaches in crop modelling can be advantageous and, once the model is developed, it can be used for different conditions by changing the parameters, without rewriting the model (Matthews, 2004).

The Soil Water Balance (SWB) model is a mechanistic, real-time, generic crop, soil water balance, irrigation scheduling model, which is based on the improved generic crop version of the NEW Soil Water Balance (NEWSWB) model (Annandale *et al.,* 1999). SWB gives a detailed description of the soil-plant-atmosphere continuum, making use of weather, soil and crop management data (Annandale *et al.,* 1999). It calculates the water balance and crop growth with weather, soil and crop units. The nman-Monteith reference crop evapotranspiration (Allen *et al.*, 1998) together with a mechanistic crop growth model, which uses soil water and grows a realistic canopy and root system, provide the best possible estimate of the soil water balance. Most irrigators, however, could in the past not use this approach because it requires specialised knowledge, weather data and computers to run the model. On the other hand, high costs, associated with the management of the model, would be reduced by packaging the model in a user-friendly format, avoiding the need for detailed understanding of the soil-plant-atmosphere continuum (Annandale *et al*., 1999). Moreover, the accuracy of the mechanistic version and the universally valid estimation procedures increase the benefits of this model (Annandale *et al*., 1999).

The mechanistic approach used to estimate crop water use has several advantages over the more empirical methods (Smith, 1992b). The use of thermal time to describe crop development overcomes the need to use different crop factors for different planting dates and regions. In addition, splitting evaporation and transpiration solves the problem of considering irrigation frequency, particularly during the crop's initial stage, where crop canopy cover is low and evaporation from the soil is more important (Villalobos & Fereres, 1990). It also more accurately describes deficit irrigation strategies where water use is supply-limited (Annandale *et al*., 1999).

Irrigation scheduling with crop growth models has drawn the interest of farmers since personal computers have become more accessible. Most of the existing models are either crop specific or do not simulate daily crop water use. Some models are relatively simple to use for planning purposes, but do not allow real-time scheduling. Other models accurately describe the complexity of natural processes and this makes them suitable for research purposes. However, this may not be applicable for practical purposes due to large quantities of input data required and lack of a user-friendly interface.

Since SWB is a generic crop growth model, parameters specific for each crop need to be determined experimentally prior to using it for irrigation scheduling. Therefore, the objective of this study was to generate parameters for four potato cultivars and one onion cultivar in South Africa and one tropical potato cultivar of Ethiopia. These databases are to be included in the SWB model to create a user-friendly irrigation-scheduling tool for practical application. The SWB model was then calibrate and validate for the four potato cultivars grown at Bronkhorstspruit, RSA during September to December 2003, a tropical potato grown at Debre-Zeit, Ethiopia (from January to April 2005) and onions grown under water stress conditions applied at different growth stages at the Hatfield Experimental farm of the University of Pretoria (from May to December 2004).

8.2 Model description

The sub-components of SWB, the weather, soil and crop units are described in detail by Annandale *et al*. (1999) for further references. Therefore, only a brief outline of the model is given in this chapter.

According to Annandale *et al*. (1999), the SWB was two types of models:

- The crop growth, mechanistic model, which calculates crop growth and soil water balance components; and
- The FAO-type crop factor model, which calculates the soil water balance without simulating dry matter production mechanistically.

In this particular work, however, the crop growth model that calculates the crop growth and soil water balance is used in the simulations.

The weather unit of SWB calculates the daily Penman-Monteith grass reference evapotranspiration (ETo) according to the recommendations of the Food and Agriculture Organization of the United Nations (Smith *et al.*, 1996; Smith, 1992a). In the weather unit of SWB, potential evapotranspiration (PET) is divided into potential evaporation and potential transpiration by calculating canopy radiant interception from simulated leaf area (Ritchie, 1972). Under conditions where actual transpiration is less than potential transpiration, the crop has undergone stress that reduced leaf area development. This makes the crop growth model of SWB very suitable for predicting crop water requirements when deficit irrigation strategies are applied (Oliver & Annandale, 1998; Annandale *et al.*, 1999). SWB calculates the potential evapotranspiration (PET) according to eq 8.1:

$$PET = ETo * Kc_{max} \qquad (8.1)$$

Where

Kc_{max} represents the maximum value (Kc) following rain or irrigation (Allen *et al.,* 1998)

Transpiration rate depends on the atmospheric evaporative demand, the soil-water potential and FI of solar radiation by the crop canopy. FI is calculated from the LAI, using eq 8.2:

$$FI = 1\text{-}exp\ (-k*LAI) \qquad (8.2)$$

Hence, $$k = Ln\ (1 - FI) / - LAI \qquad (8.3)$$

Where

K represents the canopy extinction coefficient, it can be calculated using field measurements of LAI and FI. K is calculated from FI measurements with the ceptometer, which measures photosynthetically active radiation.

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

$$K_S = K_{bd} \sqrt{a_s} \quad (8.4)$$

$$K_{bd} = K_{PAR} / \sqrt{a_p} \quad (8.5)$$

$$a_s = \sqrt{a_p a_n} \quad (8.6)$$

Where

K_{bd} = Canopy radiation extinction coefficient for black leaves with diffuse radiation

a_s = Leaf absorptance of solar radiation

a_p = Leaf absorptance of PAR

a_n = Leaf absorptance of near infrared radiation (NIR) (0.7-3 µm)

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

In the crop unit, SWB calculates crop dry matter accumulation in direct proportion to transpiration corrected for vapour pressure deficit (Tanner & Sinclair, 1983). It also calculates radiation-limited growth (Monteith, 1997) and takes the lower of the two.

This dry matter is partitioned to roots, stems, leaves and grains or fruits. Partitioning depends on phenology calculated with thermal time and modified by water stress.

The crop specific growth parameters required by SWB is generated to enable simulation of growth and water use of crops. According to Tanner & Sinclair (1983), the relationship between dry matter production and crop transpiration need to be corrected to account for atmospheric conditions, mainly for vapour pressure deficit (VPD). Hence, dry matter-water ratio (DWR) is calculated using eq 8.7 (Annandale *et al.*, 1999).

$$DWR = (DM*VPD) / ET \qquad (8.7)$$

Where

DM (kg m^{-2}) is measured at harvest

VPD represents the average of the season

ET represents the seasonal crop evapotranspiration in mm, which is equivalent to kg m^{-2}

DWR and VPD are measured in Pa

ET is obtained using the following equation for daily time interval:

$$ET = P + I - R - Dr \pm \Delta Q \qquad (8.8)$$

Where

R = runoff, Dr = drainage and ΔQ = the change in soil water storage, which is calculated from soil water measurement at the beginning and end of the irrigation season with the neutron water meter.

Dry matter production can also be calculated from the radiation conversion efficiency (Ec), under conditions of radiation-limited growth, according to Monteith (1977).

$$DM = Ec*FI*Rs \qquad (8.9)$$

Where, Rs = the solar radiation

In SWB, the daily dry matter increment and its partitioning into different plant parts are calculated as either transpiration-limited (eq 8.8) or radiation-limited (eq 8.9). Hence, SWB calculates the LDM and SDM as follows (Annandale *et al.*, 1999):

$$LDM = CDM / (1 + PART*CDM) \quad (8.10)$$

$$SDM = CDM - LDM \quad (8.11)$$

Similarly, SWB uses the LDM to calculate LAI as:

$$LAI = SLA*LDM \quad (8.12)$$

SLA represents the specific leaf area, which is calculated as the seasonal average of the ratio of LAI and LDM. Leaf-stem dry matter partitioning parameter (PART) is determined as a function of SLA, LAI and CDM, by combining eqs (8.10) and (8.12). Hence, the correlation between CDM and (SLA*CDM)/LAI-1 and the regression line which is forced through the origin, represents PART in

m^2 kg^{-1}. PART is described as:

$$PART = (SLA*CDM/LAI-1)/CDM \quad (8.13)$$

8.3 Materials and methods

Procedures followed during the field experiments, and materials and methods used were dealt with under each respective chapters. The growth performance and yield of potatoes (cv. Awash) grown under varying water regimes in the tropical environment of Ethiopia (January to April, 2005) were discussed in Chapter 4. The evaluation of growth performance and dry matter partitioning of the four processing potato cultivars grown at Bronkhorstspruit, South Africa (September to December, 2003) were also discussed in Chapter 5. In addition, the growth analysis and yield data of onions (cv. Texas Grano) grown under water-stress conditions applied at different growth stages was discussed in Chapter 7. In this chapter, the crop specific growth parameters developed from the field experiments are presented and discussed. In addition, the SWB model is calibrated and simulations evaluated.

Management, weather, soil and crop data are required as inputs in order to run both the crop growth and the FAO models of SWB.

Input data related to crop management include:

- starting date of the simulation;
- planting date;
- irrigation timing options;
- irrigation system; and
- area of the field (ha).

Soil data required per layer are:

- soil layer thickness (m);
- drainage factor;
- maximum drainage rate;
- volumetric water content at field capacity and permanent wilting point;
- initial volumetric water content ; and
- bulk density (Mg m^{-3}).

Weather data include:

- latitude (^{o}N or ^{o}S) and altitude (m.a.s.l.);
- maximum and minimum daily temperature (^{o}C);
- precipitation and irrigation (mm);
- solar radiation (MJ m^{-2} d^{-1});

- vapour pressure or minimum and maximum humidity (%) or wet and dry bulb temperatures (^oC); and
- wind speed ($m\ s^{-1}$) and height of the measurement (m).

Crop parameters include:

- cardinal temperatures (base and optimum temperatures for development (^oC);
- thermal time requirements (in degree days) for emergence, onset of the reproductive stage, transition period, crop maturity and leaf senescence;
- VPD-corrected dry matter water-ratio (DWR) (Pa);
- maximum RD (m);
- canopy solar radiation extinction coefficient (kc);
- radiation use efficiency ($kg\ MJ^{-1}$);
- leaf-stem partition parameters ($m^2\ kg^{-1}$); and
- maximum crop height (m).

Crop specific growth parameters for the five potato cultivars grown at two locations under different climatic conditions and an onion grown under water stress imposed at different growth stages are shown in Tables 8.2, 8.3 and 8.4. The basal temperatures, temperatures for optimum growth and cut-off temperatures were obtained from Annandale *et al.* (1999). Crop measurements recommended by Mason *et al.* (1980) were used to determine the following parameters: canopy solar radiation extinction coefficient (Kc), SLA, leaf-stem partitioning parameter (PART), canopy radiation extinction coefficient (K) and corrected dry matter water ratio (DWR).

8.4 Results and discussion

8.4.1 McCain trial

Two newly released potato cultivars, Frodo and Darius were grown along with two existing cultivars, Pentland Dell and Shepody at McCain experimental station in 2003. Table 8.2 provides the crop specific growth parameters determined from the measured data in the experimental field and some others obtained from literature.

The crop data measured from the experimental field was used to generate some of the crop specific parameters. The results revealed that the crop specific growth parameters generated were generally comparable with the other values previously published by Steyn (1997) and Annandale *et al. (*1999). The canopy solar radiation extinction coefficients generated from this experiment were generally on the lower range compared to the findings reported by Annandale *et al.* (1999). Table 8.2 reveals that the value for corrected DWR is higher for the new cultivars (Frodo and Darius) compared to the two established cultivars. Cultivar Darius exhibited a relatively high radiation conversion efficiency (Ec) of 0.0020 kg MJ^{-1} compared to the other cultivars, which had values lower than 0.00175 kg MJ^{-1} (Table 8.1). The comparably high values of DWR and Ec for Darius could be attributed to the fact that it is a slow maturing cultivar, which has long LAD. Table 8.2 also reveals that the SLA, which is the average ratio of LAI and LDM before leaf senescence, was the highest for Darius, followed by Frodo. All cultivars tested in this trial possessed high SLA values, compared to the cultivars included in the reports of Steyn (1997) and Annandale *et al. (*1999). Similarly, the thermal time requirements for different growth stages, mainly for emergence, maturity and the transition periods, were higher for Darius, compared to the other cultivars. In general, the thermal time recorded for cultivars were more or less comparable.

The crop data measured from the experimental field was used to calibrate the SWB model for the four cultivars. The performance outputs of the measured data (points) and the SWB model simulations (lines) are displayed in

- Figures 8.1a and 8.1b for Frodo;
- Figures 8.2a and 8.2b for Pentland Dell;
- Figures 8.3a and 8.3b for Darius; and
- Figures 8.4a and 8.4b for Shepody.

The SWB simulation performance was evaluated according to the statistical criteria proposed by De Jager (1994) in Table 8.1.

Table 8.1 Model evaluation parameters and their accuracy criteria levels (after De Jager, 1994)

Statistical parameters	Abbreviations	Reliability criteria
Number of measured values	N	-
Coefficient of determination	r^2	> 0.80
Willmot (1982) index of agreement	D	> 0.80
Root mean square error	RMSE	-
Mean absolute error expressed as a percentage of the mean of the measured values	MAE (%)	< 20

Table 8.2 Summary of crop growth parameters determined for the four potato cultivars from 2003 field data and from the literature, to calibrate the SWB model

Crop growth parameters	Potato cultivars				Source
	Frodo	Pentland Dell	Darius	Shepody	
Canopy radiation extinction coefficient	0.40	0.40	0.40	0.40	Data
Corrected dry matter-water ratio (Pa)	5.2	4.8	5.2	4.8	Data
Radiation conversion efficiency (kg MJ^{-1})	0.00174	0.00174	0.0020	0.00165	Data
Base temperature (°C)	2	2	2	2	Annandale *et al.*, (1999)
Temperature for optimum crop growth (°C)	10	10	10	10	Annandale *et al.*, (1999)
Cut-off temperature (°C)	28	28	28	28	Annandale *et al.*, (1999)
Emergence day degrees (d °C)	400	400	525	360	Data
Day degrees at end of vegetative growth (d °C)	730	680	1200	820	Data
Day degrees for maturity (d °C)	2635	2240	2400	2280	Data
Transition period day degrees (d °C)	520	460	520	420	Data
Day degrees for leaf senescence (d °C)	1842	1646	1826	1410	Data
Maximum crop height (m)	0.75	0.75	0.75	0.75	Data
Maximum root depth (m)	0.8	0.8	0.8	0.8	Data
Fraction of total dry matter translocated to heads/tuber	0.45	0.45	0.45	0.45	Annandale *et al.*, (1999)
Canopy storage (mm)	1	1	1	1	Annandale *et al.*, (1999)
Leaf water potential at maximum transpiration (kPa)	-550	-550	-550	-550	Annandale *et a.*, (1999)
Maximum transpiration (mm d^{-1})	8	8	7	8	Steyn, (1997)
Specific leaf area (m^2 kg^{-1})	26	25	28	25	Data
Leaf-stem partition parameter (m^2 kg^{-1})	1.5	2	2	3	Data
Total dry matter at emergence (kg m^{-2})	0.005	0.005	0.005	0.005	Annandale *et al.*, (1999)
Fraction of total dry matter partitioned to roots	0.1	0.1	0.1	0.1	Annandale *et al*,. (1999)
Root growth rate (m^2 $kg^{-0.5}$)	3	2	2	2	Steyn, (1997)
Stress index	0.98	0.98	0.98	0.98	Annandale *et al.* (1999)

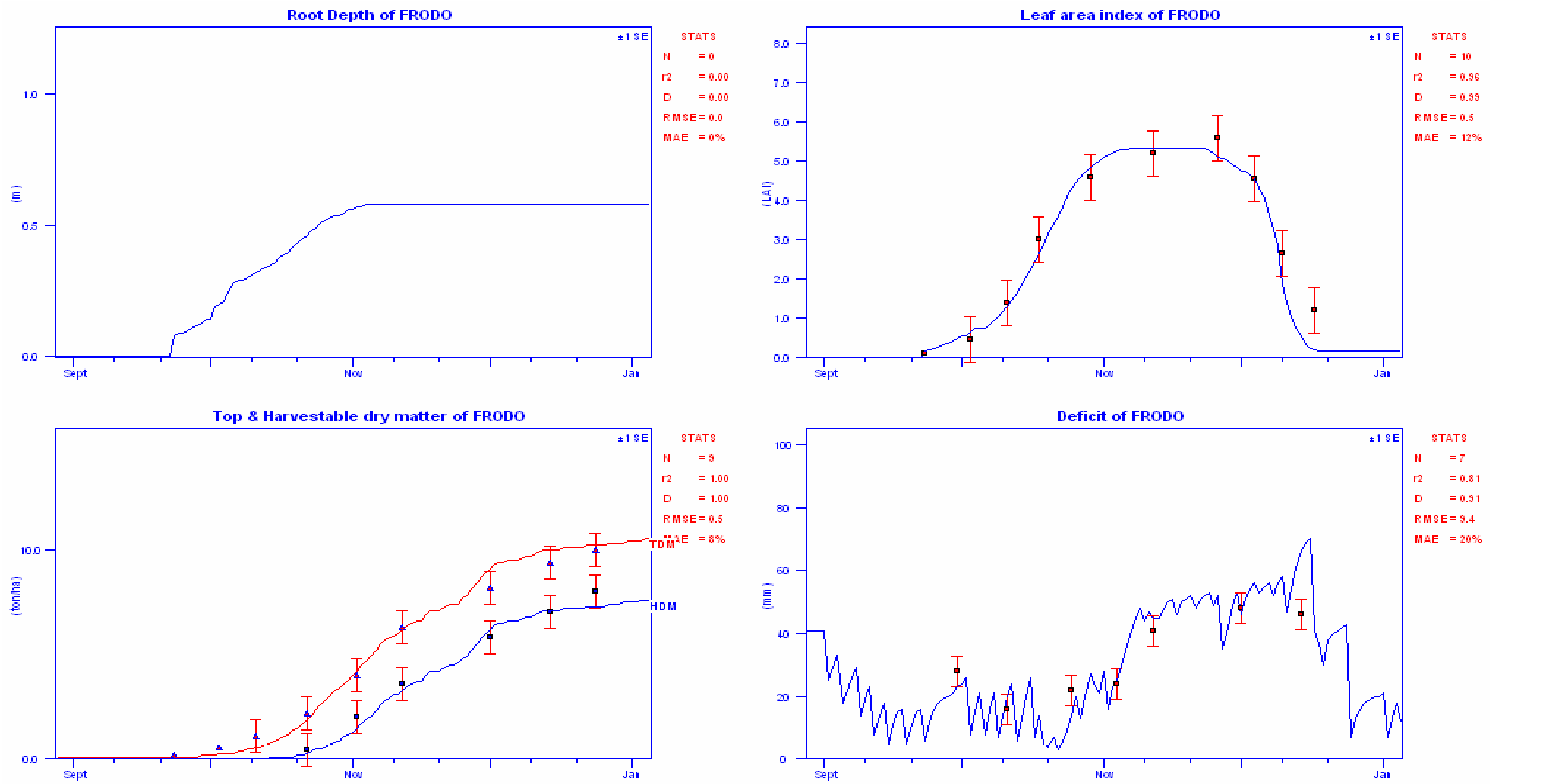

Figure 8.1a Simulated (lines) and measured values (points) of rooting depth (RD), leaf area index (LAI), total dry matter (TDM), harvestable dry matter (HDM) and soil water deficit to field capacity for Frodo.

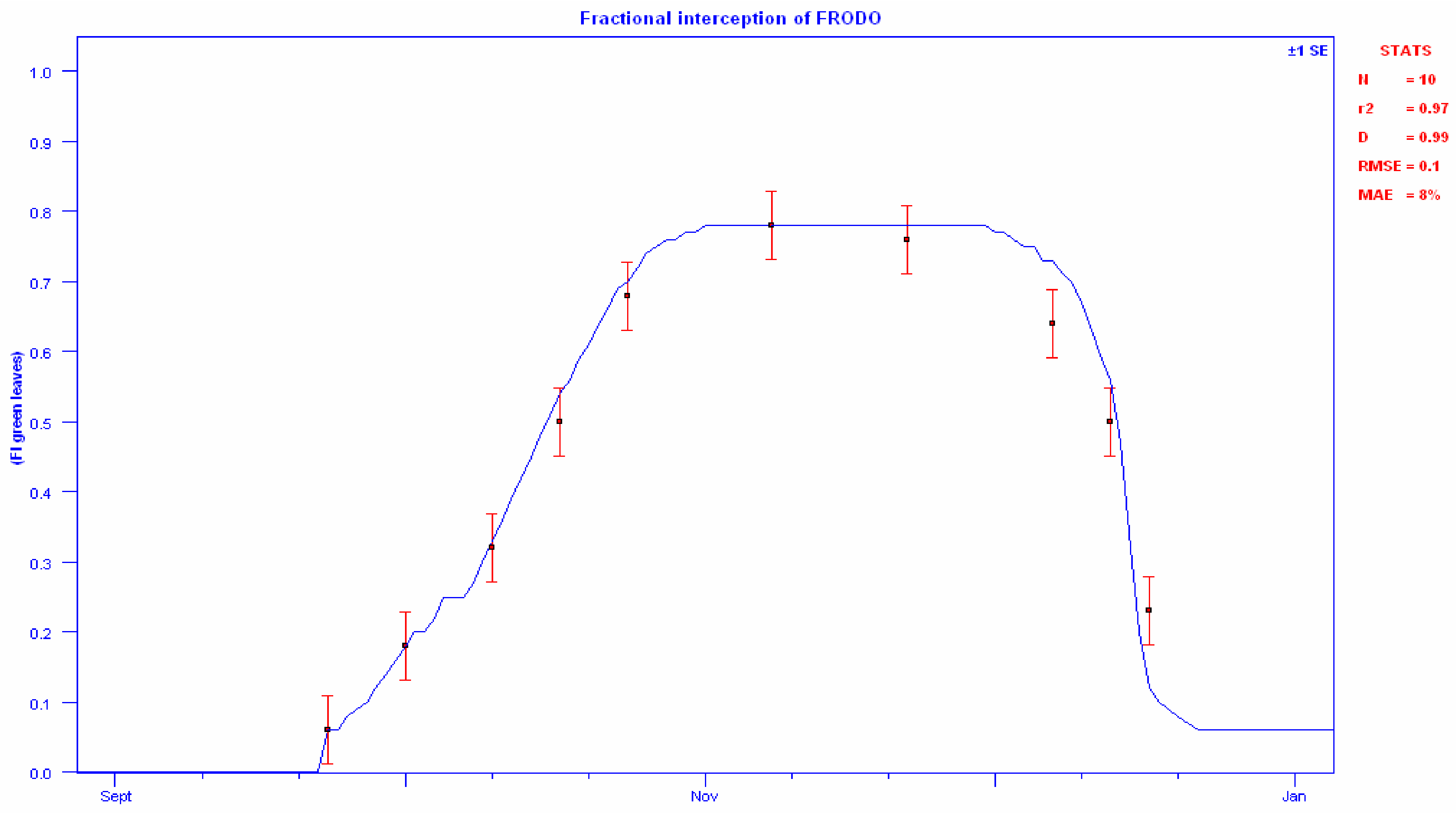

Figure 8.1b Simulated (lines) and measured values (points) of fractional interception (FI) (solar) for Frodo

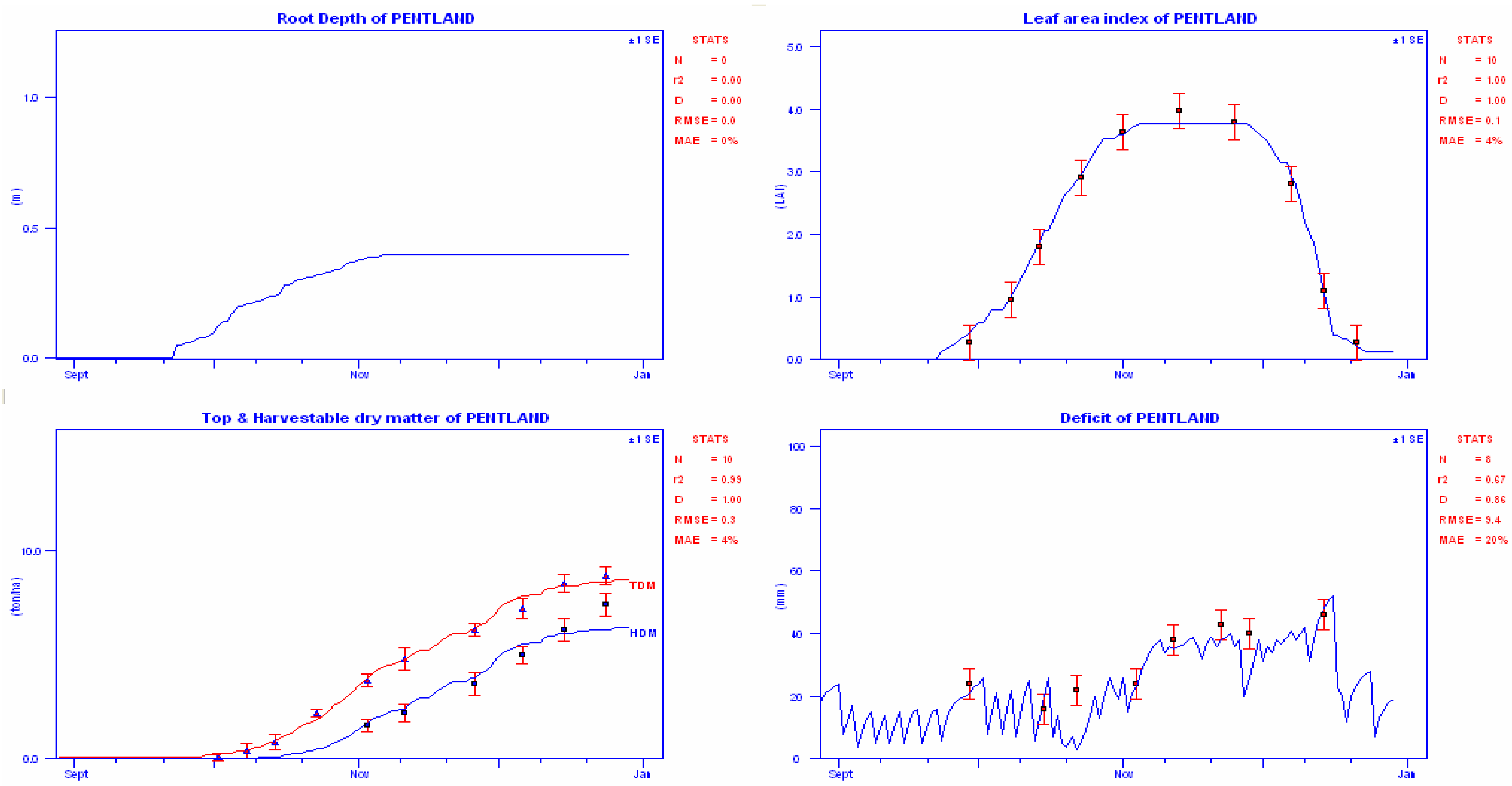

Figure 8.2a Simulated (lines) and measured values (points) of rooting depth (RD), leaf area index (LAI), total dry matter (TDM), harvestable dry matter (HDM) and soil water deficit to field capacity for Pentland Dell

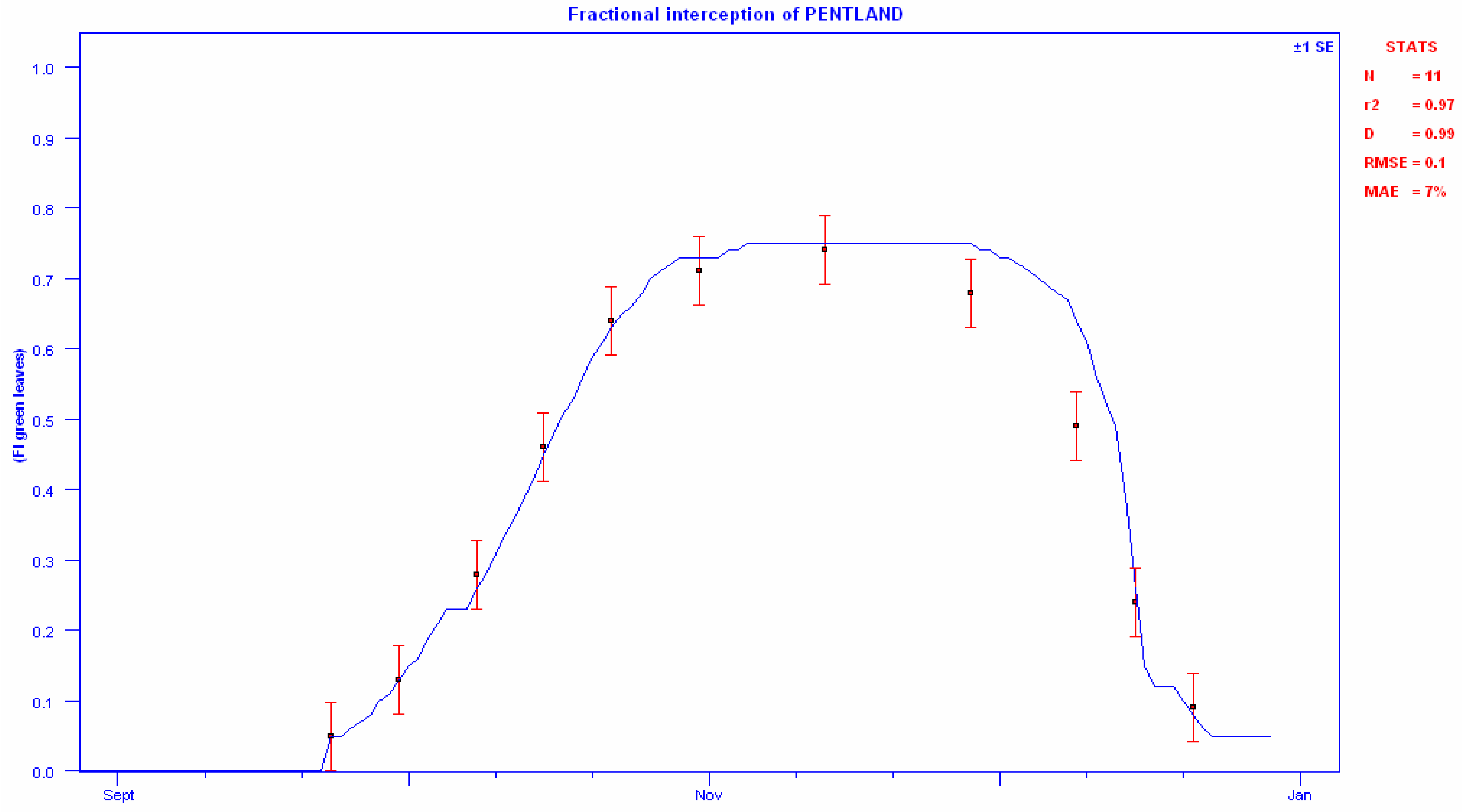

Figure 8.2b Simulated (lines) and measured values (points) of fractional interception (FI) (solar) for Pentland Dell

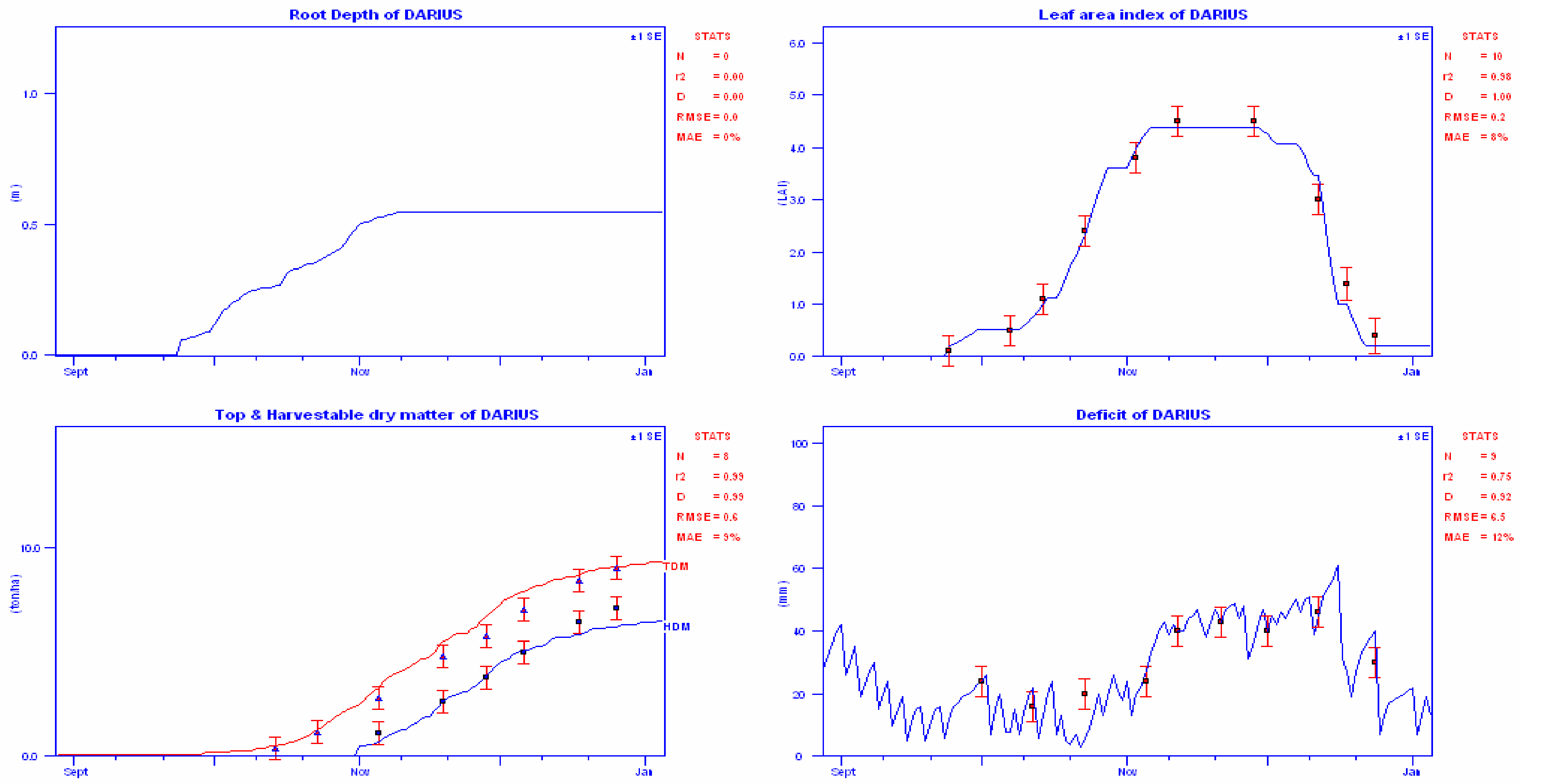

Figure 8.3a Simulated (lines) and measured values (points) of rooting depth (RD), leaf area index (LAI), total dry matter (TDM), harvestable dry matter (HDM) and soil water deficit to field capacity for Darius

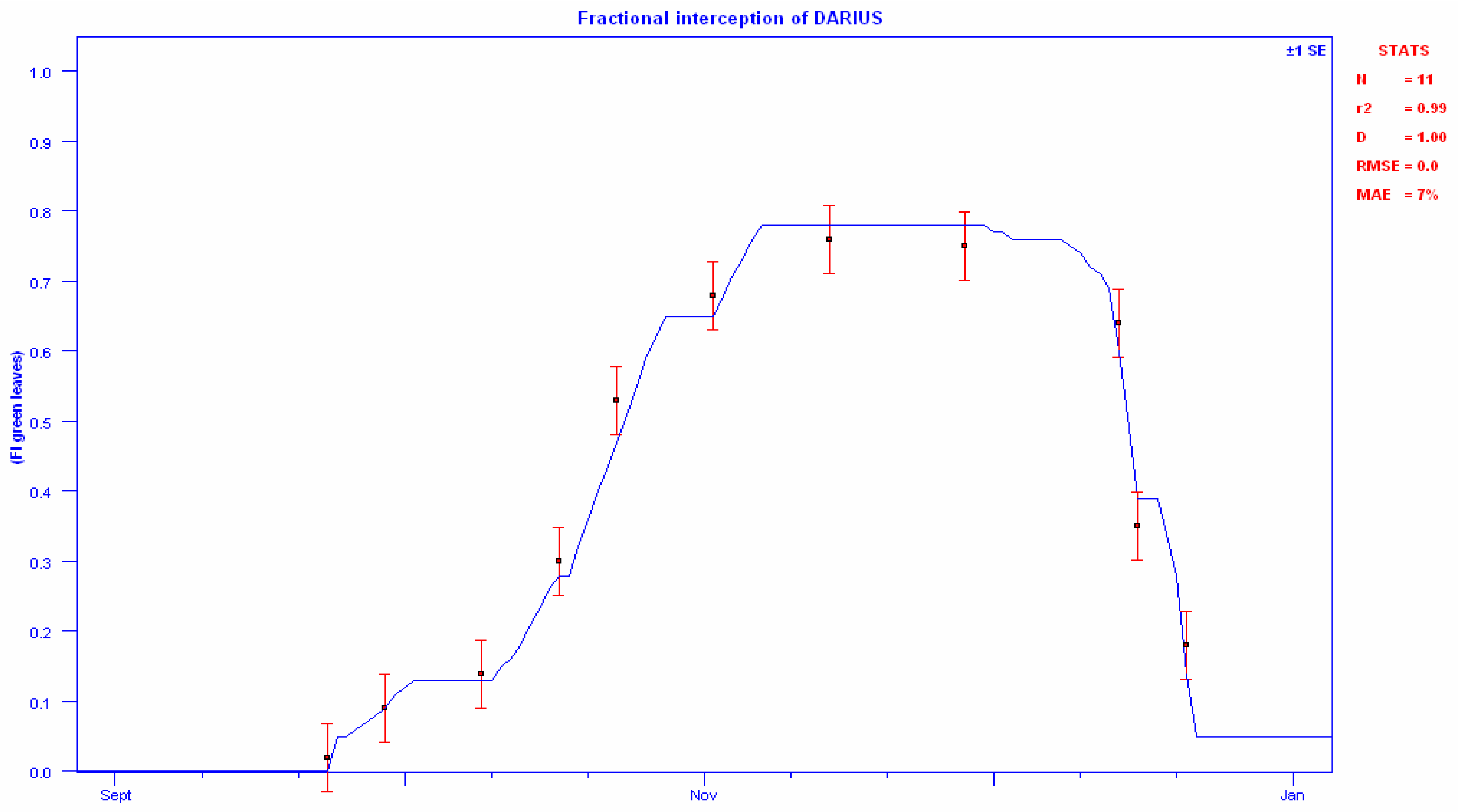

Figure 8.3b Simulated (lines) and measured values (points) of fractional interception (FI) (solar) for Darius

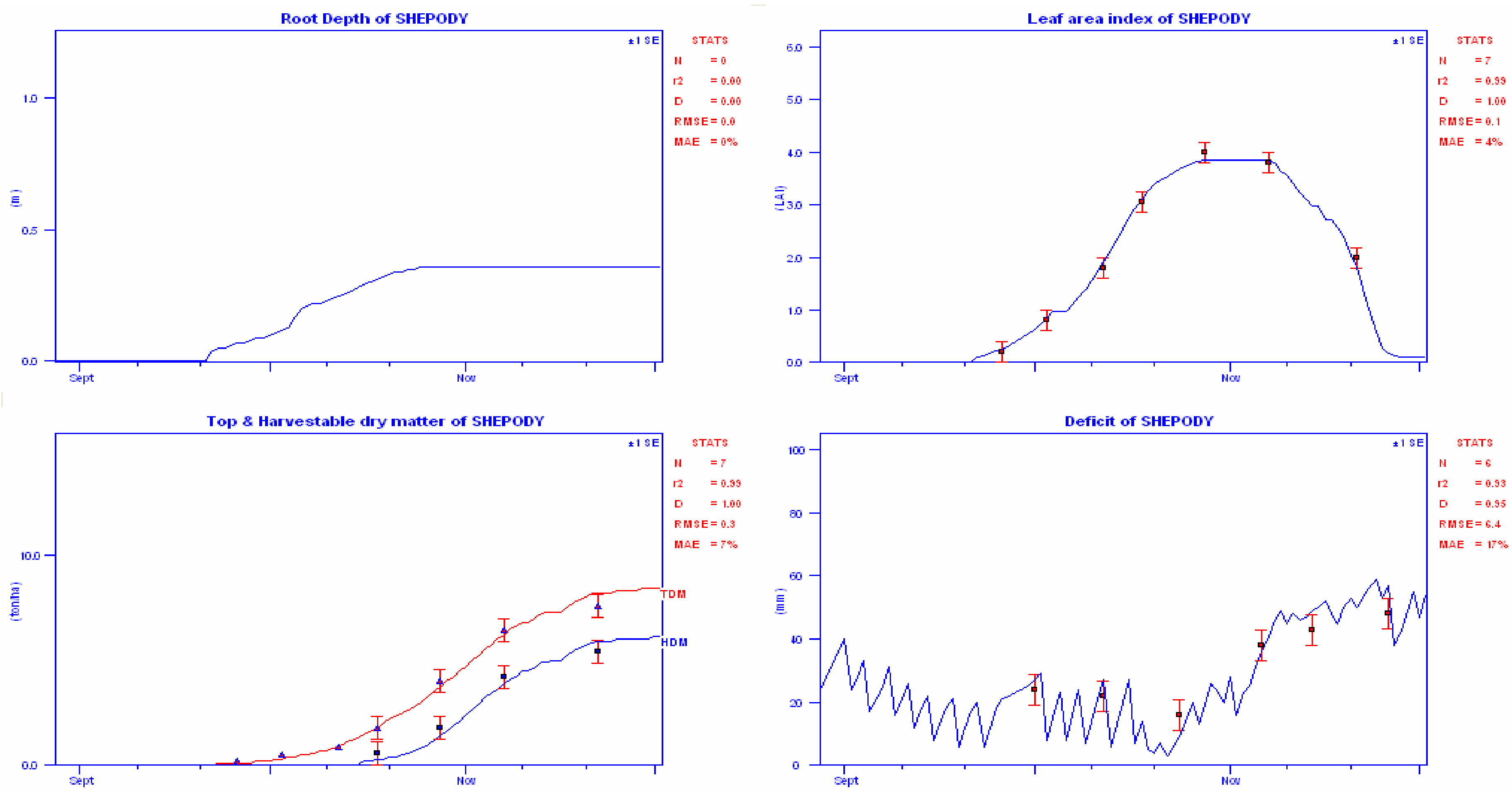

Figure 8.4a Simulated (lines) and measured values (points) of rooting depth (RD), leaf area index (LAI), total dry matter (TDM), harvestable dry matter (HDM) and soil water deficit to field capacity for Shepody

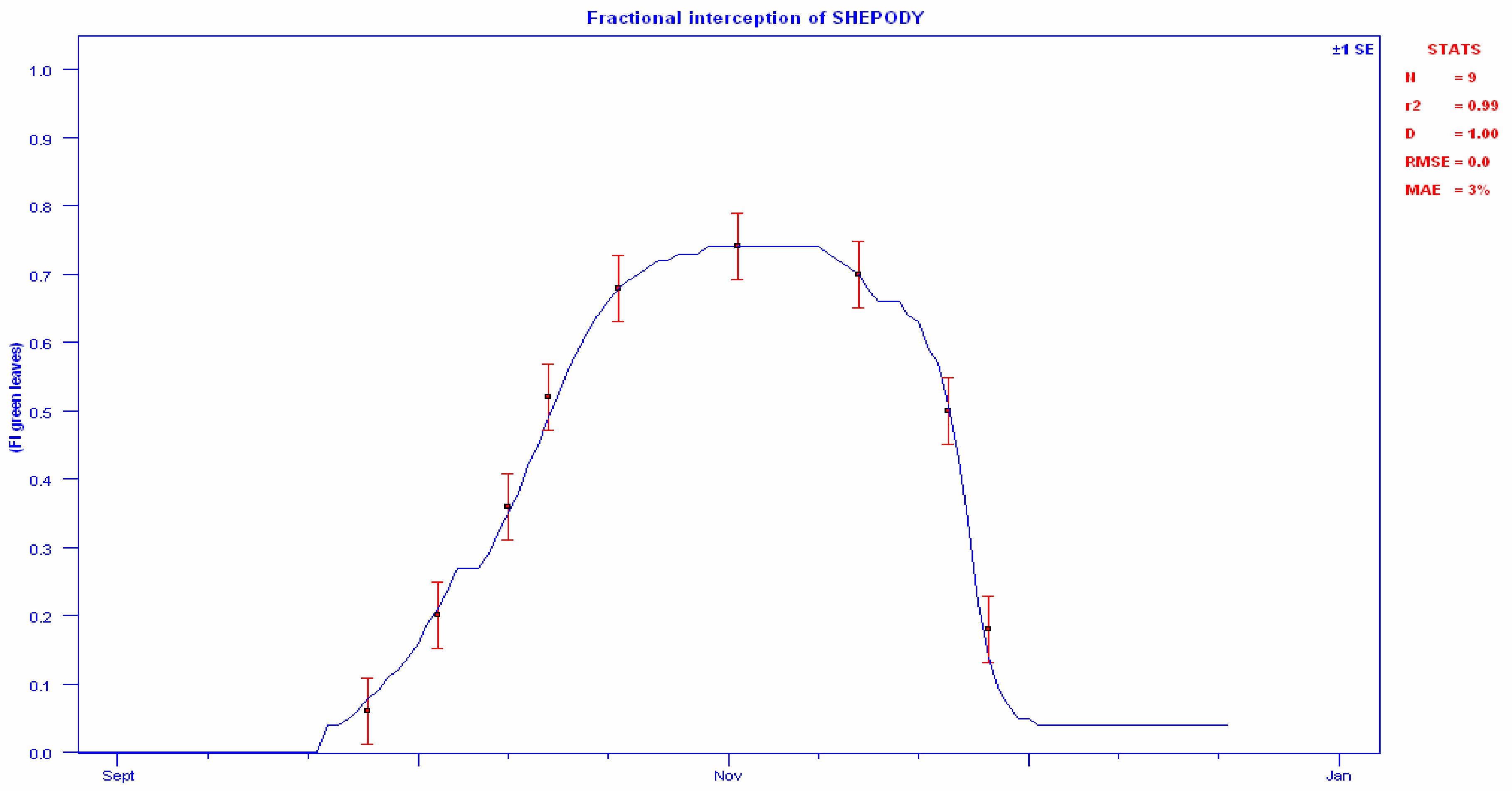

Figure 8.4b Simulated (lines) and measured values (points) of fractional interception (FI) (solar) for Shepody

Simulations of crop growth and the soil water balance were run for each potato cultivar. The root growth was not measured during the field experiment, and only the SWB model simulation is given in Figures 8.1a, 8.2a, 8.3a and 8.4a. Simulations for TDM, harvestable dry matter (HDM), the LAI and FI fitted very well for the four potato cultivars, Frodo, Pentland Dell, Darius and Shepody, as the statistical indicators lie within the accuracy limits recommended by De Jager (1994). The model, however, slightly under-estimated the LAI of cv Frodo during the vegetative growth stage, even though the statistical measures indicated acceptable simulation accuracy.

The SWB simulations revealed that all four the cultivars were probably water stressed from November to mid December (Figures 8.1a, 8.2a, 8.3a & 8.4a). The measured data for soil water deficits to field capacity also confirmed that the crops were most likely water stressed during the indicated growth periods. Water stress during crop growth also manifested on the LAI and FI simulations of Darius, where the graphs appeared to be irregular (stepped). Despite this, both the LAI and FI simulated values matched the measured values very well for all four cultivars. The water management, including irrigation was performed by McCain personnel. The soil water status was only measured to calibrate the SWB simulations and not for irrigation management. In general, the measured soil water deficits during crop growth were in good agreement with the SWB simulations for all cultivars. Both the measured data and the simulations indicated a high soil water deficit from tuber bulking to maturity, which probably resulted in growth and tuber yield reduction. Shepody, an early cultivar, senesced more than a month earlier than the other cultivars. This was confirmed from the field data collected and the model was able to simulate this too.

8.4.2 Potato irrigation regime experiment

An experiment was executed on potato (cv. Awash) at Debre-Zeit, Ethiopia in 2005, with four irrigation regime treatments. These included:

- irrigation calendars generated by the SWB model (DZ1);
- traditional water regime practiced by farmers (DZ2);
- irrigation regime practiced by the RCP (DZ3); and
- the conventional soil water monitoring by neutron water meter (DZ4). See section 4.2 for trial details. Table 8.3 shows the crop specific growth parameters determined from the measured field experimental data points and some others obtained from literature.

Table 8.3 Summary of crop growth parameters determined for potato cv. Awash at Debre-Zeit, Ethiopia in 2005 and from literature

Crop growth parameters	Values	Units	Source
Canopy solar radiation extinction coefficient (Kc)	0.36	-	Data
Corrected dry matter-water ratio (dwr)	5.0	Pa	Data
Radiation conversion efficiency (RUE)	0.00175	kg MJ^{-1}	Data
Base temperature (Tb)	2	^oC	Annandale *et al.*, (1999)
Temperature for optimum crop growth	10	^oC	Annandale *et al.*, (1999)
Cut-off temperature	28	^oC	Annandale *et al.*, (1999)
Thermal time: emergence	360	day degree	Data
Thermal time: reproductive phase	720	day degree	Data
Thermal time: maturity	2400	day degree	Data
Thermal time: transition	238	day degree	Data
Thermal time: leaf senescence	640	day degree	Data
Maximum crop height (Hc)	0.80	m	Data
Maximum root depth	0.70	m	Data
Fraction of total dry matter translocated to tuber	0.45	-	Annandale *et al.*, (1999)
Canopy storage	1.00	mm	Annandale *et al.*, (1999)
Leaf water potential at maximum transpiration	-550	kPa	Annandale *et al.*, (1999)
Maximum transpiration	8.00	mm d^{-1}	Steyn., (1997)
Specific leaf area (SLA)	26.00	m^2 kg^{-1}	Data
Leaf-stem partition parameter	2.00	m^2 kg^{-1}	Data
Total dry matter at emergence	0.005	m^2 kg^{-1}	Annandale *et al.*, (1999)
Fraction of total dry matter partitioned to roots	0.10	-	Annandale *et al.*, (1999)
Root growth rate	3.00	m^2 $kg^{-0.5}$	Steyn, (1997)
Stress index	0.98	-	Annandale *et al.*, (1999)

The crop growth data measured from the field experiment was compared with the SWB crop growth simulations. The performance output for the measured data set (points) and the SWB model simulation (lines) are displayed in:

- Figures 8.5a and 8.5b for the irrigation treatment predicted by SWB (DZ1);

- Figures 8.6a and 8.6b for water management traditionally practiced by farmers (DZ2);
- Figures 8.7a and 8.7b for water management practiced by the nearby RCP (DZ3); and
- Figures 8.8a and 8.8b for the water deficit refilled to field capacity as measured by the neutron water meter (DZ4).

The graphs represent simulated RD, TDM and HDM, LAI and the soil water deficit (SWD). No measured data points were available for root depth. The model simulation performances were evaluated by the statistical criteria according to De Jager (1994), which are given in Table 8.1.

The crop growth parameters determined from the irrigation regime experiment at Debre-Zeit appeared to be more or less comparable to the previously reported parameters of Steyn (1997) and Annandale *et al.* (1999). However, as for the previously discussed experimental results (Table 8.2), some parameters like canopy radiation extinction coefficient and dry matter-water ratio values are slightly lower than those determined by Steyn (1997) and Annandale *et al.* (1999). This could be attributed to genetic differences between cultivars and different climatic conditions under which the crops were grown. Kooman *et al.* (1996b) and Jovanovic *et al.* (2002) further explain that the small canopy size and low yield potential of potatoes in the tropics and subtropics result from high temperatures and short day lengths, to which most potato cultivars are less adapted. This usually results in a low final tuber yield.

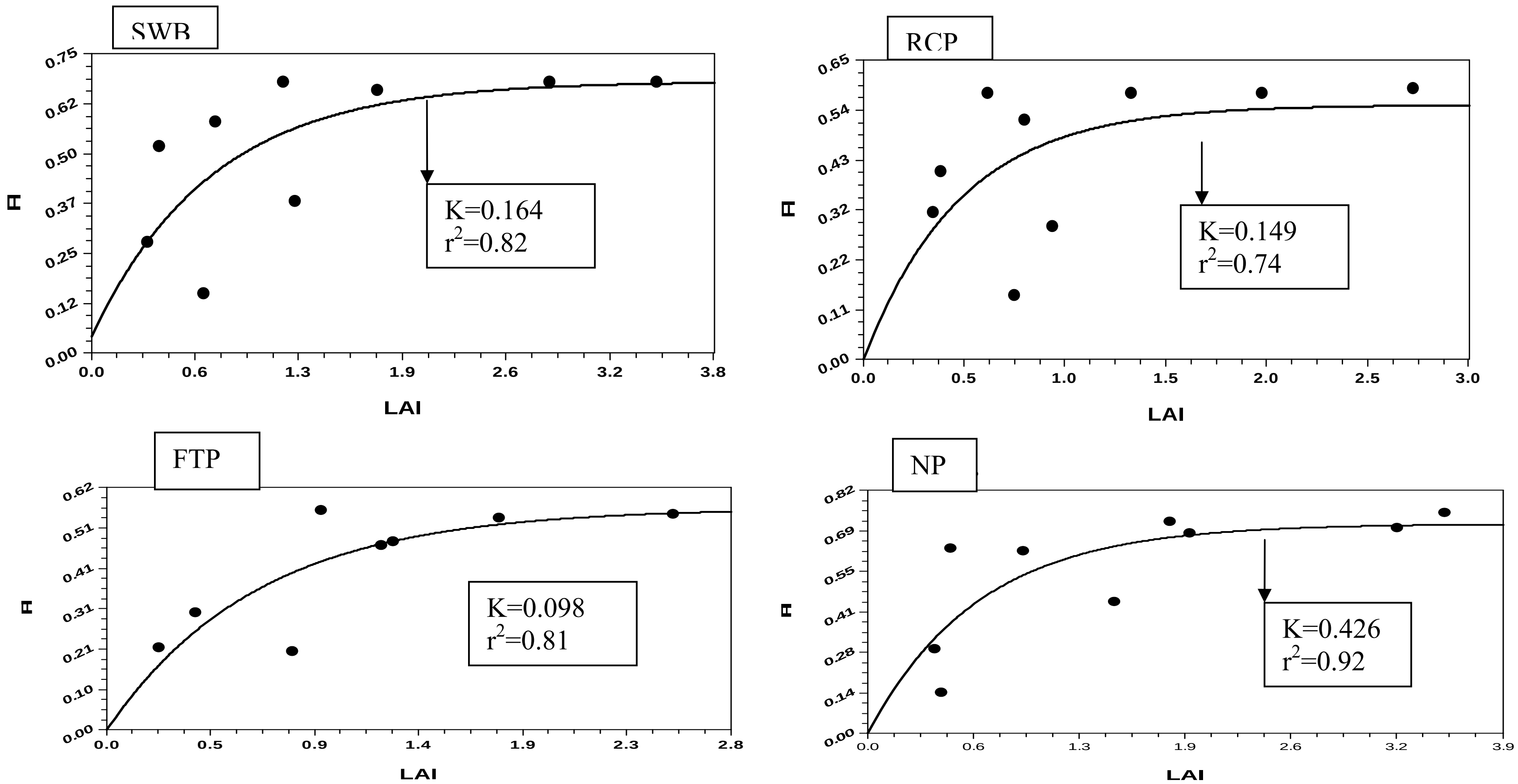

Figure 8.5 Correlation between leaf area index (LAI) and fractional interception (FI) of radiation for potato cv Awash. Canopy extinction coefficient (K) and coefficient of determination (r^2) of the exponential regression function.

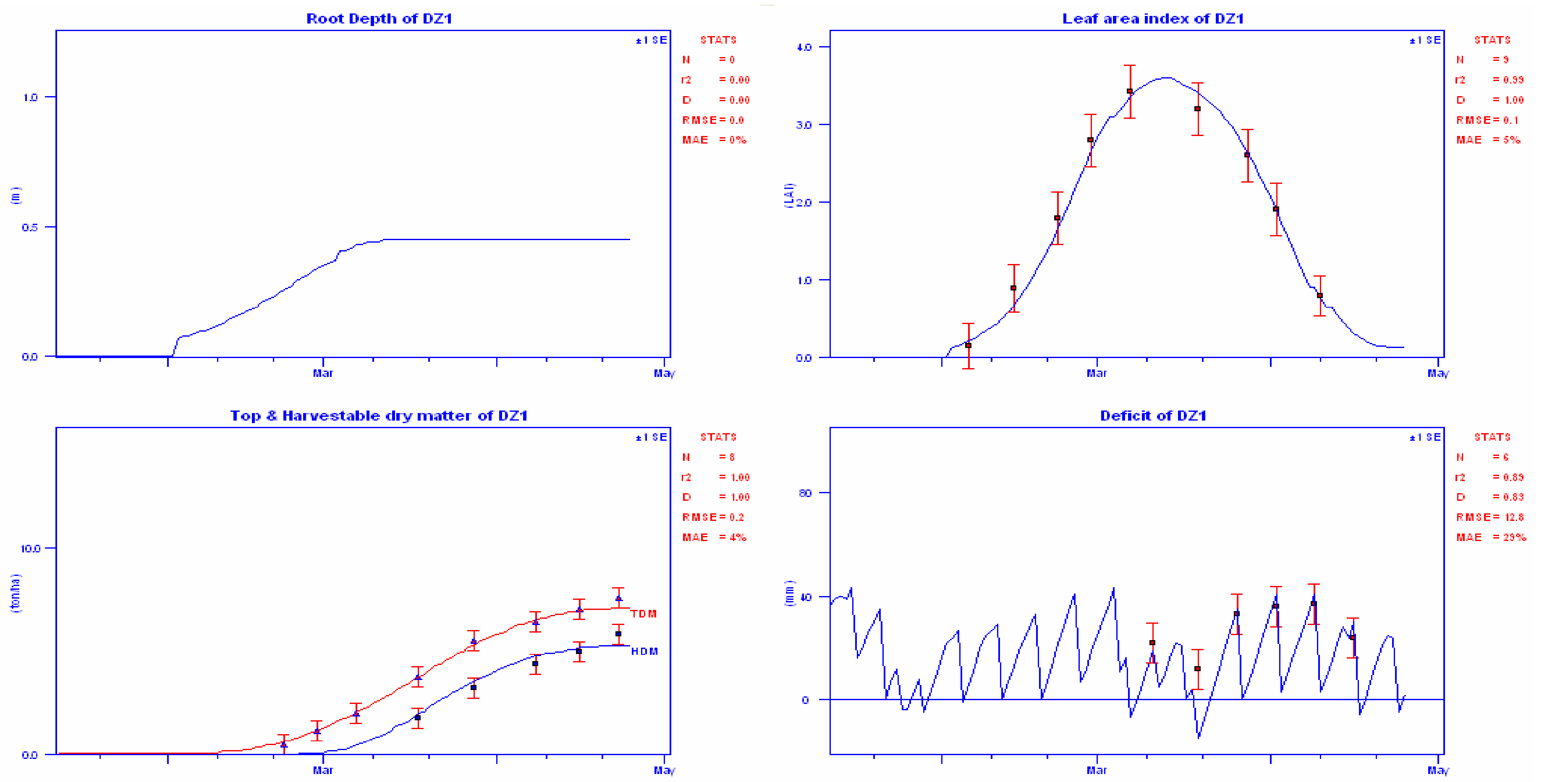

Figure 8.6a Simulated (lines) and measured values (points) of rooting depth (RD), leaf area index (LAI), total dry matter (TDM), harvestable dry matter (HDM) and soil water deficit to field capacity for SWB treatment (DZ1)

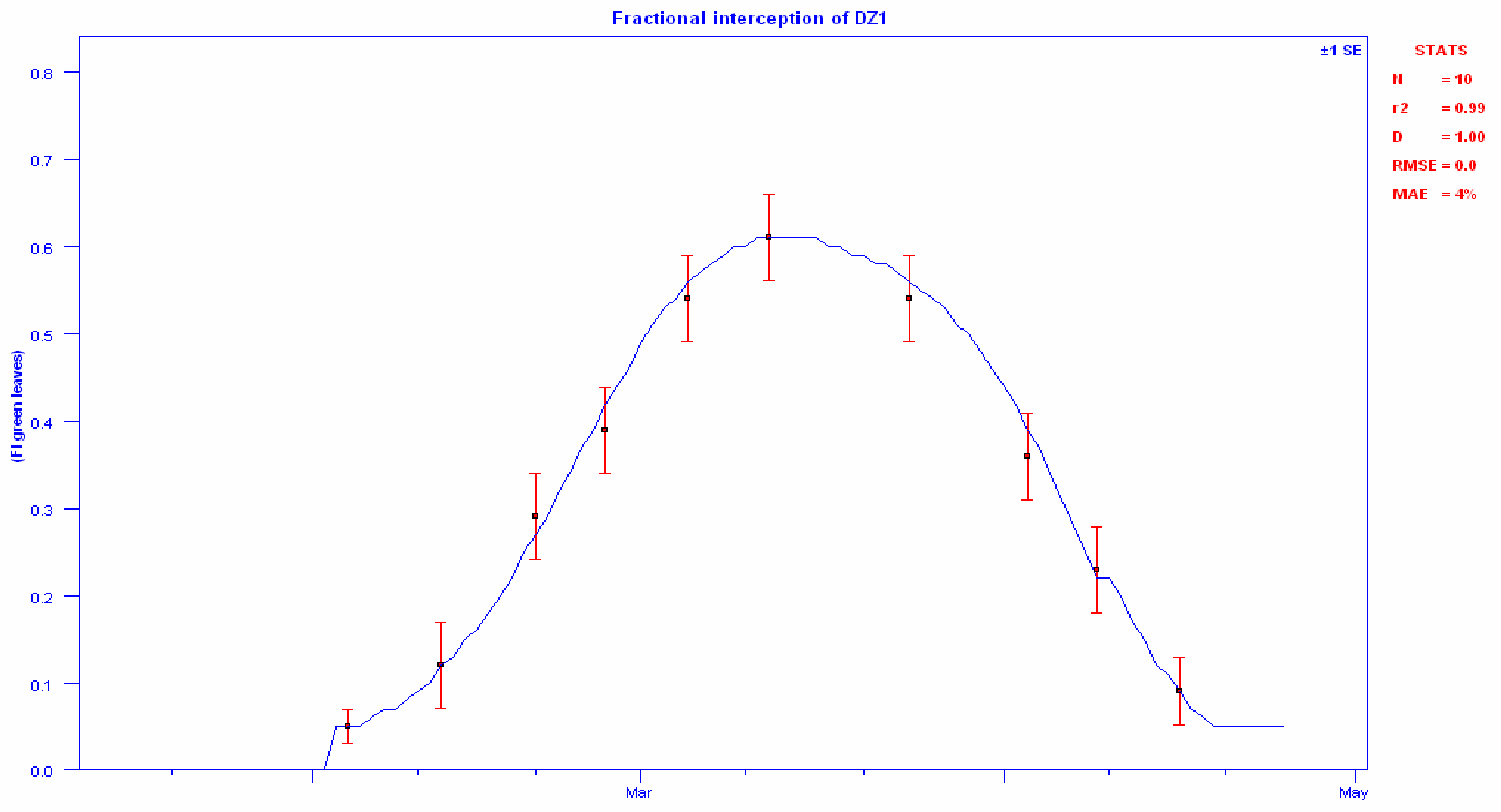

Figure 8.6b Simulated (lines) and measured values (points) of fractional interception (FI) (solar) for SWB treatment (DZ1)

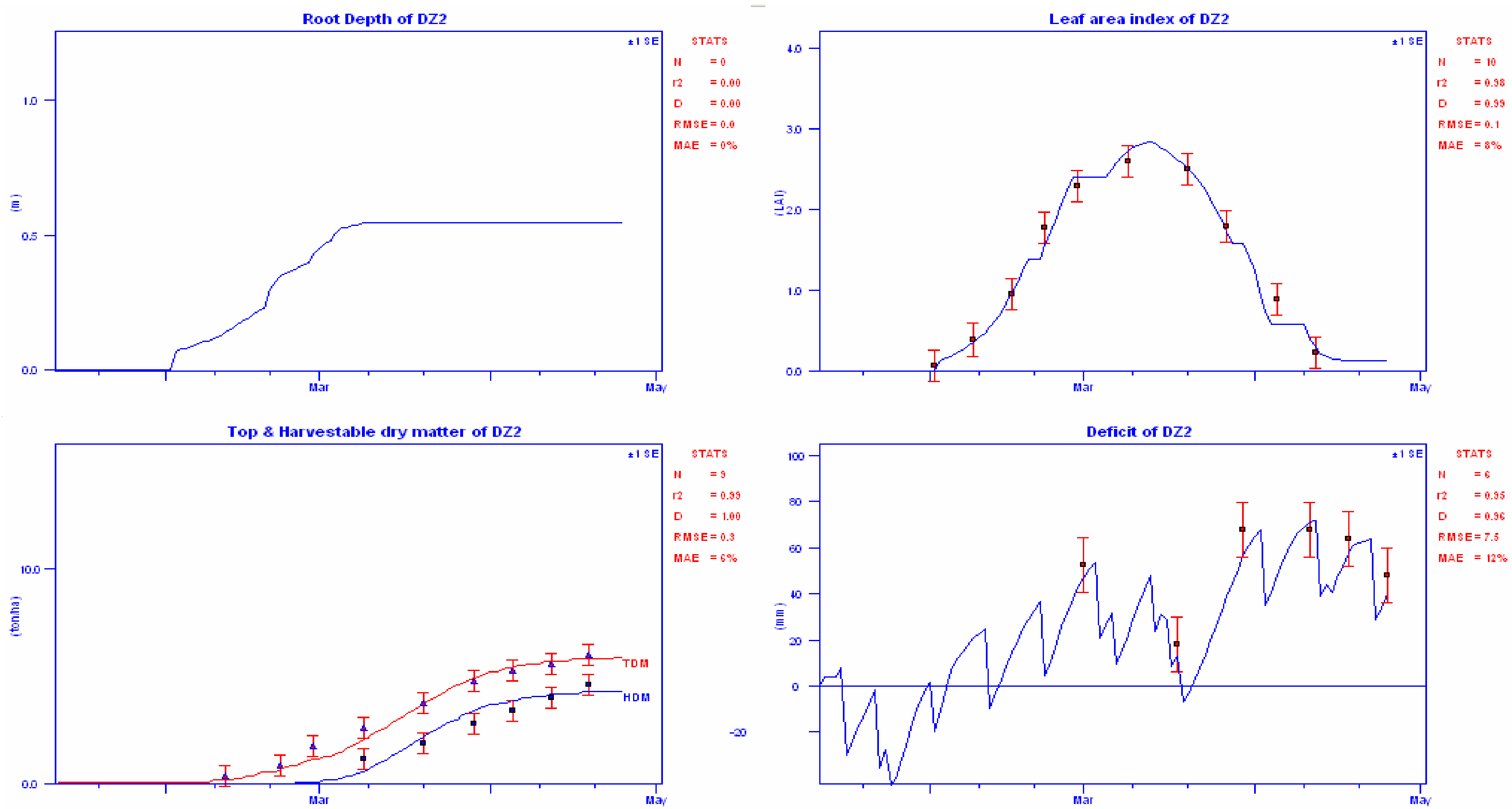

Figure 8.7a Simulated (lines) and measured values (points) of rooting depth (RD), leaf area index (LAI), total dry matter (TDM), harvestable dry matter (HDM) and soil water deficit to field capacity for FTP treatment (DZ2)

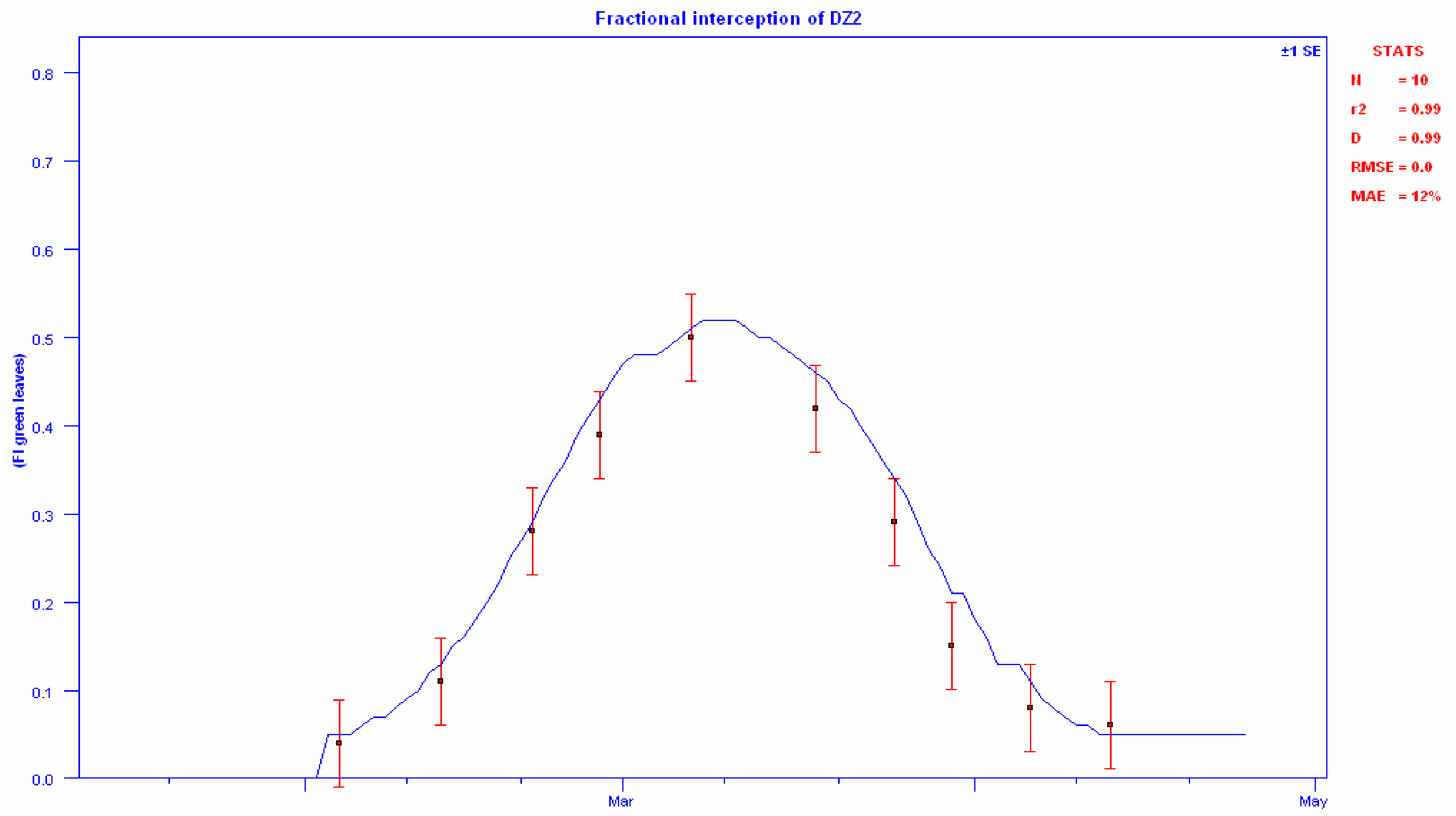

Figure 8.7b Simulated (lines) and measured values (points) of fractional interception (FI) (solar) for FTP treatment (DZ2)

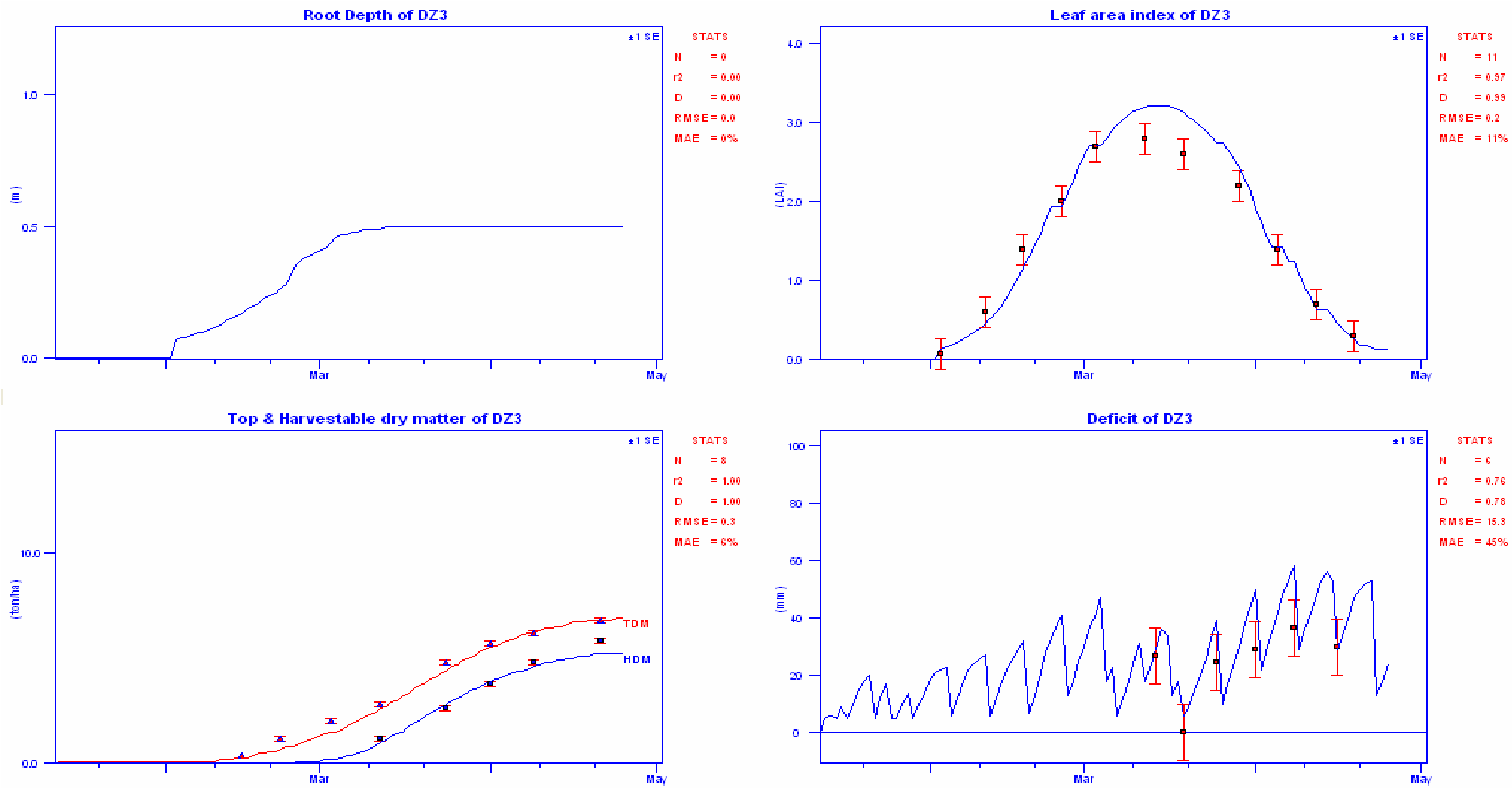

Figure 8.8a Simulated (lines) and measured values (points) of rooting depth (RD), leaf area index (LAI), total dry matter (TDM), harvestable dry matter (HDM) and soil water deficit to field capacity for RCP treatment (DZ3)

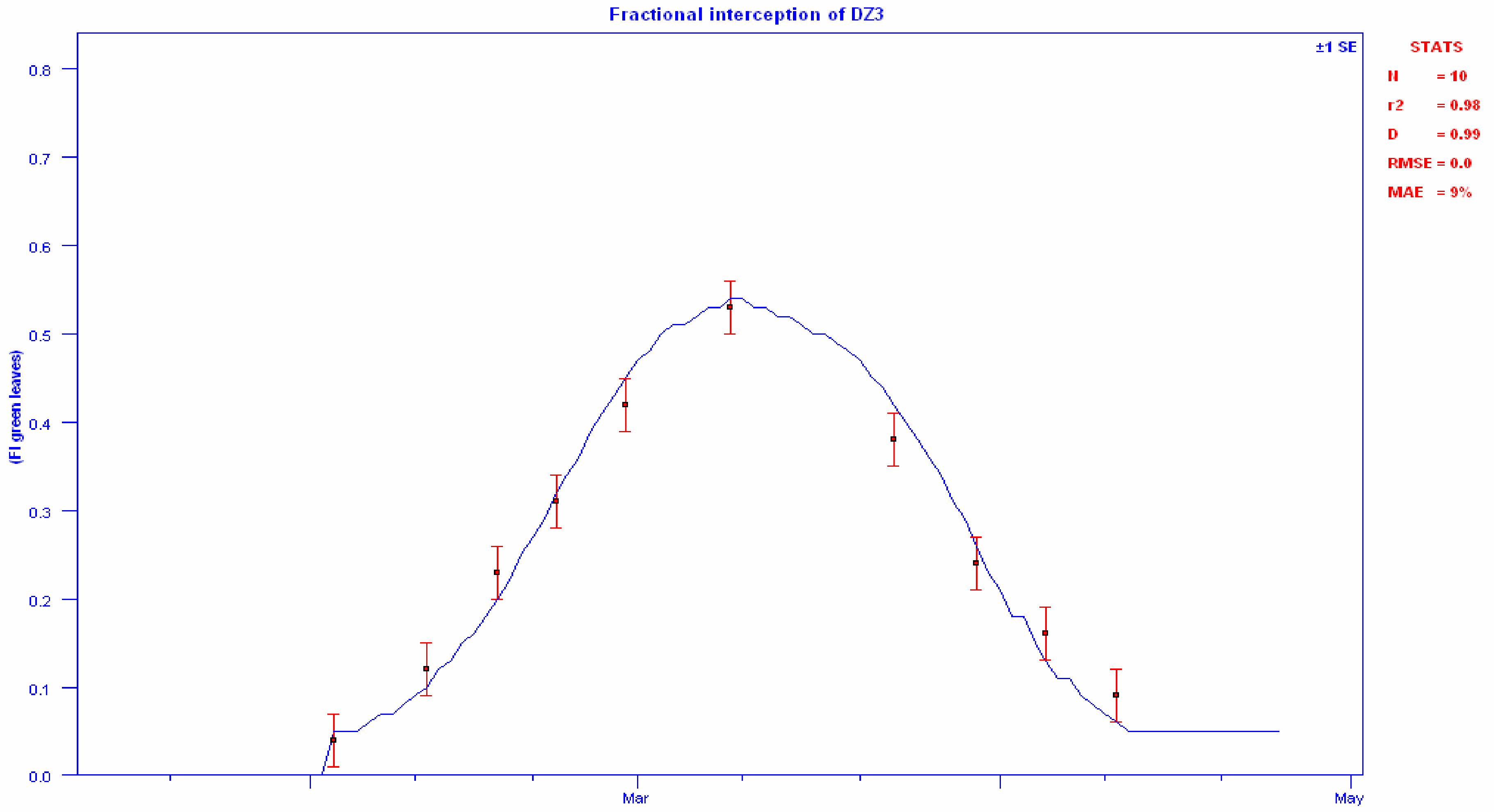

Figure 8.8b Simulated (lines) and measured values (points) of fractional interception (FI) (solar) for RCP treatment (DZ3)

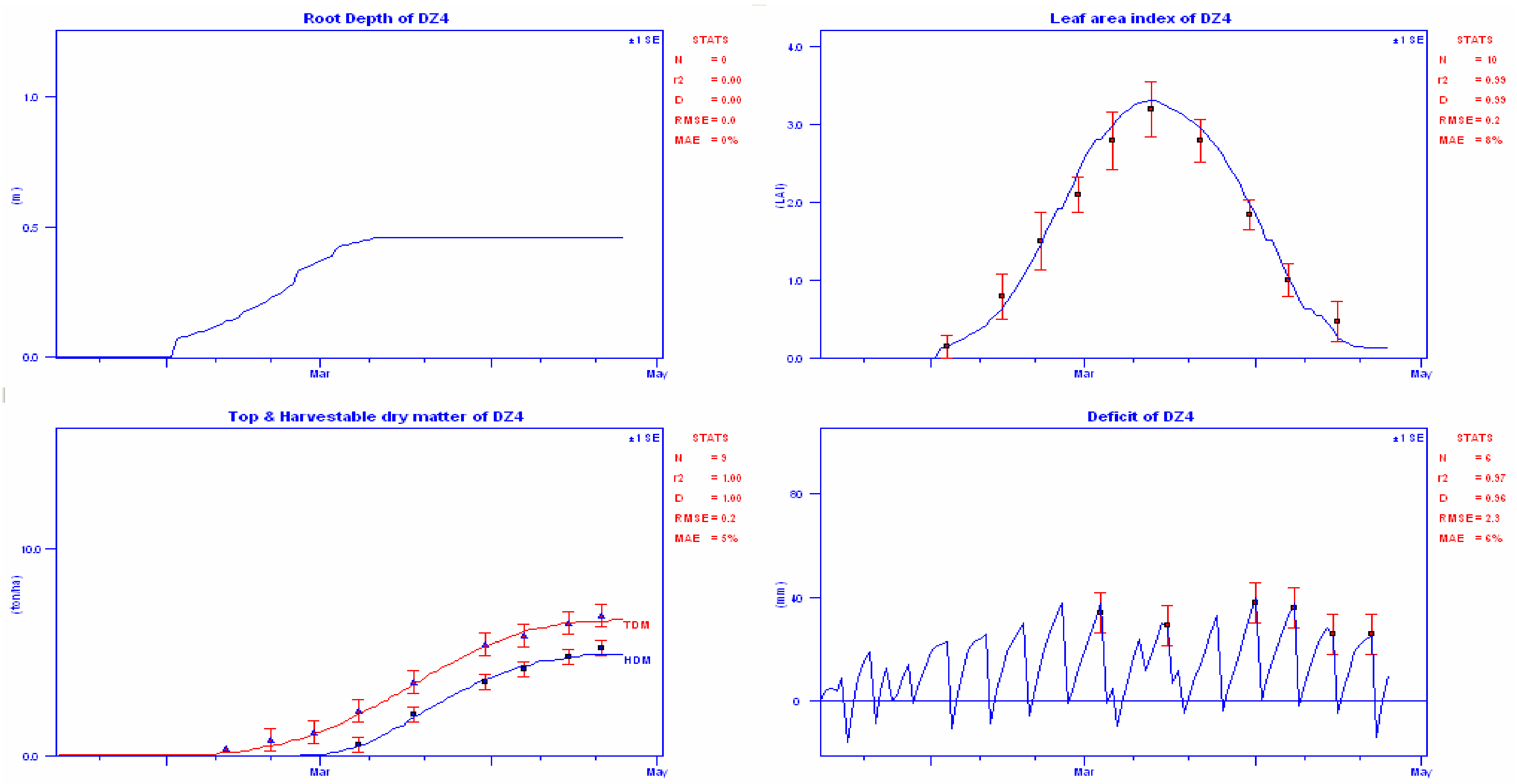

Figure 8.9a Simulated (lines) and measured values (points) of rooting depth (RD), leaf area index (LAI), total dry matter (TDM), harvestable dry matter (HDM) and soil water deficit to field capacity for NP treatment (DZ4)

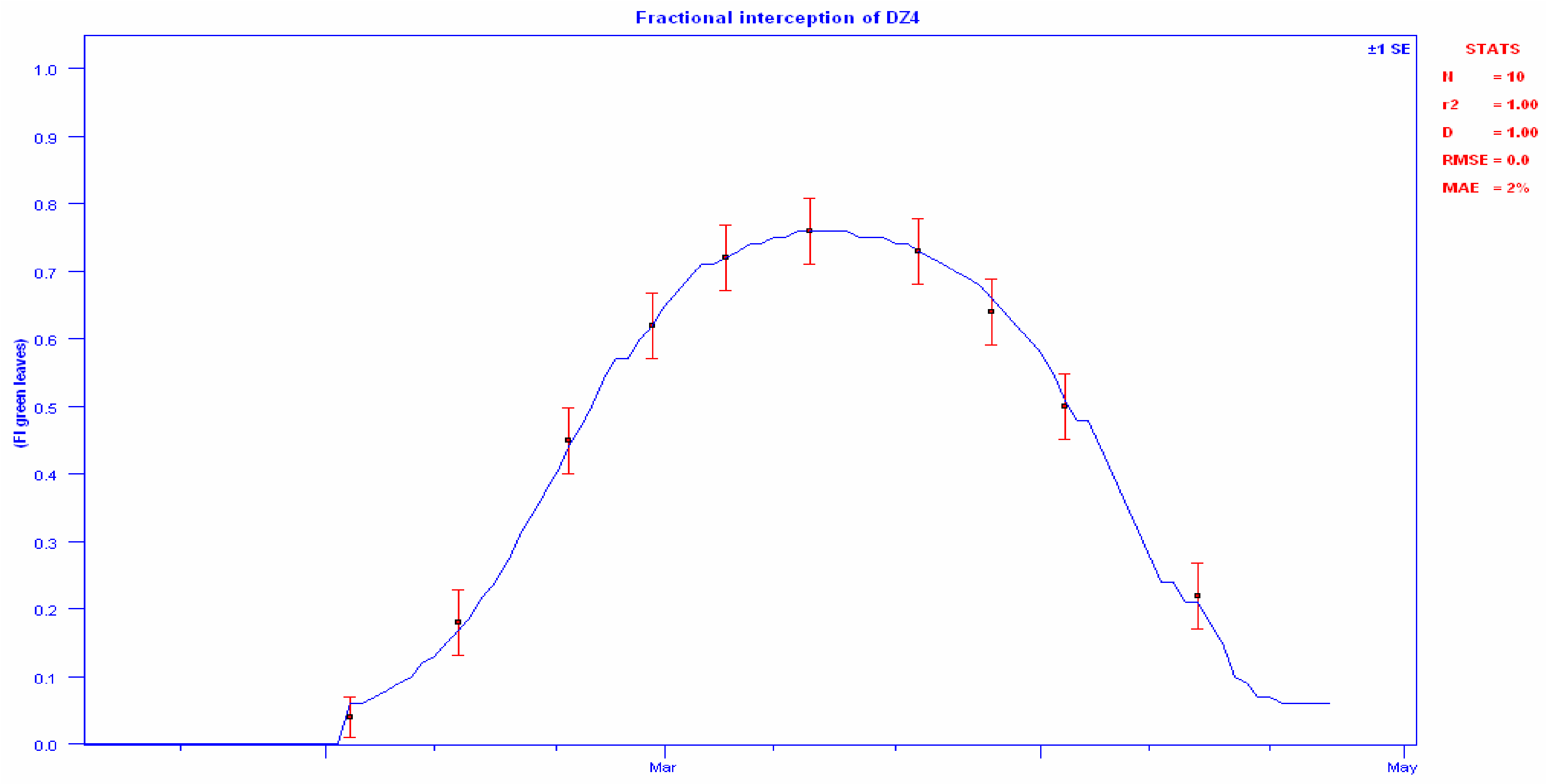

Figure 8.9b Simulated (lines) and measured values (points) of fractional interception (solar) for NP treatment (DZ4)

There was no independent data set developed prior to simulating these parameters. As a result the model was parameterised to the NP (DZ4) treatment, which was managed to refill the deficit soil water to field capacity according to the NP reading. The parameterised treatment (NP) was then tested against the others.

The SWB (DZ1) simulations for TDM, HDM, LAI and FI fitted the crop data measured from the experimental field well, and met the statistical criteria used (De Jager, 1994).

The farmer traditional scheduling (DZ2) revealed a severe water deficit throughout the growth period (Fig. 8.6a). The soil water balance graph (Fig. A6) of this treatment showed a high deficit that was more than the allowable depletion level, mainly during the second half of the growing season, except after the heavy rainfall of mid-March. The application of the irrigation amount traditionally used by farmers (50 mm every 10 days), could not re-fill the soil profile to field capacity, especially during the late growth stage. From the soil water deficit graph, it is clear that this treatment (with too long an irrigation interval) provided insufficient water. The low irrigation depth and too long frequency of this schedule resulted in poor crop growth and finally low tuber yield in the high evaporative demand conditions of the tropical climate.

On the other hand, the model simulations were slightly lower than the measured data points for TDM and HDM (Fig. 8.6a) around the crop maturity stage, even though the statistical parameters indicated a very high agreement. The soil water balance simulation fitted the measured data reasonably well, showing a severe water stress between March and April. Simulations for LAI and FI fitted very well, except that the graphs have a stepped shape which indicates water stress conditions during the growing period. Finally, the treatment (DZ2) resulted in higher soil water deficits and lower TDM and HDM. The crop growth analysis and yield (Chapter 4) indicate that this treatment resulted in significantly lower dry matter production and final tuber yield compared with DZ1 and DZ4, thus revealing that this particular schedule was under-irrigating the crop. It was also substantiated by both measured and simulated SWD that was increasingly building up after planting. Moreover, the stepped behaviour of LAI and FI simulation graphs are indicative of water stress during the growth period, mainly during the tuber bulking stage. It can thus be concluded that the farmer traditional irrigation scheduling was inferior compared to the other methods, which indicate the need for improvement or replacement by more efficient schedules.

DZ3 is the irrigation regime practiced by the nearby research centre and was also included in the comparison. The soil water balance graph for this treatment also reveals a high soil water deficit below the allowable depletion level (Fig. A7). From the graph, it is clear that the irrigation depth was not adequate to re-fill the soil profile to field capacity. Simulations for TDM, HDM, LAI and FI fitted the data sets collected from the field well, as the statistical parameters used for evaluation were all in a good accuracy range. On the other hand, the SWD predicted by the model did not show a good fit to the measured data sets and resulted in a low coefficient of determination (r^2 = 0.76), according to the recommendation of De Jager (1994). This, once again, could be attributed to less water actually applied to the field than intended, due to the low irrigation efficiency under furrow condition. The simulated graph for FI is slightly irregular, that once again indicates that this particular treatment was exposed to water stress.

The treatment used as a control for this experiment was DZ4, which was re-filled to field capacity every seven days as measured by the neutron water meter. For this treatment, the soil water balance summary graph indicated that the model simulation fitted to the experimental data points well and resulted in high statistical correlation (De Jager, 1994). Similarly, the model has shown high degree of accuracy simulations for TDM, HDM, LAI and FI. Generally, this treatment (DZ4) and the SWB irrigation calendar (DZ1) exhibited a good simulation fit when compared to the individual measured data sets, while the two traditional scheduling methods resulted in water stress conditions during crop growth. On the other hand, it has been widely observed that the actual water amount reaching the soil was less than the intended amount.

8.4.3 Onion water stress experiment

The influence of water stress on growth and yield of onions (cv. Texas Grano) induced at different growth stages were examined during the 2004 winter season at the Hatfield experimental farm. The crop growth parameters developed from the field experiment are displayed in Table 8.4, while the SWB model simulation in comparison to the measured data are given in Figures 8.9a to 8.12b. The accuracy of simulations are evaluated according to the De Jager (1994) criteria, which are detailed in Table 8.1. Crop-specific growth parameters were not developed prior to this experiment to test the model simulation against it. Hence, the model is parameterised using the NNN (control) treatment, which was non-stressed and the remaining treatment simulations were tested against that.

Table 8.4 Summary of crop growth parameters determined for onions (cv. Texas Grano) water stressed at different growth stages during the field experiment in 2004 at the Hatfield experimental farm, and obtained from literature, to calibrate the SWB model

Crop growth parameters	Values	Units	Source
Canopy radiation extinction coefficient (Kc)	0.40	-	Data
Corrected dry matter-water ratio (DWR)	7.8	Pa	Data
Radiation conversion efficiency (RUE)	0.0015	kg MJ^{-1}	Data
Base temperature (Tb)	7.2	^oC	Annandale *et al.*, (1999)
Temperature for optimum crop growth	20	^oC	Annandale *et al.*, (1999)
Cut-off temperature	29.4	^oC	Annandale *et al.*, (1999)
Thermal time: emergence	0	day degree	Seedling used for planting
Thermal time: reproductive phase	480	day degree	Data
Thermal time: maturity	1860	day degree	Data
Thermal time: transition	280	day degree	Data
Thermal time: leaf senescence	1860	day degree	Data
Maximum crop height	0.60	m	Data
Maximum root depth	0.80	m	Annandale *et al.*, (1999)
Fraction of total dry matter translocated to bulb	0.50	-	Annandale *et al.*, (1999)
Canopy storage	1.00	mm	Annandale *et al.*, (1999)
Leaf water potential at maximum transpiration	-1500	kPa	Annandale *et al.*, (1999)
Maximum transpiration	9.00	mm d^{-1}	Annandale *et al.*, (1999)
Specific leaf area	9	m^2 kg^{-1}	Data
Leaf-stem partition parameter	1.12	m^2 kg^{-1}	Data
Total dry matter at emergence	0.007	m^2 kg^{-1}	Annandale *et al.*, (1999)
Fraction of total dry matter partitioned to roots	0.20	-	Annandale *et al.*, (1999)
Root growth rate	7.00	m^2 $kg^{-0.5}$	Annandale *et al.*, (1999)
Stress index	0.95	-	Annandale *et al.*, (1999)

The crop growth parameters were determined for onions (cv. Texas Grano) from the crop growth data measured during the field experiment. Some parameters that were not determined from the experimental field data were obtained from similar results obtained earlier by Annandale *et al.* (1999) and are indicated in Table 8.4. Some parameters determined for this cultivar are slightly lower than parameters determined for other onion cultivars. For instance, the Kc (solar) determined for Texas Grano was 0.40, compared to 0.75 for cv. Mercedes (Annandale *et al.,* 1999). On the other hand, DWR was 7.5 Pa for this cultivar, compared to 7.0 Pa for cv. Mercedes (Annandale *et al.,* 1999). Similarly, the thermal time for transition period was 280 d^{o}C for this cultivar as compared to 10 d^{o}C for cv. Mercedes (Annandale *et al.,* 2005). The thermal time determined for maturity and leaf senescence were also higher for this cultivar as compared to the values reported by Annandale *et al.* (1999) for cv. Mercedes. Other parameters determined in this experiment are comparable to the values reported by Annandale *et al.* (2000).

The crop growth data measured from the experimental field and the SWB simulations were run for all the treatments. Treatments included non-stressed (NNN), or stressed from 35 to 70 DATP (SNN), from 70 to 110 (NSN) DATP and from 110 to 145 (NNS) DATP.

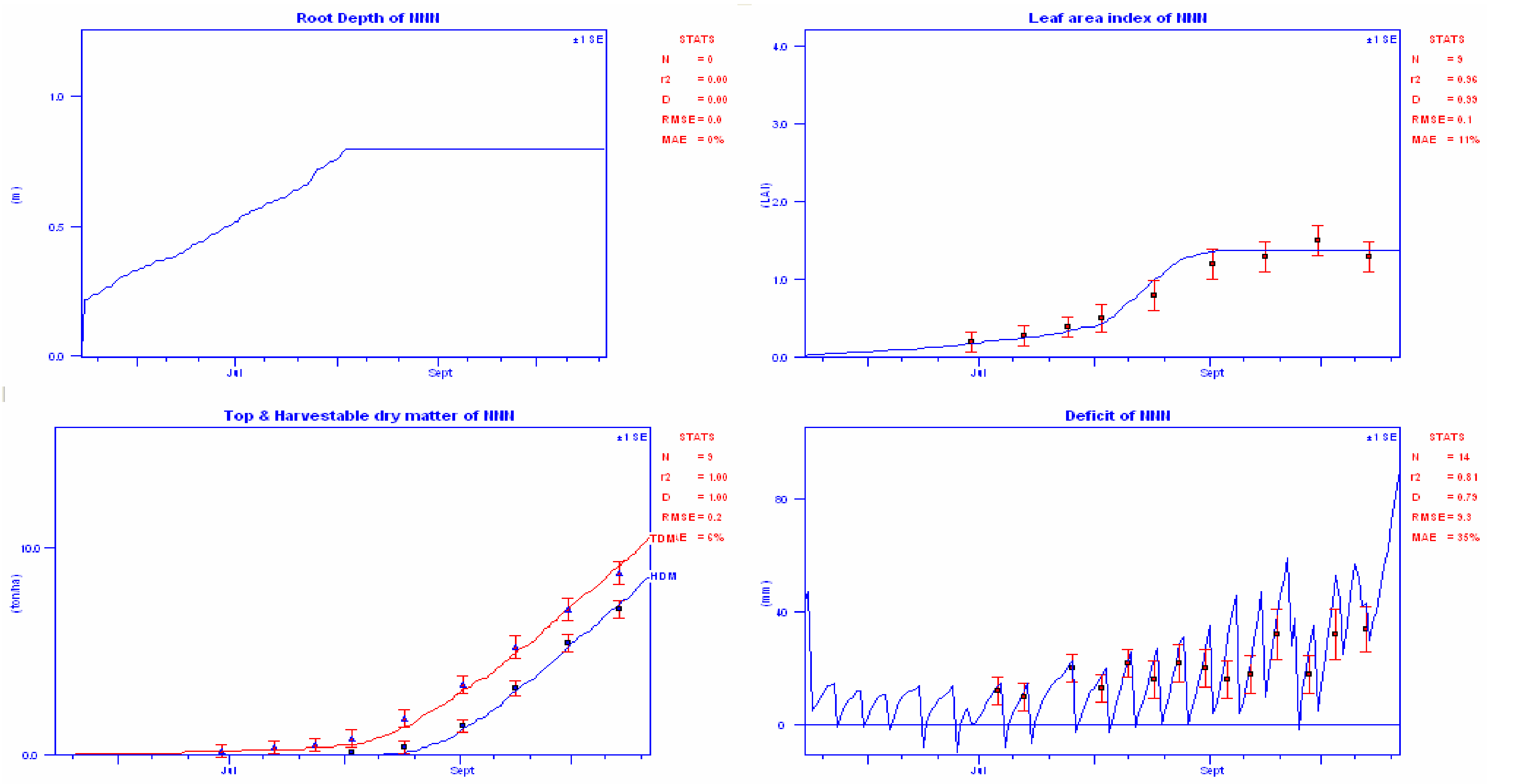

Figure 8.10a Simulated (lines) and measured values (points) of rooting depth (RD), leaf area index (LAI), total dry matter (TDM), harvestable dry matter (HDM) and soil water deficit to field capacity for NNN treatment of onions.

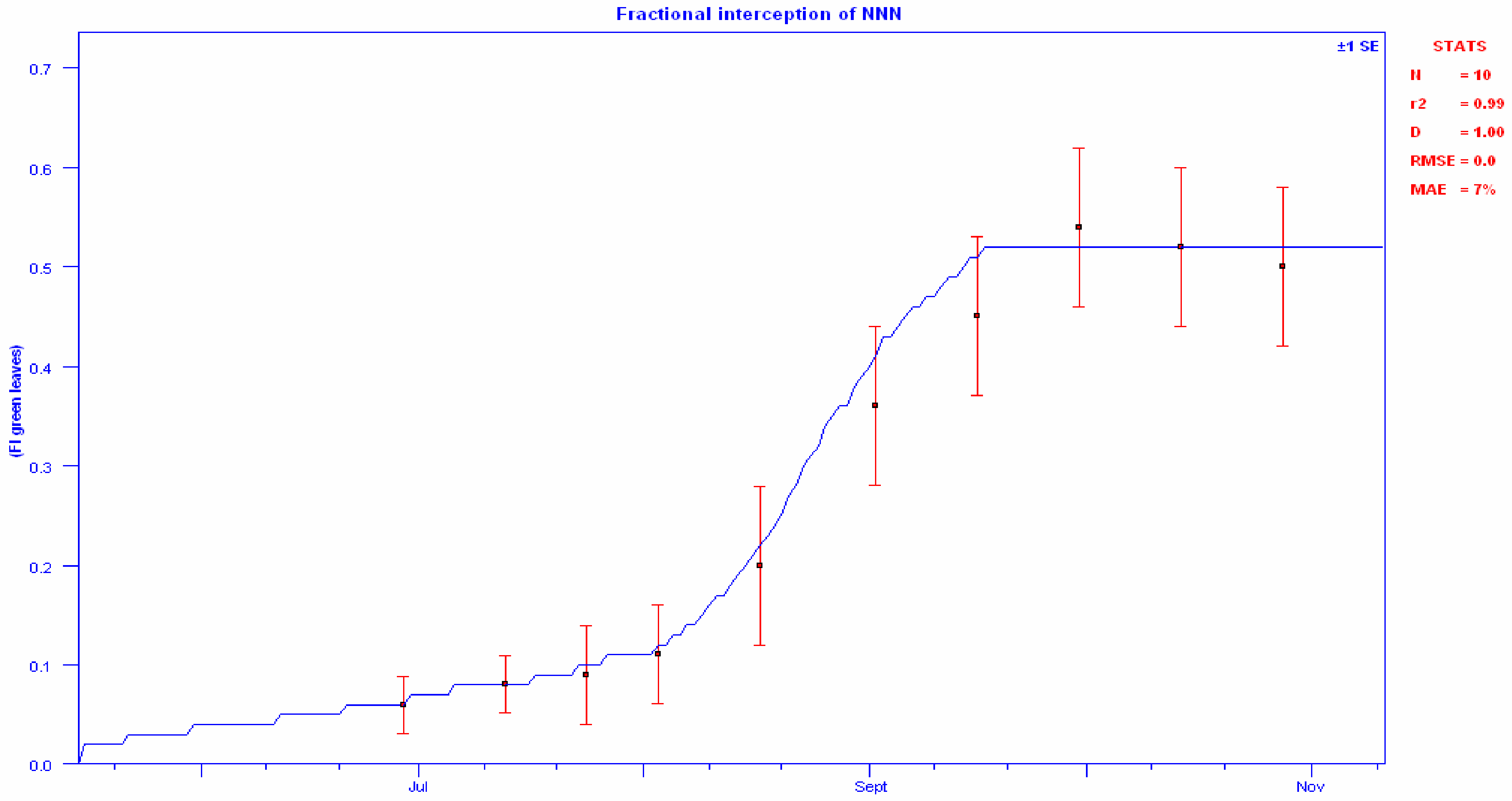

Figure 8.10b Simulated (lines) and measured values (points) of fractional interception (FI) (solar) for NNN treatment

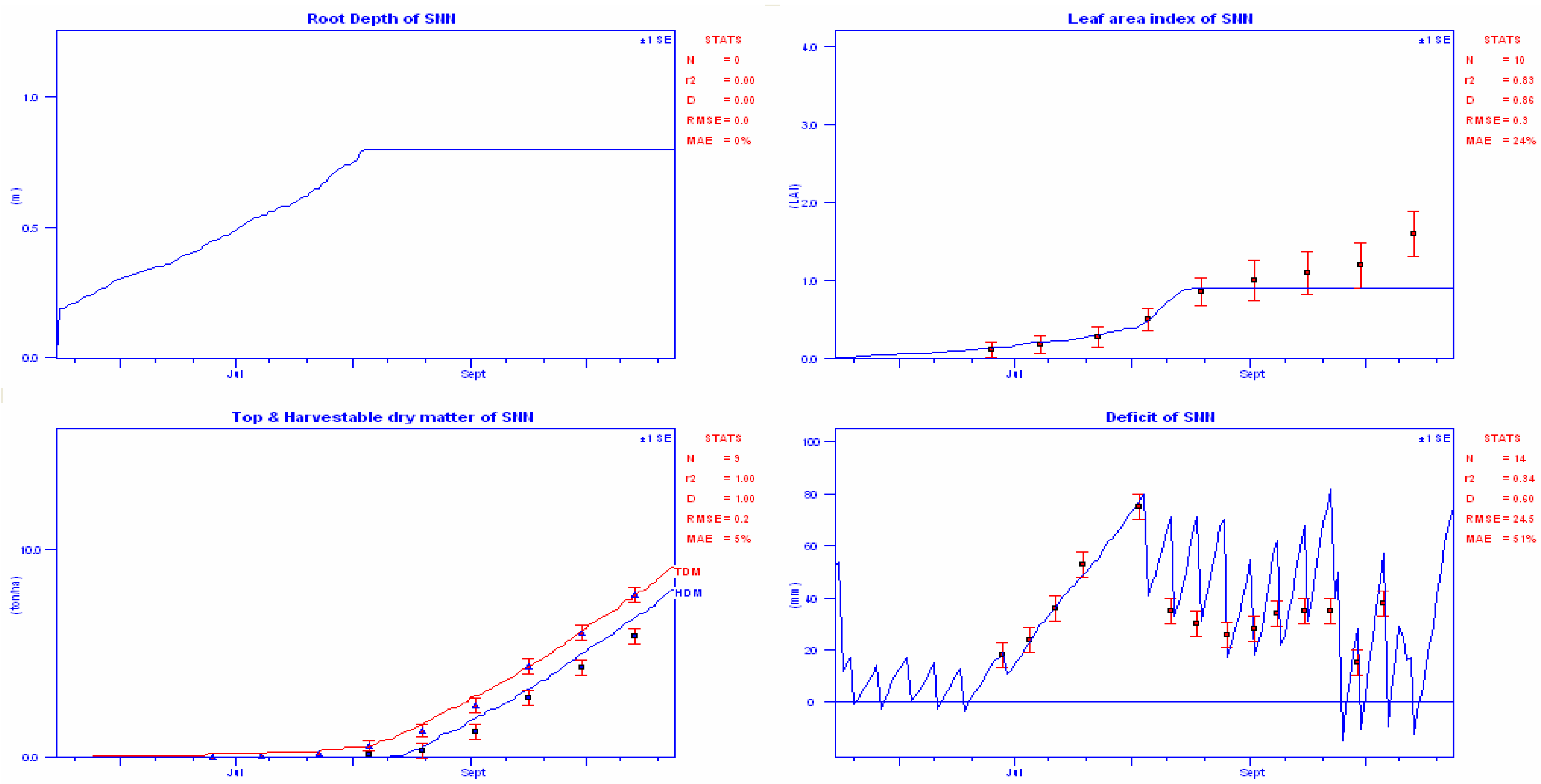

Figure 8.11a Simulated (lines) and measured values (points) of rooting depth (RD), leaf area index (LAI), total dry matter (TDM), harvestable dry matter (HDM) and soil water deficit to field capacity for SNN treatment of onions.

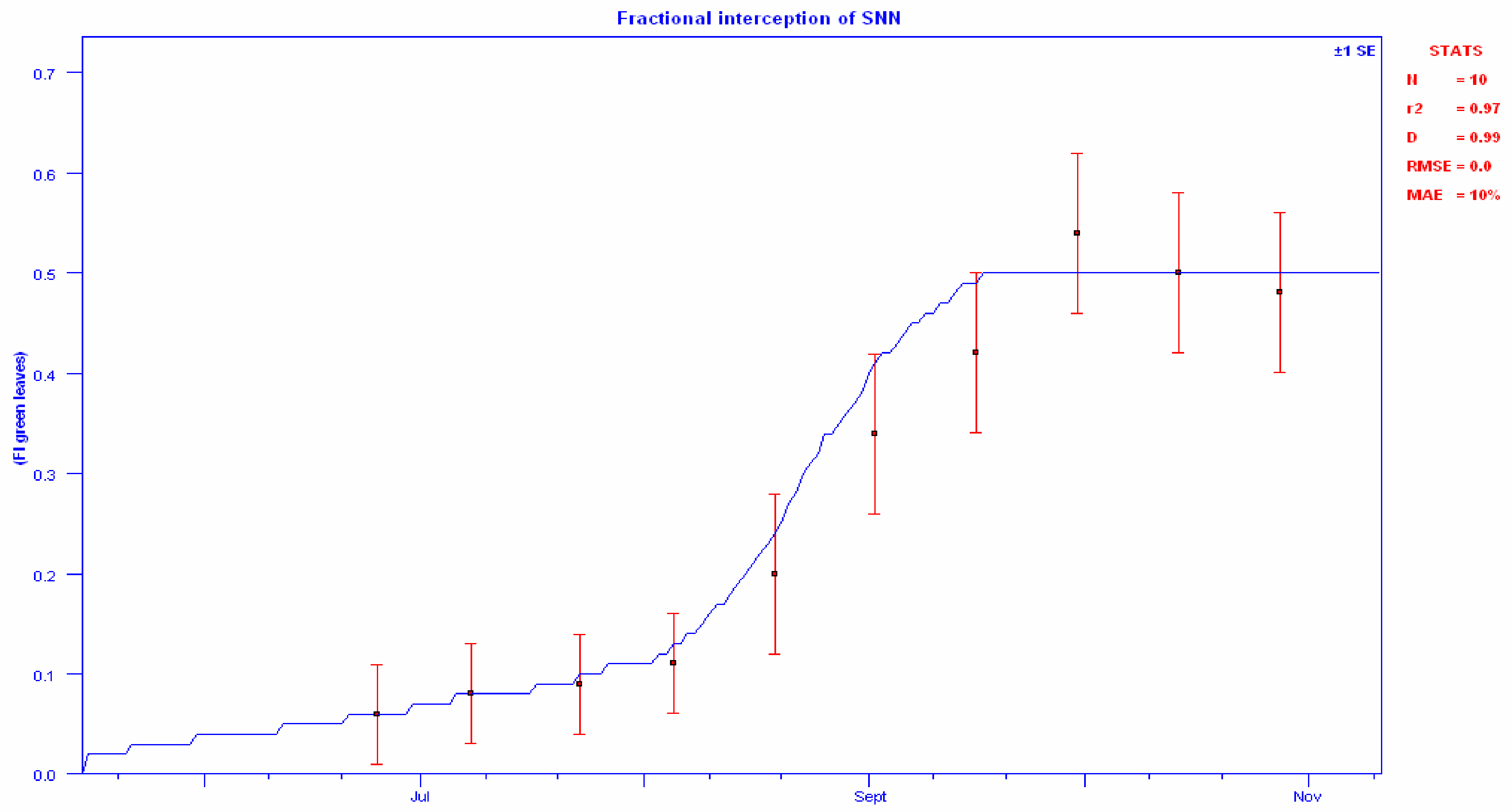

Figure 8.11b Simulated (lines) and measured values (points) of fractional interception (FI) (solar) for SNN treatment

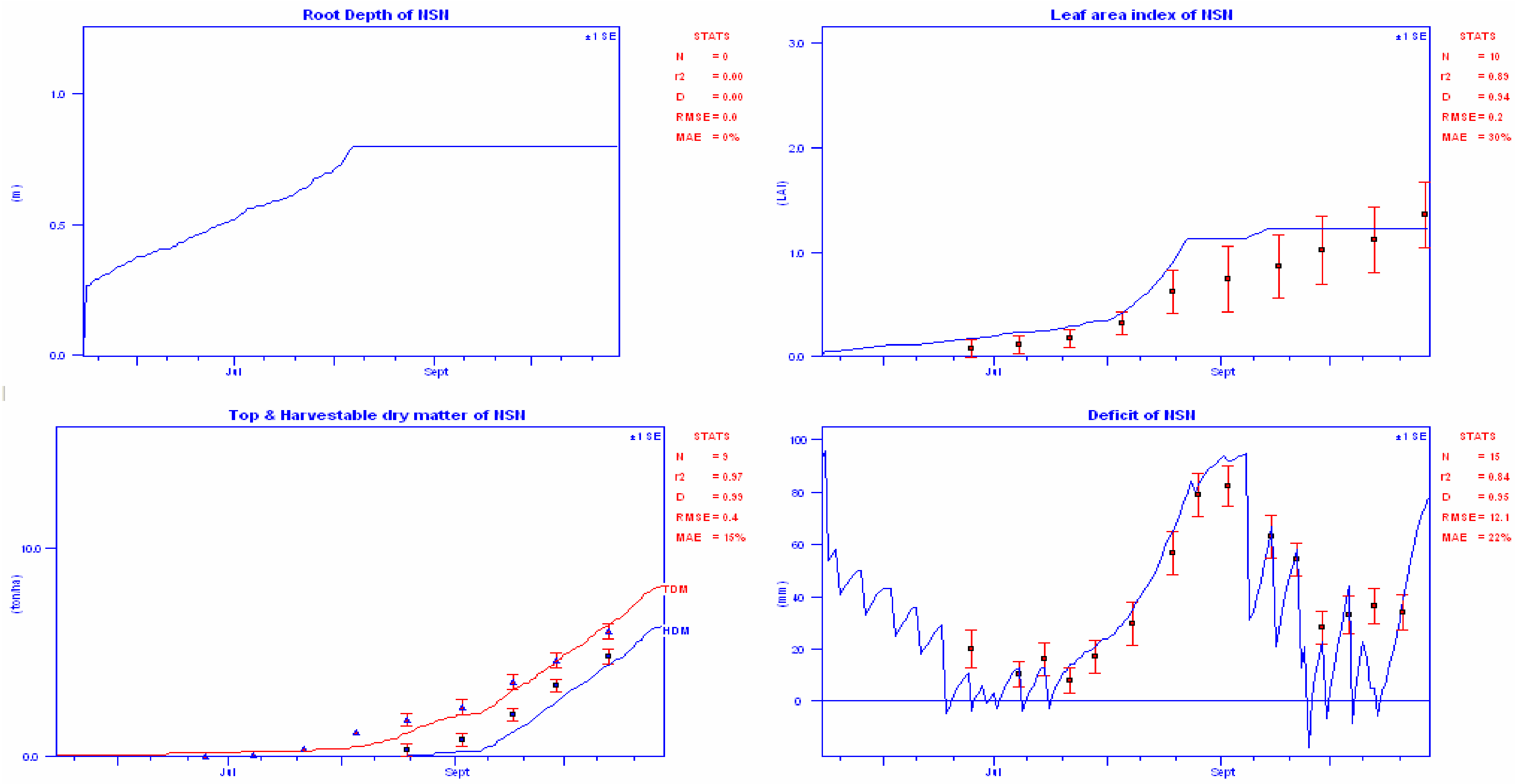

Figure 8.12a Simulated (lines) and measured values (points) of rooting depth (RD), leaf area index (LAI), total dry matter (TDM), harvestable dry matter (HDM) and soil water deficit to field capacity for NSN treatment

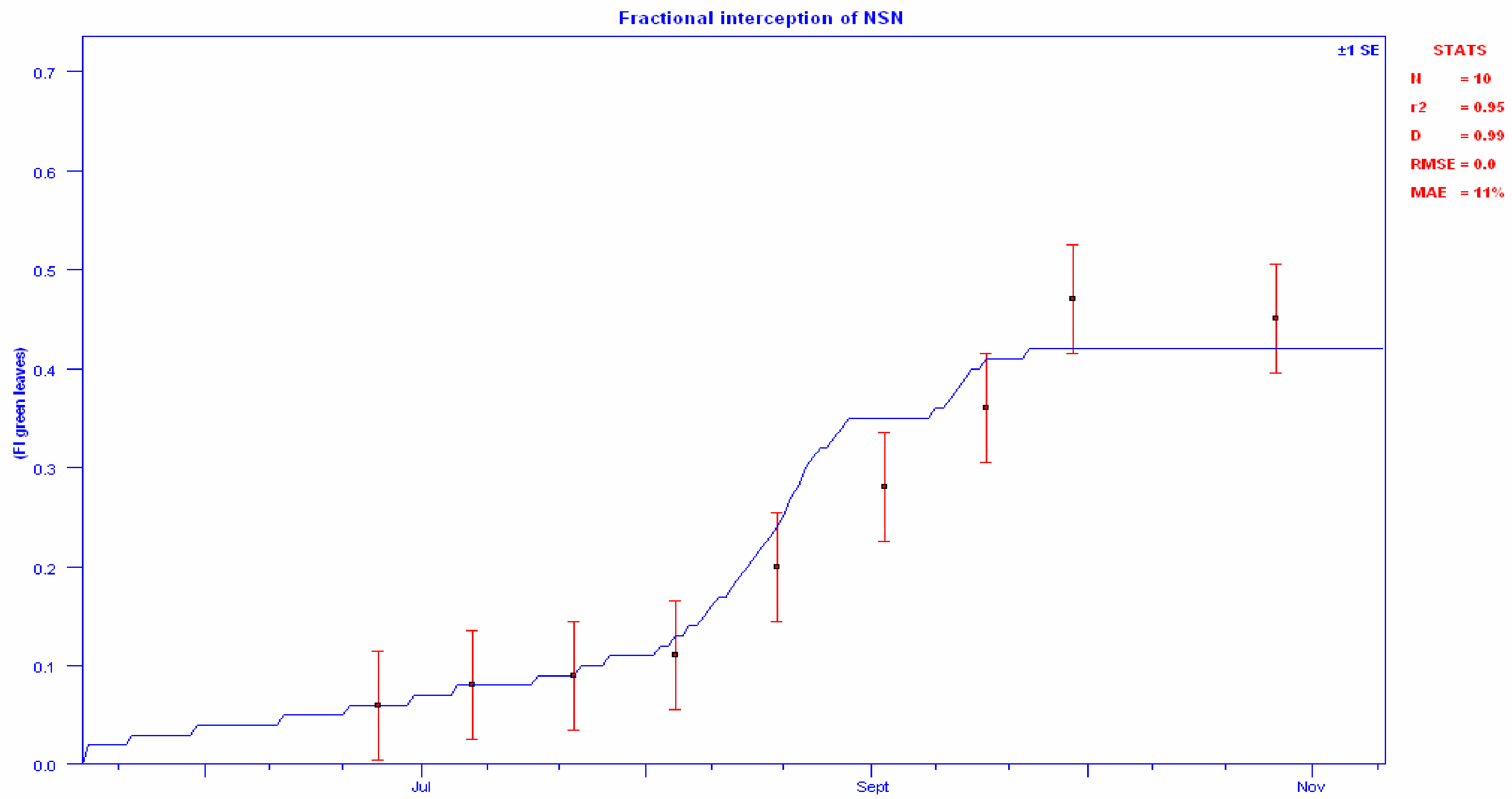

Figure 8.12b Simulated (lines) and measured values (points) of fractional interception (FI) (solar) for NSN treatment

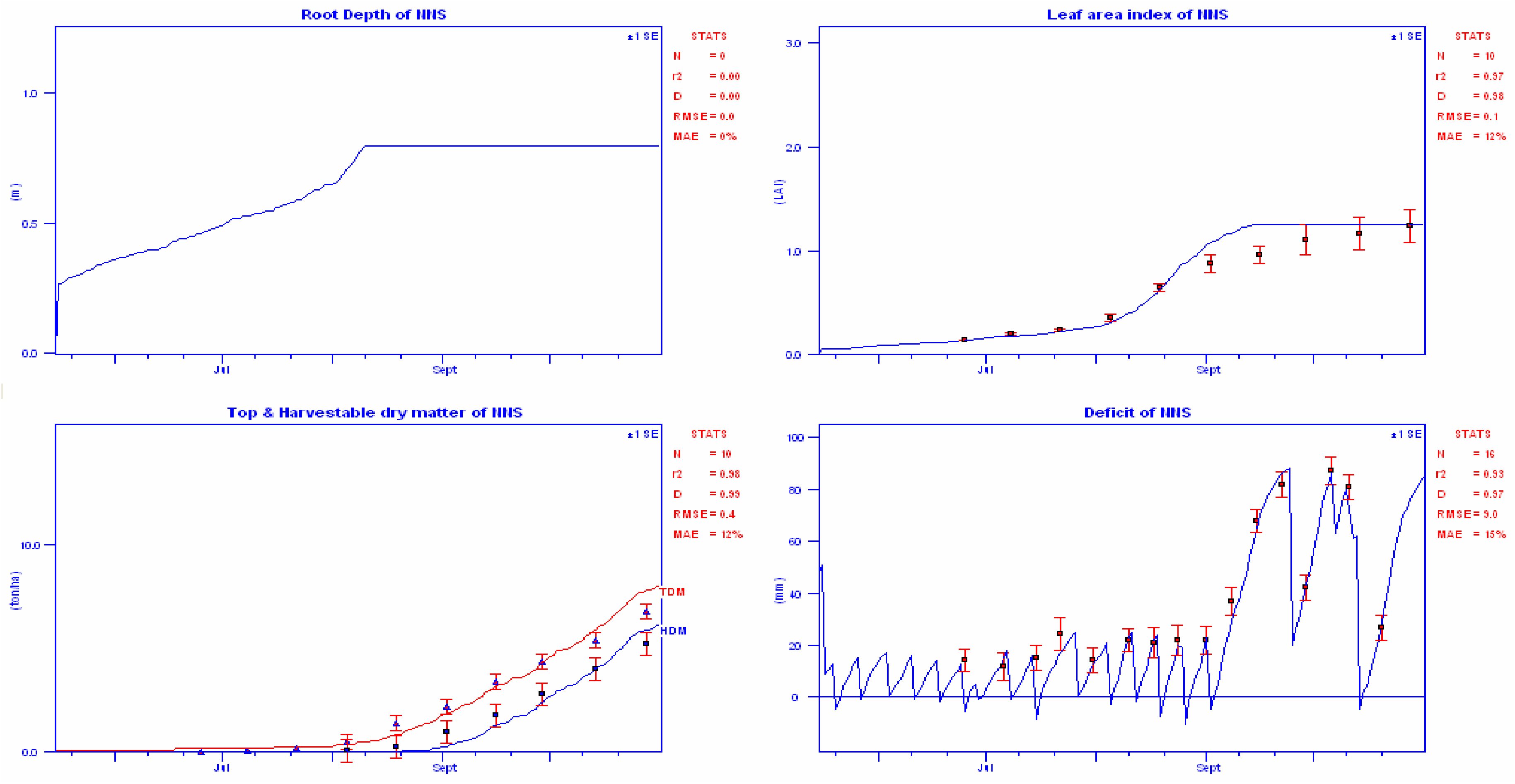

Figure 8.13a Simulated (lines) and measured values (points) of rooting depth (RD), leaf area index (LAI), total dry matter (TDM), harvestable dry matter (HDM) and soil water deficit to field capacity for NNS treatment

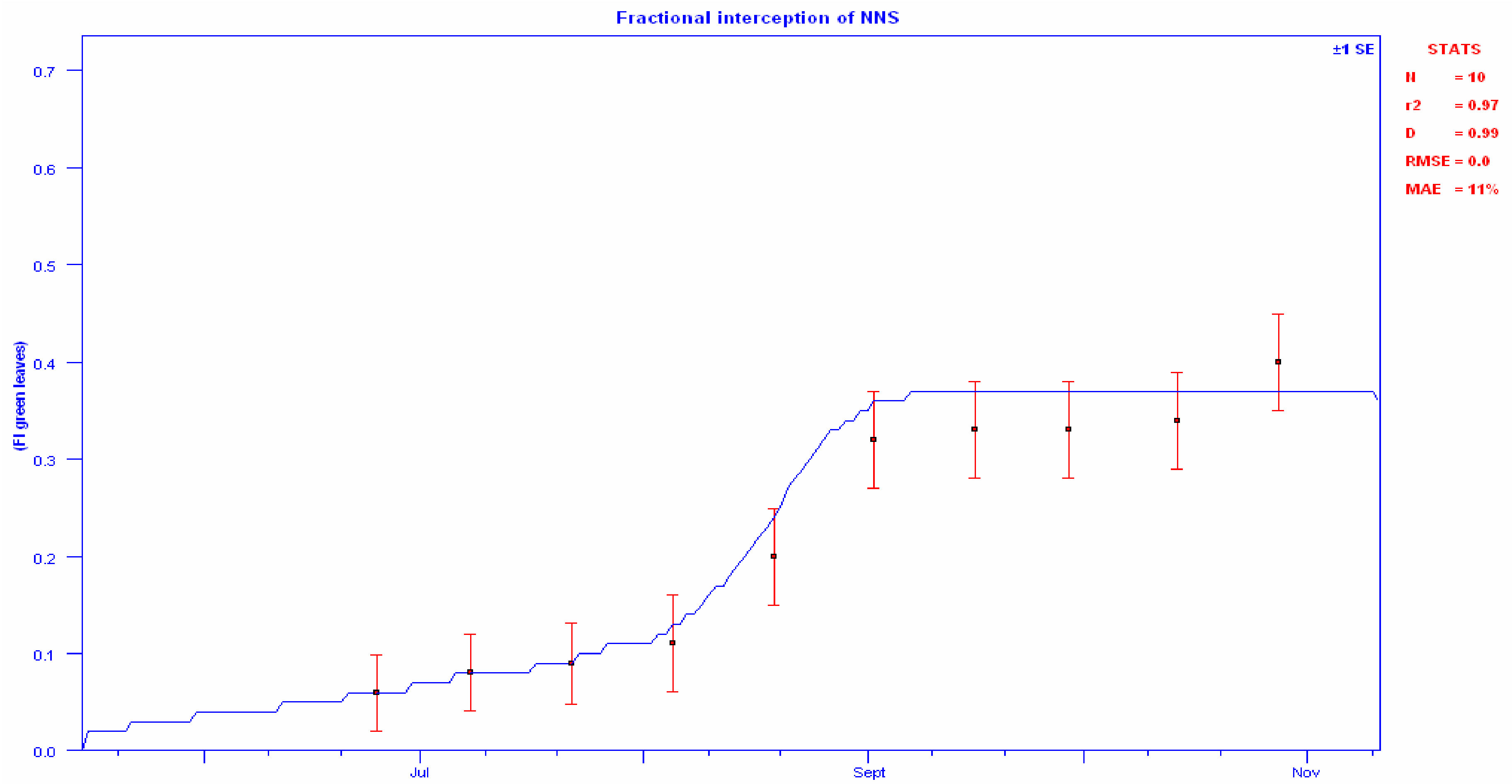

Figure 8.13b Simulated (lines) and measured values (points) of fractional interception (FI) (solar) for NNS treatment

NNN represents the non-stressed treatment, where the soil water deficit was measured every week and refilled to field capacity. The SWB model simulations revealed that it fitted the data collected from the experimental field very well for most parameters, except for LAI, which was slightly lower even though the evaluation criteria (De Jager, 1994) showed high accuracy levels. The summary of SWD simulation, however, shows slight over-simulations for some measured data points and slight under-estimations for others. In addition, the model slightly over-estimated FI during the mid-growth period in September (Fig. 8.9b).

SNN is the treatment for which water stress was induced between 35 and 70 DATP, whereafter the water deficit was refilled to field capacity on a weekly basis. During the stress period, there were a few days of high rain and these helped the crop to tolerate the stress. From the soil water balance simulation, the deficit remained higher than the allowable water depletion level during the stress period. The model simulations for TDM, HDM and FI fitted the experimental data points well, while the model under-estimated LAI during the late part of the growth period, from mid August to maturity (Fig. 8.10a). The treatment was stressed when it was in the early growth stage, which might have helped the crop to develop a deeper root system to cover larger soil volume for soil water and plant nutrient uptake. Other possible reasons why the model under-estimated the LAI could be the cool climate of the season when the stress was imposed. This treatment was stressed for 35 days from mid-June onwards, which was the coolest time of the year, with low daily ET. In addition, there were a few rain showers during the stress period that further helped the crop to withstand the stress effect. The growth and yield of this treatment also confirmed that stress during this period did not impose significant growth and bulb yield reduction as compared to the non-stressed treatment.

The NSN and NNS treatments both revealed the highest SWD during their stress periods (Fig. 8.11a & 8.12a). The measured and simulated SWDs revealed a high degree of agreement, although the statistical output parameters indicated some predictions were outside, or marginally inside the reliability criteria. The simulated SWDs during the stress periods of the NSN and NNS treatments were slightly higher than those measured at the time of the experiment. During the early growth stages, simulations for TDM and HDM were slightly lower than the data points for NSN, while these were slightly higher than measured data points for NNS, mainly during the crop maturity stage. The model over-estimated the LAI simulation for both NSN and NNS during crop maturity, even though the statistical parameters were within the required limits. The overall model simulations were in good agreement with the measured data for most parameters considered, according to the statistical accuracy used for evaluation (De Jager, 1998).

In general, high SWD is detected for NSN and NNS during water stress periods for both the measured and simulated data sets (Fig. A12). Onion water stress between 70 and 145 DATP, the most critical growth period, significantly reduced growth and final yield (data shown in Chapter 7). This is also confirmed by the dry matter and fresh bulb yield data (Chapter 7), which indicated that water stress during this growth stage resulted in a significant yield reduction.

8.5 Conclusions

A database for crop growth parameters was generated for potato and onion crops from three experiments, namely: evaluation of growth performance and dry matter partitioning of four potato cultivars under sprinkler irrigation; potato irrigation regime experiment under tropical climatic conditions using furrow irrigation; and determination of the critical growth stages of onions, grown under drip irrigation.

Detailed weather, soil and irrigation data from field trials, carried out at their respective sites, were used in the SWB model and simulations were run in order to calibrate the crop growth and soil water balance units of the model. Crop growth measurements from the field trial and SWB model simulations were evaluated according to the statistical accuracy parameters recommended by De Jager (1994).

Crop growth parameters were determined for the four potato cultivars, Frodo, Pentland Dell, Darius and Shepody and results were found to be comparable to the previous results reported by Steyn (1997) and Annandale *et al.* (1999). Summaries of soil water balance for the evaluation of these cultivars indicated that cultivars with longer growing seasons were water stressed during the peak tuber bulking stage. Simulations for TDM, HDM, LAI and FI, fitted with a high degree of accuracy the measured data sets. Simulations for the SWD also indicated a good fit and the statistical accuracies obtained were inside, or marginally outside, the recommended standards.

Crop growth parameters were generated for the potato cultivar Awash, grown under tropical climate using furrow irrigation. The parameters generated were generally comparable to the values reported by Steyn (1997) and Annandale *et al*. (1999), with slight variations around thermal time accumulation. Calibration of the crop growth and soil water balance units of the model were carried out using weather, soil and irrigation data from the field experiment. Simulations of the crop growth, TDM, HDM, LAI and FI fitted the measured data points very well, according to the reliability criteria used. Nevertheless, simulations for LAI and FI appeared to be irregular (stepped) for the treatment irrigated according to the traditional farmer schedule, showing typical behaviour of crop grown under water stress conditions. Even though the SWD simulations appeared to fit measured data well, some statistical parameters were slightly outside the set criteria. This performance could be attributed to the fact that actual water reaching the crop was probably less than the amount applied, due to low application efficiency of furrow irrigation. The irrigation efficiency of that experiment was estimated to be about 60%, due to water wastage during water distribution within the farm and on the plot.

A similar database for crop growth parameters were generated for onions (cv. Texas Grano) which was water stressed at different growth stages. Data measured from the Hatfield experimental farm was used in the SWB model and simulations were run in order to calibrate the crop growth and soil water balance units of the model. The crop specific growth parameters determined for this cultivar were generally comparable to the parameters reported by other researchers (Annandale *et al.,* 1999). The result depicted that SWB simulations for crop growth were inside, while some for SWD marginally outside the reliability criteria imposed (De Jager (1994).

In general, the SWB simulation performances against crop growth data sets were observed to be good. All simulations of TDM, HDM, LAI and FI were in agreement with measured values, with mostly a high degree of statistical accuracy (De Jager, 1994). Under furrow irrigation, even though the SWD simulations were found to fit well, some of the statistical measures were often low compared to the recommended values. This could be due to the low application efficiency of water under furrow irrigation that indicated a typical characteristic of water stress. Hence, in this activity crop parameters were for successfully generated five specific potato cultivars and one onion cultivar, for inclusion in the SWB database, in order to facilitate irrigation scheduling. Thus, it can be concluded that a powerful tool, the SWB model, has been parameterised, which will facilitate the generation of irrigation management guidelines for various irrigation districts in Ethiopia.

CHAPTER 9

PREDICTING CROP WATER REQUIREMENTS FOR POTATOES AND ONIONS GROWN AT DIFFERENT LOCATIONS IN ETHIOPIA USING THE SOIL WATER BALANCE MODEL

9.1 Introduction

Irrigation scheduling is an activity of optimum water supply for crop productivity, by managing soil water close to the field capacity or within a limited allowable depletion level (Jones, 2004; Shock, 2004). Broner (2005) explains that irrigation scheduling is the decision of when and how much water to apply to a field. The same author further explains that the purpose of irrigation scheduling is to maximise irrigation efficiency by applying the exact amount of water needed to replenish the soil water to the desired level and save water and energy. Before irrigation scheduling is attempted, however, it is essential to determine crop water requirements, or the depth of water needed to meet the water loss through evapotranspiration (ETcrop) (Doorenbos & Pruitt, 1992). The same authors explain that the effects of climate, crop characteristics and local agricultural conditions have to be taken into consideration when calculating ETcrop. The effect of climate on crop water requirements is given by the ETo, which refers to "the rate of evapotranspiration from an extensive surface of 8-15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water" (Doorenbos & Pruitt, 1992). Hence, ETo is calculated using either the Blaney-Criddle, Radiation, Penman or Pan Evaporation method (mm day^{-1}) from mean daily climatic data (Doorenbos & Pruitt, 1992). The choice of method is primarily based on the type of climatic data available and on the accuracy required in determining water needs (Doorenbos & Pruitt, 1992). The same authors further explain that, for areas where measured data on temperature, humidity, wind and sunshine duration or radiation are available, the Penman-Monteith method provides the most satisfactory results. The effect of crop characteristics on crop water requirements is expressed by the crop coefficient (Kc) which reveals the relationship between ETo and ETcrop:

$$ETcrop = kc*ETo \qquad (9.1)$$

The value of kc varies with the crop type, its growth stage, growing season and prevailing weather conditions.

The computation of crop water requirement is significantly influenced by variations within a location and the agricultural practice specific to a given area. These include climate variations over time, altitude, field size, soil water content, advection, soil constraints, variations in cultivation and method of irrigation. Under such circumstances, however, field data specific to each location need to be compiled before crop water requirement is determined.

During early stages of irrigation scheduling, climate was solely used as a source of input data. As irrigation science continued developing, however, the soil water monitoring and plant stress sensing also became an important option of irrigation scheduling (Jones, 2004). Currently, the development of models for irrigation scheduling is one of the latest breakthroughs in irrigation science. The SWB model which combines a detailed description of the soil-plant-atmosphere continuum, making use of weather, soil and crop management data (Annandale *et al.*, 1999), is one example of such a model.

The irrigation regimes in the Ethiopian traditional schemes were not monitored for the past several years. A survey conducted to identify the amount and interval of water application on a pilot irrigation scheme, Godino, identified two irrigation regimes (Chapter 3). Due to the low crop yields obtained from these two irrigation practices, it was necessary to evaluate these practices in comparison with two other scientific scheduling methods using potato crop, one of the popular crops produced under irrigation, next to onions. The results showed that both traditional irrigation regimes were found to be significantly inferior to the scientific methods, SWB and re-filling SWD to field capacity as monitored by the neutron water meter (NP) (Chapter 4). This emphasized the need for improvement of the existing farmer practices, or replacement by one of the scientific methods that performed better during the comparison. Since the NP method requires basic data processing skills and would have unaffordably high initial costs to farmers, the SWB model, which is simple to use, was suggested to replace the traditional practice at the Godino scheme. Therefore, this chapter is dedicated to guide the extension agents and researchers on how to develop an irrigation schedule from average minimum and maximum temperatures for the two major crops produced at Godino. The work has covered about five locations where these two crops are mainly grown under traditional irrigation. Hence, the objective of this work was to develop. Irrigation calendars, using the SWB model, for five different locations for potato and onion crops. This help should extension agents to replicate the process for other crop species, planting dates and agro-ecological zones.

9.1.1 Potato water requirements

Potatoes (*Solanum tuberosum* L.) are water stress-sensitive crops with a shallow active root zone compared to other field crops (Tomasiewicz *et al*., 2003; CSIDC, 2005).

Water is one of the most detrimental limiting factors to potato growth, yield and quality, which is why farmers frequently apply water in amounts that exceed actual ET losses (David *et al.,* 1983; Trebejo & Midmore, 1990). The complex physiological response to water stress makes this crop sensitive to even moderate plant water deficits (Epstein & Grant, 1973; Bradley & Stark, 2005). Evaporation of water from within the leaves serves to cool the leaves, resulting in a plant canopy temperature below air temperature under well-watered conditions (Trebejo & Midmore, 1990). Stomata closure under deficit water conditions reduces further water losses and is an indication of reduced transpiration to cool the leaves, which results in a reduction of carbon dioxide diffusion into the leaves. Less carbon dioxide diffusion into the leaf restricts the duction of the photosynthetic products, starch and sugar, and their translocation from the leaf to tubers (David *et al*., 1983).

Water stress during active growth of the potato also restricts the expansion of leaves, stems and tubers. This is directly related to the reduction of internal water pressure in plant cells, which is mainly responsible for the expansion of plant organs (Tourneux *et al.,* 2003). Reduced root expansion of potatoes result in limited uptake of plant nutrients, which further limits the growth and development. Once growth is restricted, other forms of physical and quality deteriorations may result, mostly the disruption of the normal tuber expansion rate, which progressively results in tuber malformation such as pointed ends, dumbbells, bottlenecks and knobs (Tourneux *et al.,* 2003;

Bradley & Stark, 2005). Growth cracks are also associated with wide fluctuations in soil water availability and corresponding changes in tuber turgidity, as well as the volume of internal tissues (Bradley & Stark, 2005).

The effect of water stress on potatoes is manifested differently at various growth stages. One of the morphological manifestations of water stress on potatoes is a reduction in leaf size, which results in a reduction in the amount of intercepted radiation and leads to a decrease in tuber dry mass accumulation (Jefferies *et al.*, 1993). Reduced leaf growth and accelerated leaf senescence are common responses to water deficit and could be an adaptation of plants to water deficit (Lahlou *et al.*, 2003). Generally, drought-stressed crops exhibit slower and less canopy expansion and earlier senescence than irrigated crops (Jefferies *et al.*, 1993).

During tuber bulking, soil water shortage affects total tuber yield more than quality. A large photosynthetically active leaf surface area is necessary for extended periods to maintain high tuber bulking rates. Maintenance of this large active leaf surface area requires continued development of new leaves to replace older ones and others that are less efficient. Hence, water stress hastens leaf senescence and interrupts new leaf formation, resulting in an unrecoverable loss of tuber bulking (Juzl & Stefl, 2002).

Not only the soil water shortage, but also excess water can significantly affect the yield and quality of potato. Bradley and Stark (2005) indicate that excess soil water, due to intensive rainfall and/or too frequent irrigation during any growth stage, leaches nitrate nitrogen below the plant root zone, potentially resulting in deficiency of nitrogen in the plant, reduced efficiency of fertiliser use and an increased hazard to groundwater. Prolonged saturation of the soil profile can cause root damage, due to the lack of the oxygen required for normal respiration. Excess soil water, especially during planting, must be avoided as it promotes seed piece decay and delays emergence because of decreased soil temperature. In general, over-irrigated potatoes during vegetative growth and tuber initiation are liable to quality deteriorations and early-die problems. Overall, excess irrigation of potatoes can lead to poor storage conditions and finally result in low dry matter percentage (Juzl & Stefl, 2002; Bradley & Stark, 2005).

9.1.2 Water requirements of onions

Onions (*Allium cepa* L.) are also a shallow rooted crop and sensitive to water stress conditions. Water stress in onions before bulbing results in stunting the plant, which causes it to form small-sized bulbs that are below market standards (Singh & Alderfer, 1966). The same authors also explain that extended water stress after bulbing induces plant re-growth and other quality deteriorations see (Chapter 7).

9.1.3 Irrigation management

Monitoring soil water in the crop root zone would allow better management of water application to meet crop requirements. However, direct measurement of soil water in the field is tedious on large-scale production levels. Other approaches that are most accurate require an understanding of the soil-plant-atmosphere continuum as mechanistically as possible (Annandale *et al.,* 1999). Hence, crop water use is best described by considering the supply of water from the soil root system and the demand from the canopy atmosphere (Singh *et al.*, 1990). The atmospheric demand is best estimated by the Penman-Monteith reference crop evapotranspiration equation

(Smith *et al.*, 1996), together with a mechanistic crop growth model, such as SWB, which uses soil water and grows a realistic canopy and root system.

9.1.4 The Wetting Front Detectors (WFD)

The SWB model can generate Irrigation Calendars based on the long-term average daily minimum and maximum temperatures. Under some circumstances, however, the actual environment could change and may not be represented by average long-term temperatures. Such events are quite prevalent in Ethiopia, and occur for about once in five years to up to three times in ten years. Under such unique circumstances, however, a simple tool could be used to correct the developed irrigation calendar. It is known as the Wetting Front Detector (WFD) (Stirzaker, 2003).

The WFD is a device that could be used in conjunction with SWB Irrigation Calendars for irrigation scheduling. While the SWB model develops an irrigation schedule from long-term daily mean minimum and maximum temperatures, the WFD, installed at shallow and deep layers, indicates the vertical movement of applied water for correcting the next watering depth. The detector, a funnel-shaped device, is buried open end up in the soil and works on the principle of convergence (Stirzaker, 2003). As the wetting front moves into the wide opening of the funnel, the flow lines are converged, so that the water content increases towards the base of the funnel (Stirzaker, 2003). The free water produced at the base of the funnel is collected in a chamber and raises a float through a PVC pipe leading to the ejection of the float, indicating the reach of the front. The device can be reset by extracting the water inside the chamber, using a syringe via an extraction tube and, if necessary, it can be used for nitrate or salinity appraisal (Stirzaker, 2003).

9.2 Materials and methods

Irrigation Calendars were developed using the SWB model for five different locations of Ethiopia, namely Bako, Debre-Zeit, Melkassa, Zeway and Shashemene. Long-term average daily maximum and minimum temperatures of the relevant locations were used as input data for the schedule. In addition, data on soil water characteristics, initial soil water content, bulk density, crop species and planting date, irrigation system and frequency, and management options were also used for developing the calendars. For this particular work, a furrow system was considered at a fixed interval of seven days and the planting date determined as 1 January. Prior to developing the calendars, crop growth parameters were determined for potatoes and onions (Chapter 8) – the major irrigated crops for the considered locations – so that the SWB model could soil water balance for these crops.

The irrigation interval during the scheduling period is assumed to be every seven days and any rainfall during this interval would be recorded and deducted from the recommended application depth. The efficiency of rainfall is very high compared to irrigation, especially for the furrow system. Hence, rainfall amounts of more than 60% of the predicted depth could be regarded as one irrigation, which means that the next irrigation could be skipped. Under conditions where WFDs are used to correct the irrigation amount according to the response, increasing or decreasing (response factor) of 20% of the predicted water amount would be considered.

9.3 Results and discussion

Tables 9.1 and 9.2 show the Irrigation Calendar developed by the SWB model to replace the traditional farmer practice, which was found to be significantly inferior in performance compared to the more scientific schedules. Irrigation Calendars developed for the same location of similar climate, soil characteristics and management varied with crop variation (Tables 9.1 & 9.2 and Tables A1-A8). Potato crops required less water per application compared to onion crops under the same climate and soil conditions. The number of irrigations required up to maturity is also lower for potatoes than for onions grown under similar conditions. Researchers (Scherer *et al*., 1996) agree that the water requirement of different crops planted at the same location, under identical climate and soil conditions could be attributed to the growth stage and the variation in the rooting system. Different crops reach their particular growth stage and full cover at different times after planting. As the crop coefficient (kc) varies between crops and at different growth stages, both the ETo and kc result in varying water requirements of different crops grown under the same conditions. On the other hand, plants can extract only the soil water that is in contact with their roots. Plants with a high root density per unit soil volume may be able to absorb all available soil water (Al-Kaisi & Broner, 2005). The same authors explain that other plants with a low root density may not be able to obtain much water from an equal volume of the same soil. Hence, this explains why the irrigation requirements of potatoes and onions grown at the same location of identical climate varied for each irrigation interval and across the growth stages.

The irrigation calendar developed for the same crop grown at different locations also varied due to the major change in climatic conditions (Tables 9.1 & A1). Even though the minimum and maximum temperatures were used as an input for the climate data, the SWB model estimates the remaining factors for different altitude and latitude changes (Annandale *et al*., 1999). Scherer *et al.* (1996) further explain that the same crop's water requirement variation for different locations is very much dependent on climatic variables, that is, air temperature, amount of sunlight, humidity and wind speed. Hence, the variation observed among locations is mainly due to the variation in ET of the same crop, caused by the climate changes. This, once again, confirms that the irrigation schedule predicted for potatoes and onions, which differ from one location to another, was due to the climatic differences detected by the SWB scheduler. Therefore, the varied irrigation requirements observed between potatoes and onions across locations are mainly attributed to the variation in crop characteristics and the prevailing climatic conditions.

Table 9.1 Irrigation calendar output as recommended by SWB scheduler, using potato crop for Debre-Zeit climate and soil conditions

IRRIGATION CALENDAR

Farmer:
Field: Debre-Zeit
Soil type: Sandy clay loam
Irrigation system: Furrow
Management options: Fixed, every seven days
Irrigation frequency option: Interval (Days)

Crop: Potato (Awash)
Planting date: 01/01/2006
Wetting Front Detectors:
Shallow: 4
Deep: 4
Response factor (%): 20

Date and Day	* Irrigation requirement (IR), depending on number of shallow and deep Wetting Front Detector (WFD) responses			Rain since previous irrigation (mm)	Recommended irrigation amount = IR-Rain
	0-2 Shallow and 0-2 Deep	3-4 Shallow and 0-2 Deep	3-4 Shallow and 3-4 Deep		
	Irrigation requirement (mm)				
5 Jan 2006		119			
12 Jan 2006	33	26	18		
19 Jan 2006	33	26	18		
26 Jan 2006	33	26	18		
2 Feb 2006	37	29	20		
9 Feb 2006	40	31	21		
16 Feb 2006	48	37	25		
23 Feb 2006	57	44	30		
1 Mar 2006	64	50	35		
8 Mar 2006	68	53	37		
15 Mar 2006	70	54	37		
22 Mar 2006	70	54	37		
29 Mar 2006	70	54	37		
5 Apr 2006	70	54	37		
12 Apr 2006	66	51	35		
19 Apr 2006	57	44	30		
25 Apr 2006	40	31	21		

*** Notes**

- Just before irrigation, check Wetting Front Detector response (to the previous irrigation) and use to correct the irrigation requirement.
- Encircle the applicable irrigation requirement, based on WFD response.
- If 0-2 shallow 3-4 deep WFDs have responded, check your shallow WFDs for problems.
- Record rain and empty gauge just before irrigation.
- Subtract rainfall from irrigation requirement to obtain the irrigation amount.
- If IR-rain<0, then skip the irrigation, i.e. irrigation amount = 0.

Table 9.2 Irrigation calendar output as recommended by SWB scheduler, using onion crop for Debre-Zeit climate and soil conditions

IRRIGATION CALENDAR

Farmer:
Field: Debre-Zeit
Soil type: Sandy clay loam
Irrigation system: Furrow
Management options: Fixed, every seven days
Irrigation frequency option: Interval (Days)

Crop: Onion (Texas Grano)
Planting date: 01/01/2006
Wetting Front Detectors:
Shallow: 4
Deep: 4
Response factor (%): 20

Date and Day	* Irrigation requirement (IR), depending on number of shallow and deep Wetting Front Detector (WFD) responses			Rain since previous irrigation (mm)	Recommended irrigation amount = IR-Rain
	0-2 Shallow and 0-2 Deep	3-4 Shallow and 0-2 Deep	3-4 Shallow and 3-4 Deep		
	Irrigation requirement (mm)				
1 Jan 2006		60			
8 Jan 2006	45	35	24		
15 Jan 2006	45	35	24		
22 Jan 2006	48	37	25		
29 Jan 2006	48	37	25		
5 Feb 2006	51	40	28		
12 Feb 2006	55	43	30		
19 Feb 2006	61	47	32		
26 Feb 2006	68	53	37		
4 Mar 2006	75	58	40		
11 Mar 2006	77	60	42		
18 Mar 2006	77	60	42		
25 Mar 2006	77	60	42		
1 Apr 2006	77	60	42		
8 Apr 2006	77	60	42		
15 Apr 2006	77	60	42		
22 Apr 2006	77	60	42		
29 Apr 2006	77	60	42		
6 May 2006	77	60	42		
13 May 2006	77	60	42		
20 May 2006	77	60	42		
27 May 2006	77	60	42		
3 Jun 2006	75	58	40		
5 Jun 2006	23	18	12		

*** Notes**

- Just before irrigation, check Wetting Front Detector response (to the previous irrigation) and use to correct the irrigation requirement.
- Encircle the applicable irrigation requirement, based on WFD response.
- If 0-2 shallow 3-4 deep WFDs have responded, check your shallow WFDs for problems.
- Record rain and empty gauge just before irrigation.
- Subtract rainfall from irrigation requirement to obtain the irrigation amount.
- If IR-rain<0, then skip the irrigation, i.e. irrigation amount = 0.

The Wetting Front Detectors could be used in conjunction with the Irrigation Calendar developed by SWB (Tables 9.1 & 9.2 and Tables A1-A8). The WFDs installed in the representative area of the field indicate the physical movement of water in the profile, revealing a shortage of water and the adequacy or excess water applied during the previous application. The SWB model sometimes predicts less or an excess water amount where the supplied long term climate, soil and plant data are not accurate enough. The data on soil characteristics always remain less accurate, due to the high heterogeneity of soils within the small unit area in the farm. Hence, the use of WFDs avoids crop water stress induced due to under-prediction. It also prevents excess water application under conditions of over-prediction, which further avoids leaching of nutrients below the crop root zone that could pollute the groundwater.

The SWB scheduling output is very flexible and could be varied according to the preference of the individual user. A fixed irrigation interval of seven days was used in developing these irrigation calendars. However, users can also accept the intervals predicted by the model, when fixed amount or depletion % are selected.

Generally, the SWB model predicts an appropriate irrigation depth and interval once the farmer has determined the allowable depletion level for each growth development stage. Similarly, different planting dates, irrigation systems, soil types, management options, crop species and cultivars could be accommodated successfully. The SWB model can be applied under full-irrigation conditions, as well as for supplementary irrigation. It also indicates the critical crop growth stage and level of yield reduction, so that the farmer could select the growth stage at which irrigation is most important under limited irrigation conditions.

9.4 Conclusions

The experiment conducted on the comparison of four irrigation-scheduling methods revealed that the two traditional irrigation scheduling practised by the community irrigation schemes were significantly inferior to the two scientific methods (Chapter 4). From this result, it was suggested that the poor scheduling methods be improved or replaced by more efficient and affordable irrigation water management techniques. Hence, the SWB scheduler, that delivered a good performance and was affordable for farmers, was recommended to replace the traditional practice.

Therefore, the SWB model was used to generate irrigation calendars for five agro-ecological areas of Ethiopia for potatoes and onions. The SWB model predicted the irrigation calendar for five locations, namely Debre-Zeit, Melkassa, Bako, Zeway and Shashemene. The results revealed that the predicted irrigation amount and intervals varied between the two crops planted under the same conditions, because of different rooting systems for water uptake and length of growing conditions. On the other hand, the developed irrigation calendar also differed from one location to another, because of varying climate conditions: air temperature, amount of solar radiation, humidity and wind speed. The irrigation prediction, using the SWB model, should be performed separately for various climate conditions, planting dates, plant species, cultivars and soil types.

CHAPTER 10

GENERAL CONCLUSIONS AND RECOMMENDATIONS

10.1 General conclusions

Traditional irrigation has been practised since time immemorial in Ethiopia. The country is known to have adequate land and water resources for irrigation, but only a small area of land is being used at present. The current irrigation practice in the country are still not advanced and no one even knows how much water to apply and how often farmers are applying it. A survey on one of the traditional irrigation schemes, Godino, was conducted with the objective of monitoring the amount and interval of water application on traditional irrigation schemes, and identifying major constraints on the irrigated agriculture. The results revealed that irrigation depth varied from less than 30 mm to more than 60 mm, regardless of crop species and growth stage. Similarly, the watering interval on the scheme varied from 7-14 days without considering the crop species and maturity group. Furthermore, the crop productivity level under traditional water management was found to be very low for irrigated agriculture. This has led to the conclusion that most crops under this practice could be water-stressed due to low water depth per application and too long irrigation intervals, resulting from limited irrigation water supplied by the scheme.

The lack of strong commitment in the social structures responsible for water distribution was evident, as water was allocated on the basis of friendship or priority given to committee members. Even though the social aspect of this study is recommended to be dealt with by the appropriate professionals, was deemed necessary to evaluate the performance of traditional water management practices in comparison with more scientific irrigation management techniques.

Most farmers rated irrigation intervals, application depth and when to stop water application as their major constraints under the traditional irrigation practice. These constraints observed under traditional irrigation management need to be improved through research or replaced by effective and efficient water management techniques for better crop productivity.

Two average irrigation regimes observed under traditional farmer water management were evaluated in comparison with two other scientific irrigation water management techniques. The farmers' average irrigation regime included an application of 50 mm of water every 10 days (FTP) or an application of 60 mm of water every 6 days (RCP), which were evaluated in comparison with the SWB model scheduling and the soil water replenishment to field capacity depending on neutron water meter (NP) measurements. The overall result from the experiment deduced that both farmers' traditional irrigation regimes were significantly inferior to the scientific irrigation water management methods. Both the SWB and NP irrigation schedules were found to maintain good crop growth and final yield as compared to FTP and RCP under the furrow water management method, using a potato crop. The various growth components that contributed to yield and the fresh potato tuber yield confirmed that both traditional irrigation regimes proved to be inadequate in meeting crop water requirements as compared to the SWB and NP methods. The total water application revealed that the SWB scheduling resulted in the highest water use as compared to FTP, which was the lowest and resulted in relatively high water use efficiency.

Climate influences the growth and yield potential of crops across and within species. Potatoes are one of the crops that are affected by micro-climate and management conditions. Potato cultivars vary in the efficient use of climatic resources, such as solar radiation and temperature, as well as water, where some researchers agree that the growth of a potato crop is about proportional to its solar radiation absorption (Spitters, 1987; Van Delden, 2001). The total biomass production and accumulation of potato cultivars are dependent on the absorbed PAR, which is to a large extent related to the plant canopy cover (Vos & Groenwold, 1989). Not only the growth and yield, but also the processing quality of potatoes is greatly influenced by the genetic makeup of cultivars, the climate and biological property of soils (Brown, 1993). In view of this, four potato cultivars, namely Frodo, Pentland Dell, Darius and Shepody, were evaluated for their growth performance and processing quality under the same climate and management system. In addition, crop parameters were developed for these cultivars to model with SWB and generate irrigation calendars. The results revealed that potato cultivars differed in their growth performance and processing quality, even though they were grown under the same climate and management system. The dry matter partitioning into various plant parts (leaf, stem and tuber) strictly followed the growth rate of cultivars. The early maturing cultivar, Shepody, partitioned dry matter to different plant parts much earlier than the slow-maturing Frodo cultivar. The overall experiment revealed that high yield is not governed by the rate of crop growth and replacement of new leaves, but the LAD. Cultivars with a relatively longer growth period would have adequate time to collect a high proportion of solar radiation that is proportional to dry matter accumulation. Hence, Frodo, which is a slow-growing cultivar, produced a significantly higher dry matter and final tuber yield as opposed to the early cultivar, Shepody, which was the lowest yielder.

As far as tuber-processing quality is concerned, most cultivars were within the acceptable range of the USDA quality standards (USDA, 1997). However, for some particular qualities such as SG, Shepody was found to be unacceptably low. Generally, cultivars with better growth performance and yield also possessed superior tuber-processing quality, according to the USDA quality evaluation standard. Hence, the newly developed potato cultivar in South Africa, Frodo, was significantly superior in terms of growth performance, yield and tuber-processing quality.

The critical growth stage of crops to water stress is one of the important factors in irrigation management, especially under conditions of irrigation water constraint. Similarly, onions are one of the crops that responds differently to water stress at different growth stages. The result from the onion experiment exposed to water stress at different growth stages revealed that stress at any growth stage affected the growth and yield of onion bulbs to a different extent. Withholding water early after transplanting imposed little effect on onion growth and yield, but rather promoted deep root growth that probably helped capture maximum water, along with nutrients, from wider areas. On the other hand, water stress at bulb development and maturity stage was found to be critical for onion growth, with a significant reduction in growth performance and yield. Hence, under conditions of scarce irrigation water, onion producers have to avoid stressing onion crops at bulb development and maturity stage, that is, from 70-145 DAT for cultivar Texas Grano.

The SWB model simulations for potato and onion growth, development and yield were evaluated in comparison with the crop measurements collected in the experimental field for five potato cultivars and one water-stressed onion cultivar at different growth stages. The results revealed that model simulations fitted excellent by the measured data collected from the experiment for LAI and FI. For treatments grown under water-stress conditions, however, the simulated LAI and FI, had irregular (stepped) graphs. In addition, the model simulation for TDM and HDM also fitted very well the measurements, with a high accuracy of agreement, according to De Jager (1994). The SWD simulations for some experiments were either slightly underestimated or overestimated, resulting in less accuracy, according to the statistical parameters recommended by De Jager (1994). The SWB was successfully calibrated for potatoes and onions and could, therefore, be used to develop Irrigation Calendars for different areas of Ethiopia.

The irrigation schedules practised by the traditional farmers were found to be significantly inferior to the two scientific methods tested. It led to the suggestion that it needed to be replaced by a more efficient and productive schedule. The best performing schedule, the NP, involves high initial cost and also requires skilled personnel for data processing and interpretation, therefore the SWB model Irrigation Calendar was suggested to replace the traditional practice. Hence, Irrigation Calendars were developed for potato and onion crops grown in five different agro-ecologies of Ethiopia, using the SWB model. Results of the predicted calendars varied between the two crops grown under the same climate, soil and management options. The predicted calendar showed less water per application and a smaller number of irrigations for potatoes as compared to onions grown under the same conditions. Similarly, the water requirements of potatoes and onions were found to vary between locations because of the difference in climate and altitude. This suggested that the model was capable of producing different calendars for different crops at the same location, indicating the variation between crops in their water requirements under the same soil and climatic conditions. In addition, the model has also demonstrated that the water requirement of a crop varied from place to place accounting to the climate, soil and planting date. Therefore, it is envisaged that the SWB model prediction could successfully replace the poor performing traditional farmers' irrigation practice at irrigation schemes in Ethiopia. These can now be used as basis for development of irrigation calendars for different crops and locations by extension staff.

10.2 Recommendations

The traditional irrigation practised at the Godino scheme was found to be inefficient with poor water distribution, poor on-farm water application and overall low irrigation efficiency. During the survey conducted at the Godino scheme, results indicated that an improvement of the irrigation practise through research, or replacement by a system that is more efficient, would be desirable. In view of this, the following points were recommended for further improvement:

- The development of efficient water management technologies: when to irrigate, how much water to apply and how to irrigate are priorities to water users of the scheme;
- The development of high-yielding crop cultivars that would improve the economic feasibility of irrigation enterprises;
- The formation of a linkage with micro-processing units for agricultural productions to make irrigated agriculture sustainable;
- The training of farmers in general farm management, efficient water use and the use of appropriate inputs, mainly plant nutrients and market-oriented farming;

- The improvement of water users' organisational structures, their participation in water management and the strengthening of their bylaws, mainly for equitable water sharing.

The WFDs used in this experiment did not provide adequate information. It could be due to the fact that not much work has been done on its performance under the furrow irrigation method or on finer textured soils, for example, placement of WFDs, depths under furrow/flood conditions and particle sizes of filter materials. Hence, detail assessment on the performance of WFDs would be important in the future.

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APPENDICES

Table A1 Irrigation calendar output as recommended by SWB scheduler, using potato crop for Melkassa climate and soil conditions

IRRIGATION CALENDAR

Farmer:	Crop: Potato (Awash)
Field: Melkassa	Planting date: 01/01/2006
Soil type: Sandy clay loam	Wetting Front Detectors:
Irrigation system: Furrow	Shallow: 4
Management options: Fixed, every seven days	Deep: 4
Irrigation frequency option: Interval (Days)	Response factor (%): 20

Date and Day	* Irrigation requirement (IR), depending on number of shallow and deep Wetting Front Detector (WFD) responses			Rain since previous irrigation (mm)	Recommended irrigation amount = IR-Rain
	0-2 Shallow and 0-2 Deep	3-4 Shallow and 0-2 Deep	3-4 Shallow and 3-4 Deep		
	Irrigation requirement (mm)				
6 Jan 2006		68			
13 Jan 2006	42	33	23		
20 Jan 2006	42	33	23		
27 Jan 2006	42	33	23		
3 Feb 2006	49	38	26		
10 Feb 2006	61	47	32		
17 Feb 2006	75	58	40		
24 Feb 2006	87	67	46		
3 Mar 2006	88	68	47		
10 Mar 2006	84	65	45		
17 Mar 2006	84	65	45		
24 Mar 2006	84	65	45		
31 Mar 2006	87	67	46		
7 Apr 2006	87	67	46		
14 Apr 2006	87	67	46		
21 Apr 2006	84	65	45		
28 Apr 2006	87	67	46		
5 May 2006	87	67	46		
12 May 2006	71	55	38		
19 May 2006	54	42	29		
26 May 2006	48	37	25		

*** Notes**

- Just before irrigation, check Wetting Front Detector response (to the previous irrigation) and use to correct the irrigation requirement.
- Encircle the applicable irrigation requirement, based on WFD response.
- If 0-2 shallow 3-4 deep WFDs have responded, check your shallow WFDs for problems.
- Record rain and empty gauge just before irrigation.
- Subtract rainfall from irrigation requirement to obtain the irrigation amount.
- If IR-rain<0, then skip the irrigation, i.e. irrigation amount = 0.

Table A2 Irrigation calendar output as recommended by SWB scheduler, using onion crop for Melkassa climate and soil conditions

IRRIGATION CALENDAR

Farmer:
Field: Melkassa
Soil type: Sandy clay loam
Irrigation system: Furrow
Management options: Fixed, every seven days
Irrigation frequency option: Interval (Days)

Crop: Onion (Texas Grano)
Planting date: 01/01/2006
Wetting Front Detectors:
Shallow: 4
Deep: 4
Response factor (%): 20

Date and Day	* Irrigation requirement (IR), depending on number of shallow and deep Wetting Front Detector (WFD) responses			Rain since previous irrigation (mm)	Recommended irrigation amount = IR-Rain
	0-2 Shallow and 0-2 Deep	3-4 Shallow and 0-2 Deep	3-4 Shallow and 3-4 Deep		
	Irrigation requirement (mm)				
6 Jan 2006		70			
13 Jan 2006	48	37	25		
20 Jan 2006	48	37	25		
27 Jan 2006	49	38	26		
3 Feb 2006	51	40	28		
10 Feb 2006	58	45	31		
17 Feb 2006	64	50	35		
24 Feb 2006	75	58	40		
3 Mar 2006	81	63	44		
10 Mar 2006	81	63	44		
17 Mar 2006	81	63	44		
24 Mar 2006	84	65	45		
31 Mar 2006	84	65	45		
7 Apr 2006	84	65	45		
14 Apr 2006	84	65	45		
21 Apr 2006	84	65	45		
28 Apr 2006	81	63	44		
5 May 2006	81	63	44		
12 May 2006	81	63	44		
19 May 2006	81	63	44		
26 May 2006	81	63	44		
29 May 2006	35	27	18		

*** Notes**

- Just before irrigation, check Wetting Front Detector response (to the previous irrigation) and use to correct the irrigation requirement.
- Encircle the applicable irrigation requirement, based on WFD response.
- If 0-2 shallow 3-4 deep WFDs have responded, check your shallow WFDs for problems.
- Record rain and empty gauge just before irrigation.
- Subtract rainfall from irrigation requirement to obtain the irrigation amount.
- If IR-rain<0, then skip the irrigation, i.e. irrigation amount = 0.

Table A3 Irrigation calendar output as recommended by SWB scheduler, using potato crop for Bako climate and soil conditions

IRRIGATION CALENDAR

Farmer:
Field: Bako
Soil type: Sandy clay loam
Irrigation system: Furrow
Management options: Fixed, every seven days
Irrigation frequency option: Interval (Days)

Crop: Potato (Awash)
Planting date: 01/01/2006
Wetting Front Detectors:
Shallow: 4
Deep: 4
Response factor (%): 20

Date and Day	* Irrigation requirement (IR), depending on number of shallow and deep Wetting Front Detector (WFD) responses			Rain since previous irrigation (mm)	Recommended irrigation amount = IR-Rain
	0-2 Shallow and 0-2 Deep	3-4 Shallow and 0-2 Deep	3-4 Shallow and 3-4 Deep		
	Irrigation requirement (mm)				
7 Jan 2006		70			
14 Jan 2006	45	35	24		
21 Jan 2006	42	33	23		
28 Jan 2006	48	37	25		
4 Feb 2006	55	43	30		
11 Feb 2006	71	55	38		
18 Feb 2006	84	65	45		
25 Feb 2006	90	70	49		
4 Mar 2006	90	70	49		
11 Mar 2006	93	72	50		
18 Mar 2006	93	72	50		
25 Mar 2006	94	73	51		
1 Apr 2006	94	73	51		
8 Apr 2006	90	70	49		
15 Apr 2006	75	58	40		
22 Apr 2006	55	43	30		
29 Apr 2006	49	38	26		
6 May 2006	48	37	25		
13 May 2006	48	37	25		
20 May 2006	48	37	25		
23 May 2006	35	27	18		

*** Notes**

- Just before irrigation, check Wetting Front Detector response (to the previous irrigation) and use to correct the irrigation requirement.
- Encircle the applicable irrigation requirement, based on WFD response.
- If 0-2 shallow 3-4 deep WFDs have responded, check your shallow WFDs for problems.
- Record rain and empty gauge just before irrigation.
- Subtract rainfall from irrigation requirement to obtain the irrigation amount.
- If IR-rain<0, then skip the irrigation, i.e. irrigation amount = 0.

Table A4 Irrigation calendar output as recommended by SWB scheduler, using onion crop for Bako climate and soil conditions

IRRIGATION CALENDAR

Farmer:
Field: Bako
Soil type: Sandy clay loam
Irrigation system: Furrow
Management options: Fixed, every seven days
Irrigation frequency option: Interval (Days)

Crop: Onion (Texas Grano)
Planting date: 01/01/2006
Wetting Front Detectors:
Shallow: 4
Deep: 4
Response factor (%): 20

Date and Day	* Irrigation requirement (IR), depending on number of shallow and deep Wetting Front Detector (WFD) responses			Rain since previous irrigation (mm)	Recommended irrigation amount = IR-Rain
	0-2 Shallow and 0-2 Deep	3-4 Shallow and 0-2 Deep	3-4 Shallow and 3-4 Deep		
	Irrigation requirement (mm)				
3 Jan 2006		58			
10 Jan 2006	48	37	25		
17 Jan 2006	45	35	24		
24 Jan 2006	45	35	24		
31 Jan 2006	45	35	24		
7 Feb 2006	45	35	24		
14 Feb 2006	45	35	24		
21 Feb 2006	45	35	24		
28 Feb 2006	45	35	24		
7 Mar 2006	45	35	24		
14 Mar 2006	45	35	24		
21 Mar 2006	45	35	24		
28 Mar 2006	45	35	24		
4 Apr 2006	45	35	24		
11 Apr 2006	45	35	24		
18 Apr 2006	45	35	24		
25 Apr 2006	45	35	24		
2 May 2006	45	35	24		
9 May 2006	45	35	24		
16 May 2006	45	35	24		
23 May 2006	45	35	24		

*** Notes**

- Just before irrigation, check Wetting Front Detector response (to the previous irrigation) and use to correct the irrigation requirement.
- Encircle the applicable irrigation requirement, based on WFD response.
- If 0-2 shallow 3-4 deep WFDs have responded, check your shallow WFDs for problems.
- Record rain and empty gauge just before irrigation.
- Subtract rainfall from irrigation requirement to obtain the irrigation amount.
- If IR-rain<0, then skip the irrigation, i.e. irrigation amount = 0.

Table A5 Irrigation calendar output as recommended by SWB scheduler, using onion crop for Zeway climate and soil conditions

IRRIGATION CALENDAR

Farmer:
Field: Zeway
Soil type: Sandy clay loam
Irrigation system: Furrow
Management options: Fixed, every seven days
Irrigation frequency option: Interval (Days)

Crop: Potato (Awash)
Planting date: 01/01/2006
Wetting Front Detectors:
Shallow: 4
Deep: 4
Response factor (%): 20

Date and Day	* Irrigation requirement (IR), depending on number of shallow and deep Wetting Front Detector (WFD) responses			Rain since previous irrigation (mm)	Recommended irrigation amount = IR-Rain
	0-2 Shallow and 0-2 Deep	3-4 Shallow and 0-2 Deep	3-4 Shallow and 3-4 Deep		
	Irrigation requirement (mm)				
3 Jan 2006		55			
10 Jan 2006	42	33	23		
17 Jan 2006	41	32	22		
24 Jan 2006	41	32	22		
31 Jan 2006	48	37	25		
7 Feb 2006	55	43	30		
14 Feb 2006	68	53	37		
21 Feb 2006	74	57	39		
28 Feb 2006	75	58	40		
7 Mar 2006	80	62	43		
14 Mar 2006	81	63	44		
21 Mar 2006	81	63	44		
28 Mar 2006	81	63	44		
4 Apr 2006	80	62	43		
11 Apr 2006	80	62	43		
18 Apr 2006	77	60	42		
25 Apr 2006	62	48	33		
2 May 2006	49	38	26		
9 May 2006	48	37	25		
16 May 2006	48	37	25		
23 May 2006	48	37	25		
29 May 2006	45	35	24		

*** Notes**

- Just before irrigation, check Wetting Front Detector response (to the previous irrigation) and use to correct the irrigation requirement.
- Encircle the applicable irrigation requirement, based on WFD response.
- If 0-2 shallow 3-4 deep WFDs have responded, check your shallow WFDs for problems.
- Record rain and empty gauge just before irrigation.
- Subtract rainfall from irrigation requirement to obtain the irrigation amount.
- If IR-rain<0, then skip the irrigation, i.e. irrigation amount = 0.

Table A6 Irrigation calendar output as recommended by SWB scheduler, using onion crop for Zeway climate and soil conditions

IRRIGATION CALENDAR

Farmer:	Crop: Onion (Texas Grano)
Field: Zeway	Planting date: 01/01/2006
Soil type: Sandy clay loam	Wetting Front Detectors:
Irrigation system: Furrow	Shallow: 4
Management options: Fixed, every seven days	Deep: 4
Irrigation frequency option: Interval (Days)	Response factor (%): 20

Date and Day	* Irrigation requirement (IR), depending on number of shallow and deep Wetting Front Detector (WFD) responses			Rain since previous irrigation (mm)	Recommended irrigation amount = IR-Rain
	0-2 Shallow and 0-2 Deep	3-4 Shallow and 0-2 Deep	3-4 Shallow and 3-4 Deep		
	Irrigation requirement (mm)				
7 Jan 2006		70			
14 Jan 2006	48	37	25		
21 Jan 2006	48	37	25		
28 Jan 2006	49	38	26		
4 Feb 2006	51	40	28		
11Feb 2006	58	45	31		
18 Feb 2006	64	50	35		
25 Feb 2006	68	53	37		
4 Mar 2006	71	55	38		
11 Mar 2006	74	57	39		
18 Mar 2006	74	57	39		
25 Mar 2006	74	57	39		
1 Apr 2006	74	57	39		
8 Apr 2006	71	55	38		
15 Apr 2006	71	55	38		
22 Apr 2006	71	55	38		
29 Apr 2006	71	55	38		
6 May 2006	71	55	38		
13 May 2006	71	55	38		
18 May 2006	55	43	30		

*** Notes**

- Just before irrigation, check Wetting Front Detector response (to the previous irrigation) and use to correct the irrigation requirement.
- Encircle the applicable irrigation requirement, based on WFD response.
- If 0-2 shallow 3-4 deep WFDs have responded, check your shallow WFDs for problems.
- Record rain and empty gauge just before irrigation.
- Subtract rainfall from irrigation requirement to obtain the irrigation amount.
- If IR-rain<0, then skip the irrigation, i.e. irrigation amount = 0.

Table A7 Irrigation calendar output as recommended by SWB scheduler, using potato crop for Shashemene climate and soil conditions

IRRIGATION CALENDAR

Farmer:
Field: Shashemene
Soil type: Sandy clay loam
Irrigation system: Furrow
Management options: Fixed, every seven days
Irrigation frequency option: Interval (Days)

Crop: Potato (Awash)
Planting date: 01/01/2006
Wetting Front Detectors:
Shallow: 4
Deep: 4
Response factor (%): 20

Date and Day	* Irrigation requirement (IR), depending on number of shallow and deep Wetting Front Detector (WFD) responses			Rain since previous irrigation (mm)	Recommended irrigation amount = IR-Rain
	0-2 Shallow and 0-2 Deep	3-4 Shallow and 0-2 Deep	3-4 Shallow and 3-4 Deep		
	Irrigation requirement (mm)				
7 Jan 2006		68			
14 Jan 2006	45	35	24		
21 Jan 2006	42	33	23		
28 Jan 2006	42	33	23		
4 Feb 2006	49	38	26		
11 Feb 2006	62	48	33		
18 Feb 2006	80	62	43		
25 Feb 2006	88	68	47		
4 Mar 2006	87	67	46		
11 Mar 2006	84	65	45		
18 Mar 2006	84	65	45		
25 Mar 2006	84	65	45		
1 Apr 2006	84	65	45		
8 Apr 2006	84	65	45		
15 Apr 2006	84	65	45		
22 Apr 2006	84	65	45		
29 Apr 2006	84	65	45		
6 May 2006	81	63	44		
13 May 2006	67	52	36		
20 May 2006	51	40	28		
27 May 2006	48	37	25		
30 May 2006	35	27	18		

*** Notes**

- Just before irrigation, check Wetting Front Detector response (to the previous irrigation) and use to correct the irrigation requirement.
- Encircle the applicable irrigation requirement, based on WFD response.
- If 0-2 shallow 3-4 deep WFDs have responded, check your shallow WFDs for problems.
- Record rain and empty gauge just before irrigation.
- Subtract rainfall from irrigation requirement to obtain the irrigation amount.
- If IR-rain<0, then skip the irrigation, i.e. irrigation amount = 0.

Table A8 Irrigation calendar output as recommended by SWB scheduler, using onion crop for Shashemene climate and soil conditions

IRRIGATION CALENDAR

Farmer:
Field: Shashemene
Soil type: Sandy clay loam
Irrigation system: Furrow
Management options: Fixed, every seven days
Irrigation frequency option: Interval (Days)

Crop: Onion (Texas Grano)
Planting date: 01/01/2006
Wetting Front Detectors:
Shallow: 4
Deep: 4
Response factor (%): 20

Date and Day	* Irrigation requirement (IR), depending on number of shallow and deep Wetting Front Detector (WFD) responses			Rain since previous irrigation (mm)	Recommended irrigation amount = IR-Rain
	0-2 Shallow and 0-2 Deep	3-4 Shallow and 0-2 Deep	3-4 Shallow and 3-4 Deep		
	Irrigation requirement (mm)				
7 Jan 2006		72			
14 Jan 2006	48	37	25		
21 Jan 2006	48	37	25		
28 Jan 2006	49	38	26		
4 Feb 2006	54	42	29		
11 Feb 2006	58	45	31		
18 Feb 2006	67	52	36		
25 Feb 2006	77	60	42		
4 Mar 2006	84	65	45		
11 Mar 2006	81	63	44		
18 Mar 2006	84	65	45		
25 Mar 2006	84	65	45		
1 Apr 2006	84	65	45		
8 Apr 2006	84	65	45		
15 Apr 2006	81	63	44		
22 Apr 2006	81	63	44		
29 Apr 2006	81	63	44		
6 May 2006	81	63	44		
13 May 2006	81	63	44		
20 May 2006	80	62	43		
27 May 2006	80	62	43		
30 May 2006	35	27	18		

*** Notes**

- Just before irrigation, check Wetting Front Detector response (to the previous irrigation) and use to correct the irrigation requirement.
- Encircle the applicable irrigation requirement, based on WFD response.
- If 0-2 shallow 3-4 deep WFDs have responded, check your shallow WFDs for problems.
- Record rain and empty gauge just before irrigation.
- Subtract rainfall from irrigation requirement to obtain the irrigation amount.
- If IR-rain<0, then skip the irrigation, i.e. irrigation amount = 0.

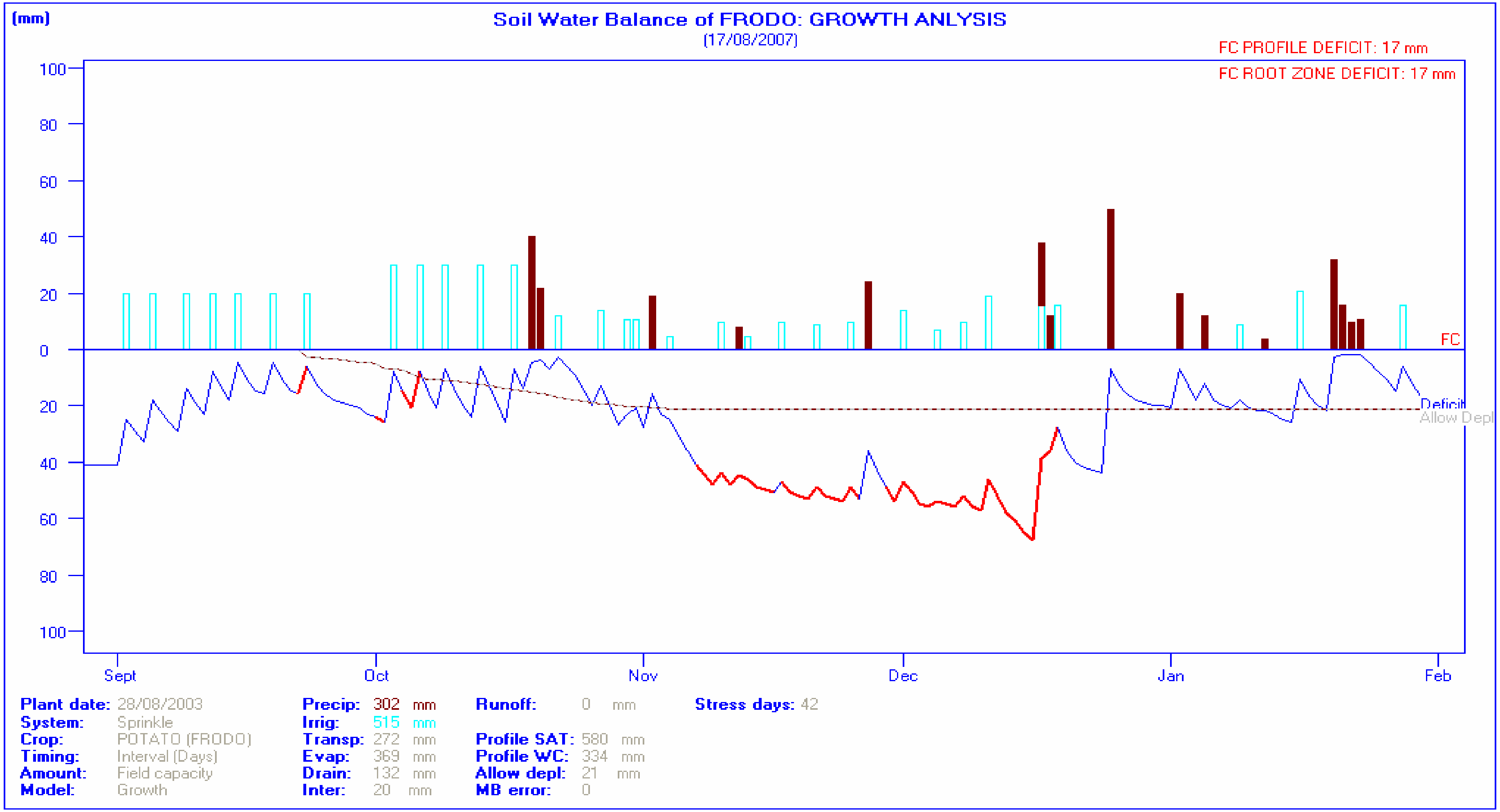

Figure A1 Irrigation, rainfall and the soil water balance during the growing period of potato, cv. Frodo

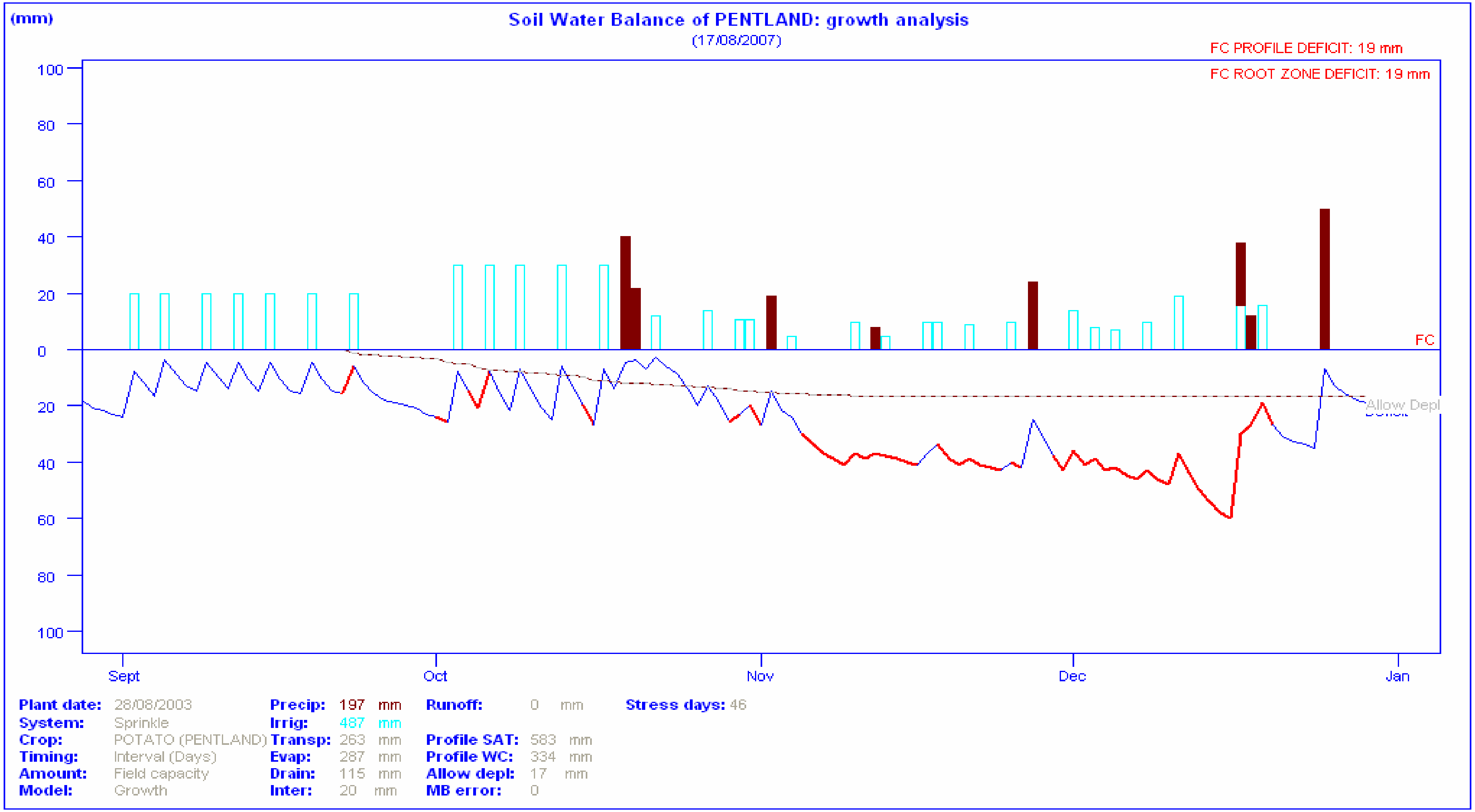

Figure A2 Irrigation, rainfall and the soil water balance during the growing period of Potato, cv. Pentland Dell

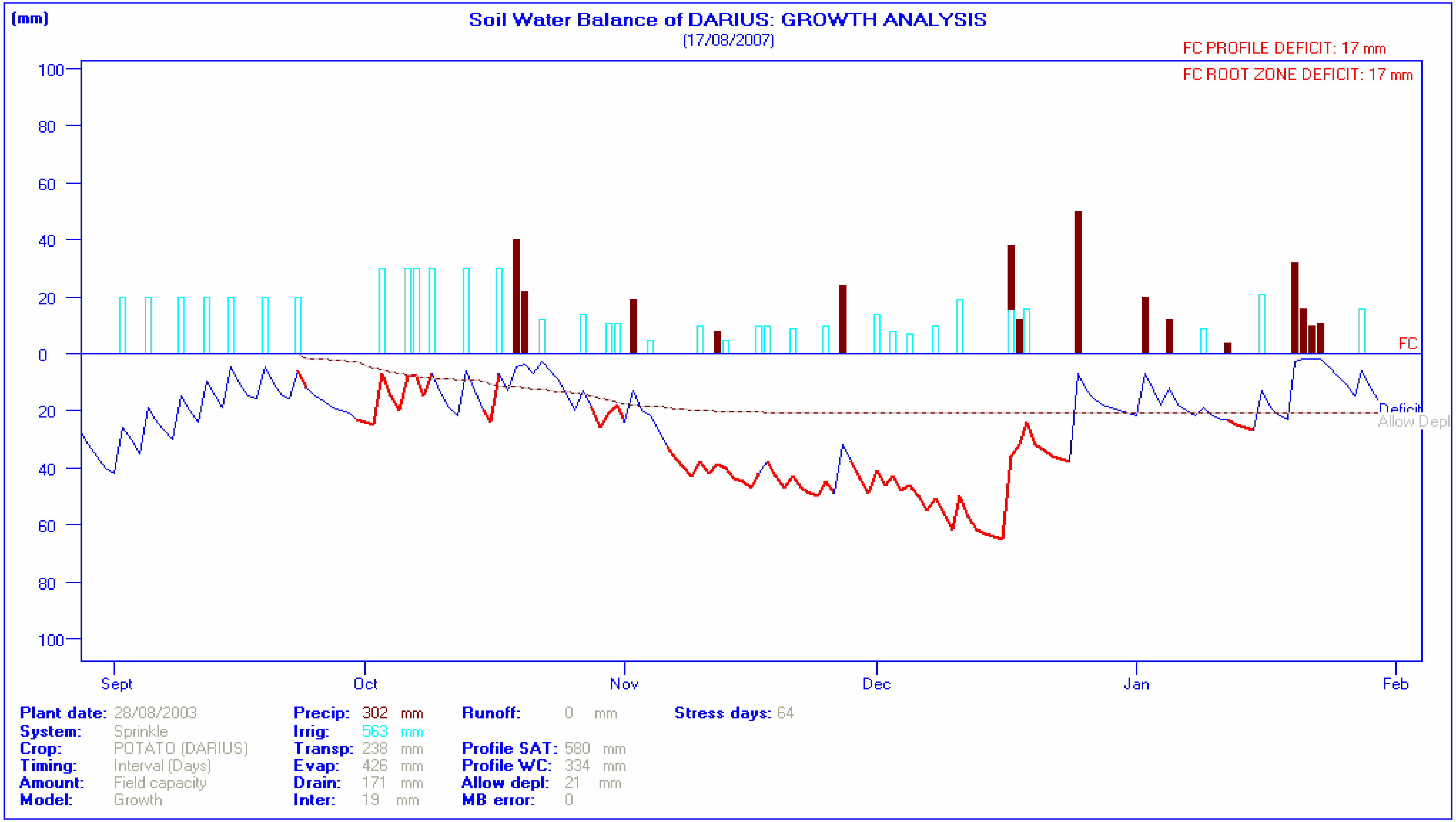

Figure A3 Irrigation, rainfall and the soil water balance during the growing period of potato, cv. Darius

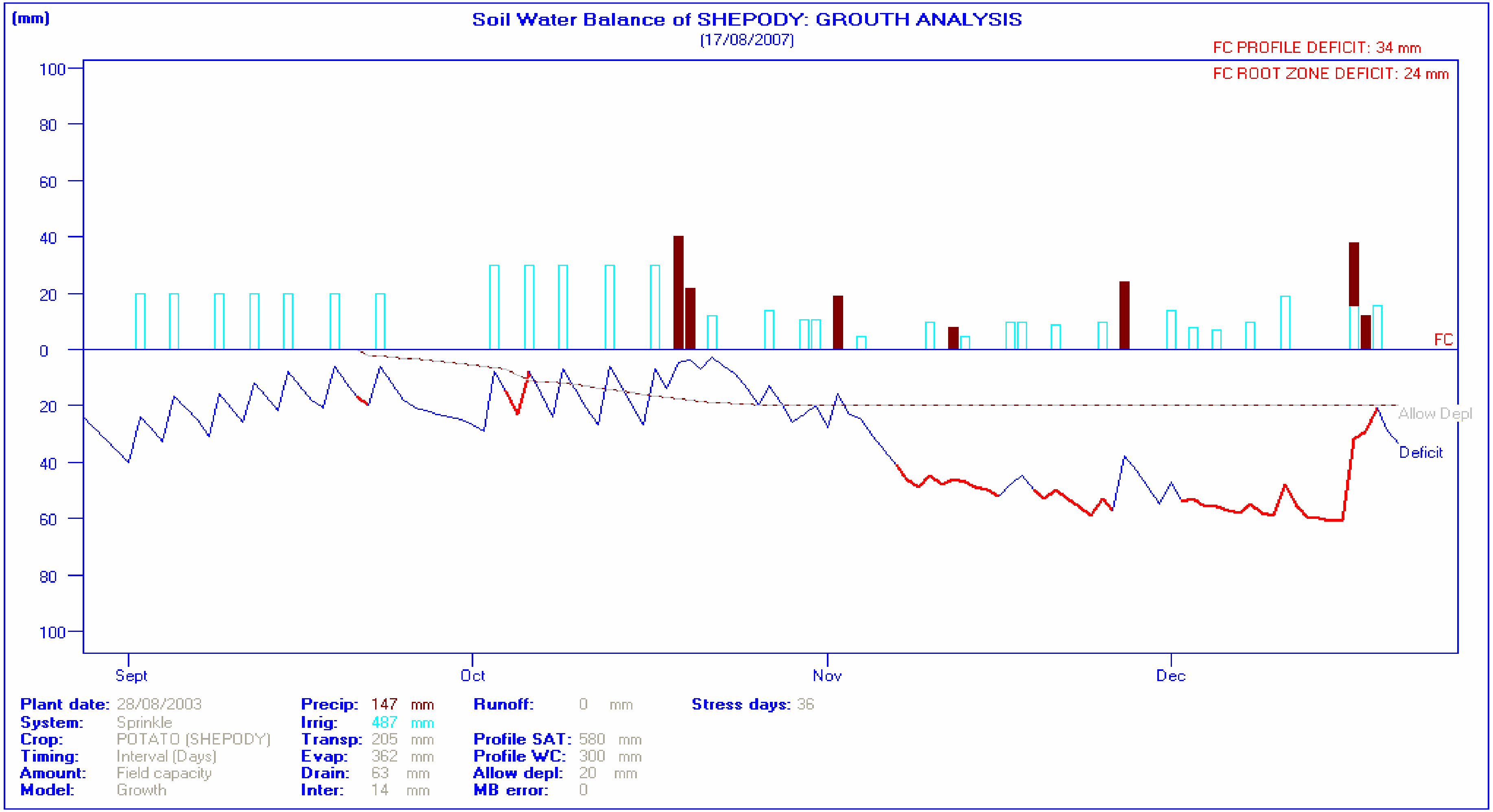

Figure A4 Irrigation, rainfall and the soil water balance during the growing period of potato, cv. Shepody

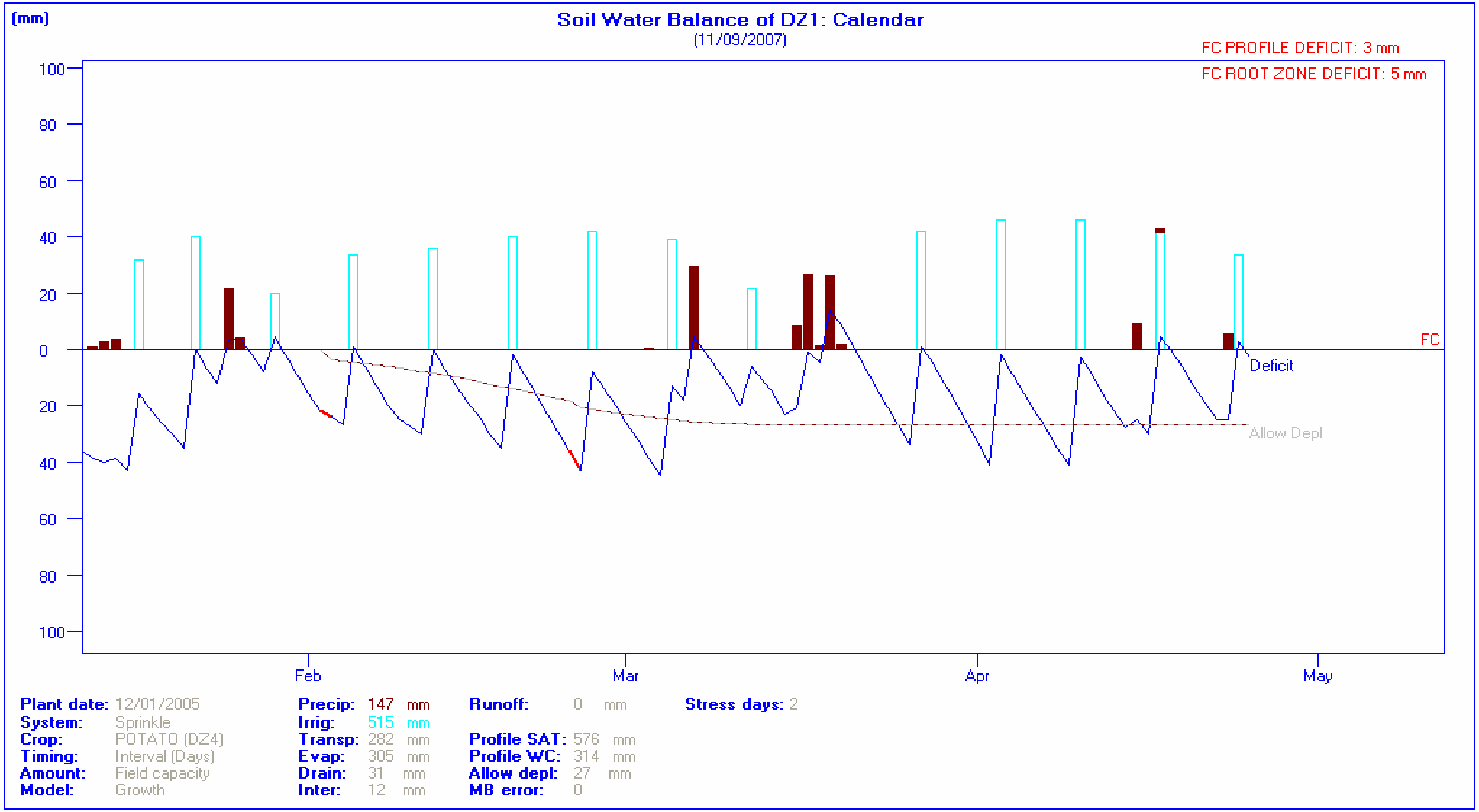

Figure A5 Irrigation, rainfall and the soil water balance during the growing period of Soil Water Balance (DZ1) treatment

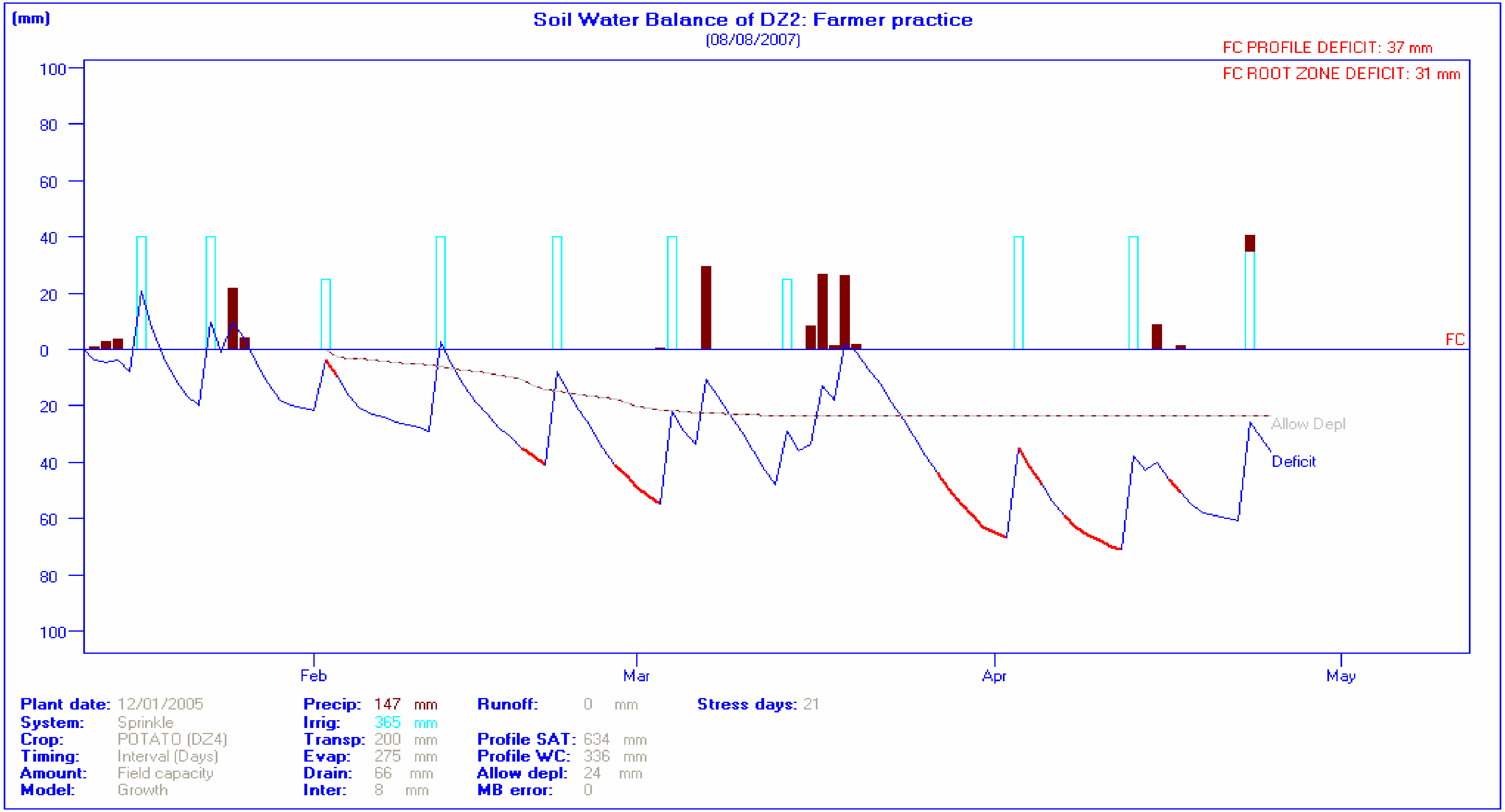

Figure A6 Irrigation, rainfall and the soil water balance during the growing period of Farmer's Traditional Practice (DZ2) treatment

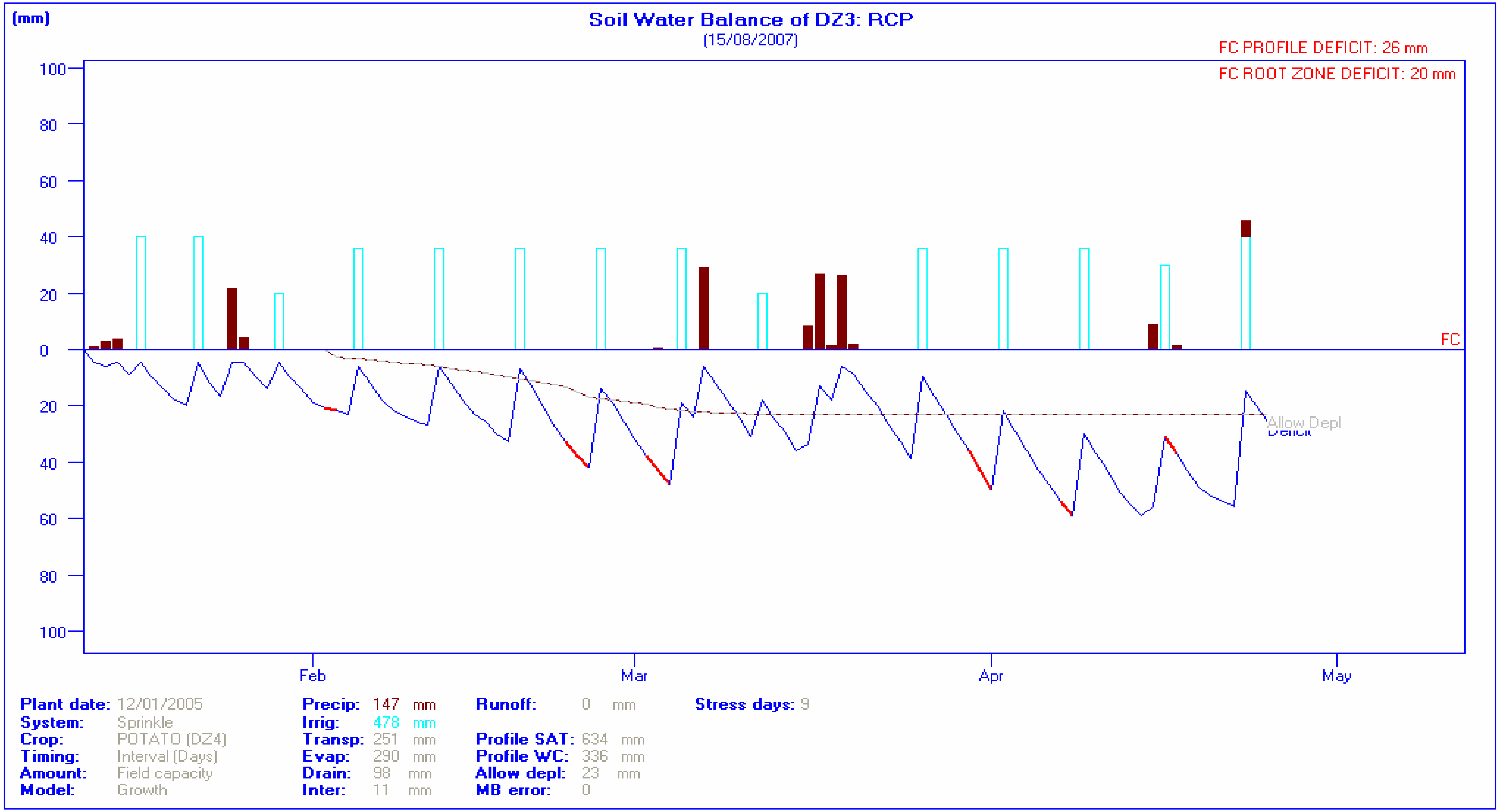

Figure A7 Irrigation, rainfall and the soil water balance during the growing period of Research Centre Practice (DZ3) treatment

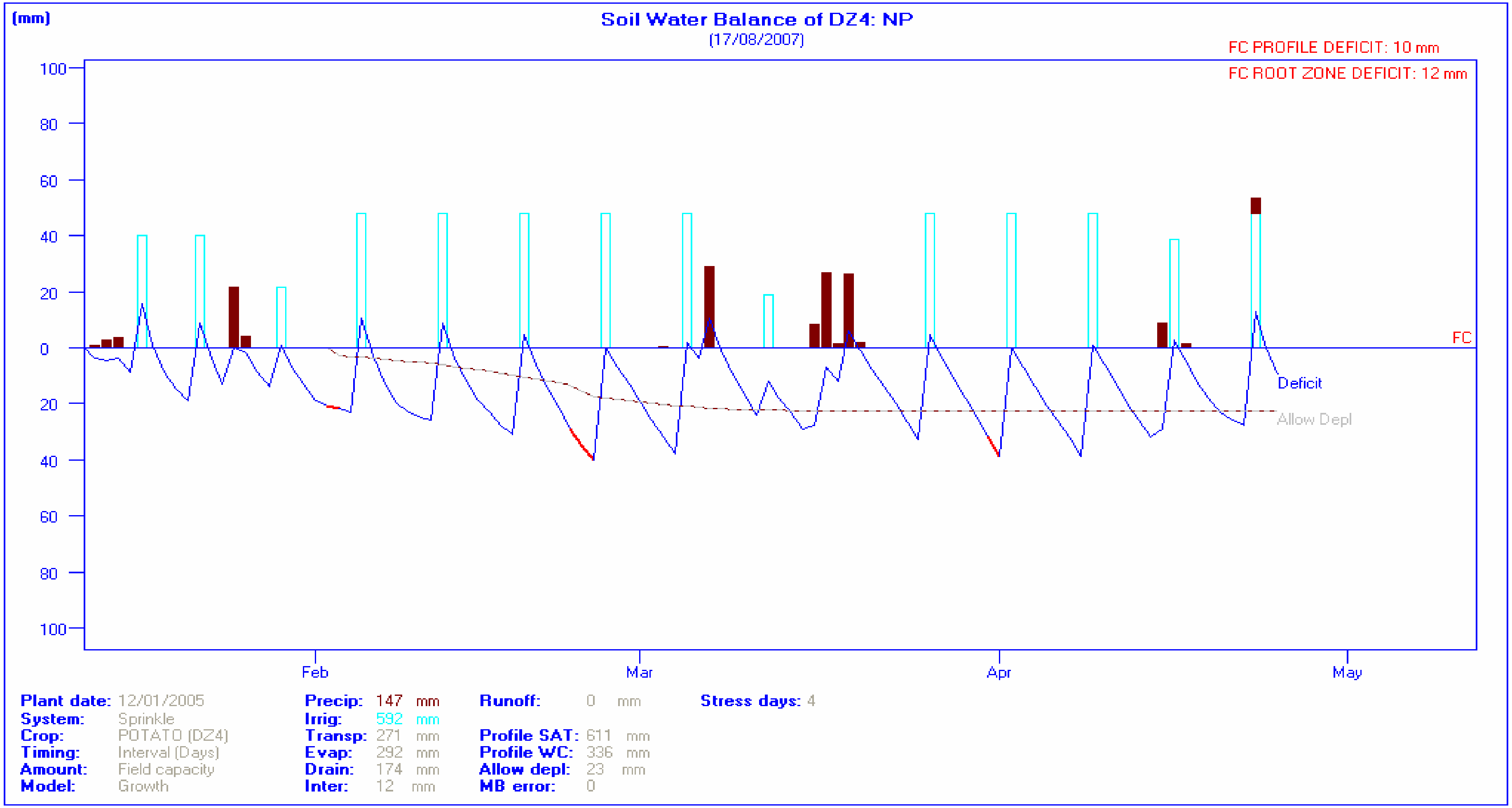

Figure A8 Irrigation, rainfall and the soil water balance during the growing period of Neutron Probe (DZ4) treatment

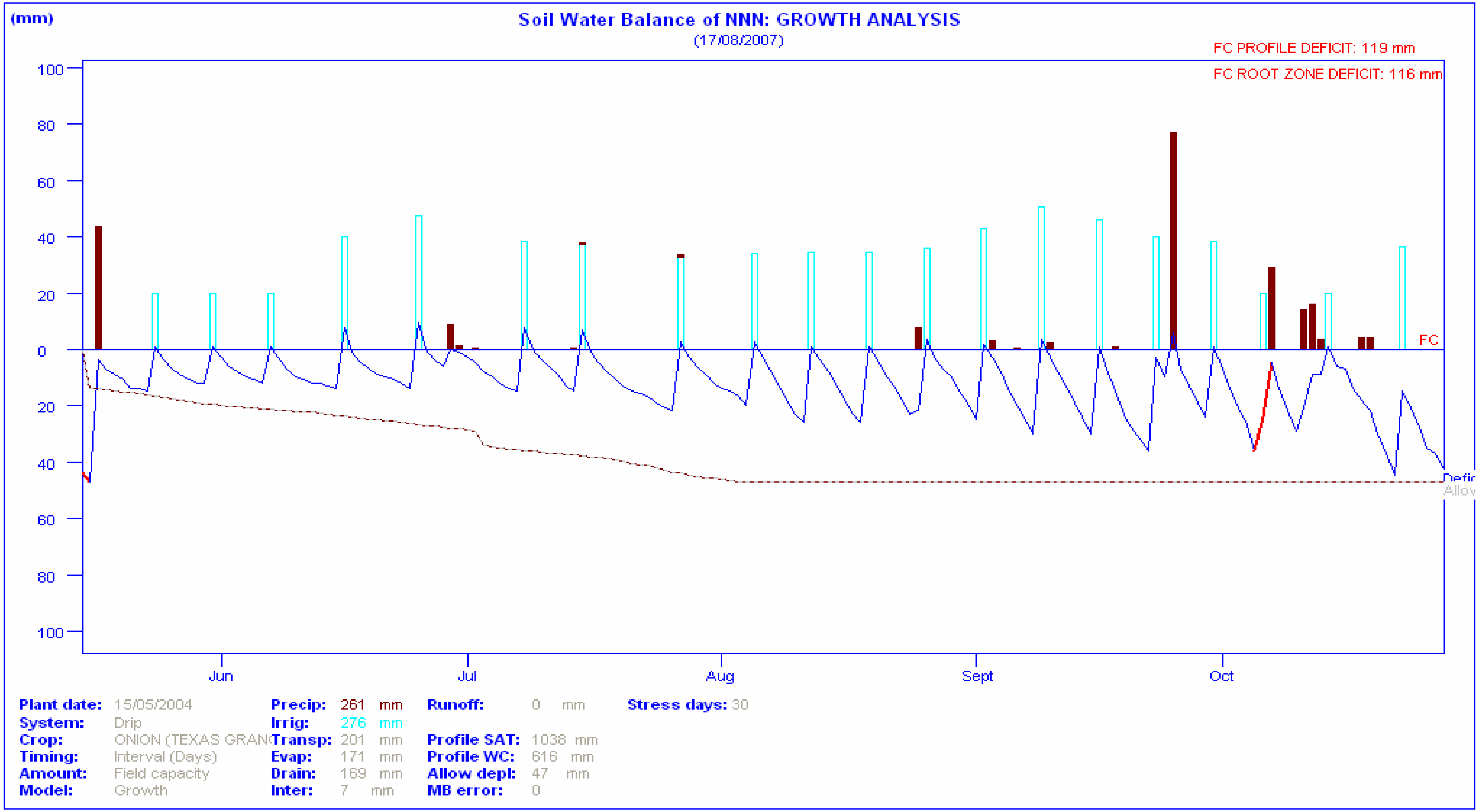

Figure A9 Irrigation, rainfall and the soil water balance during the growing period of onion (NNN) treatment

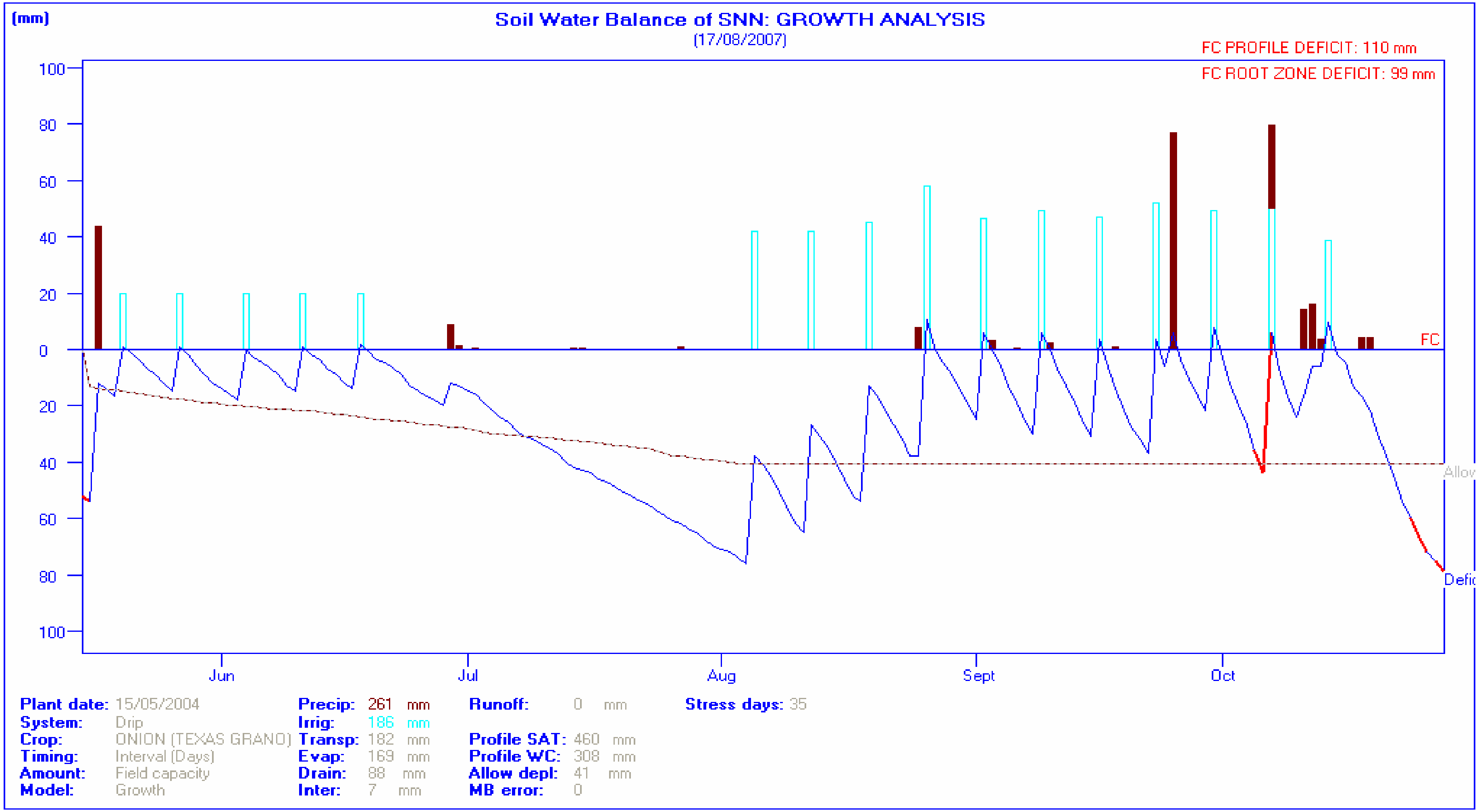

Figure A10 Irrigation, rainfall and the soil water balance during the growing period of onion (SNN) treatment

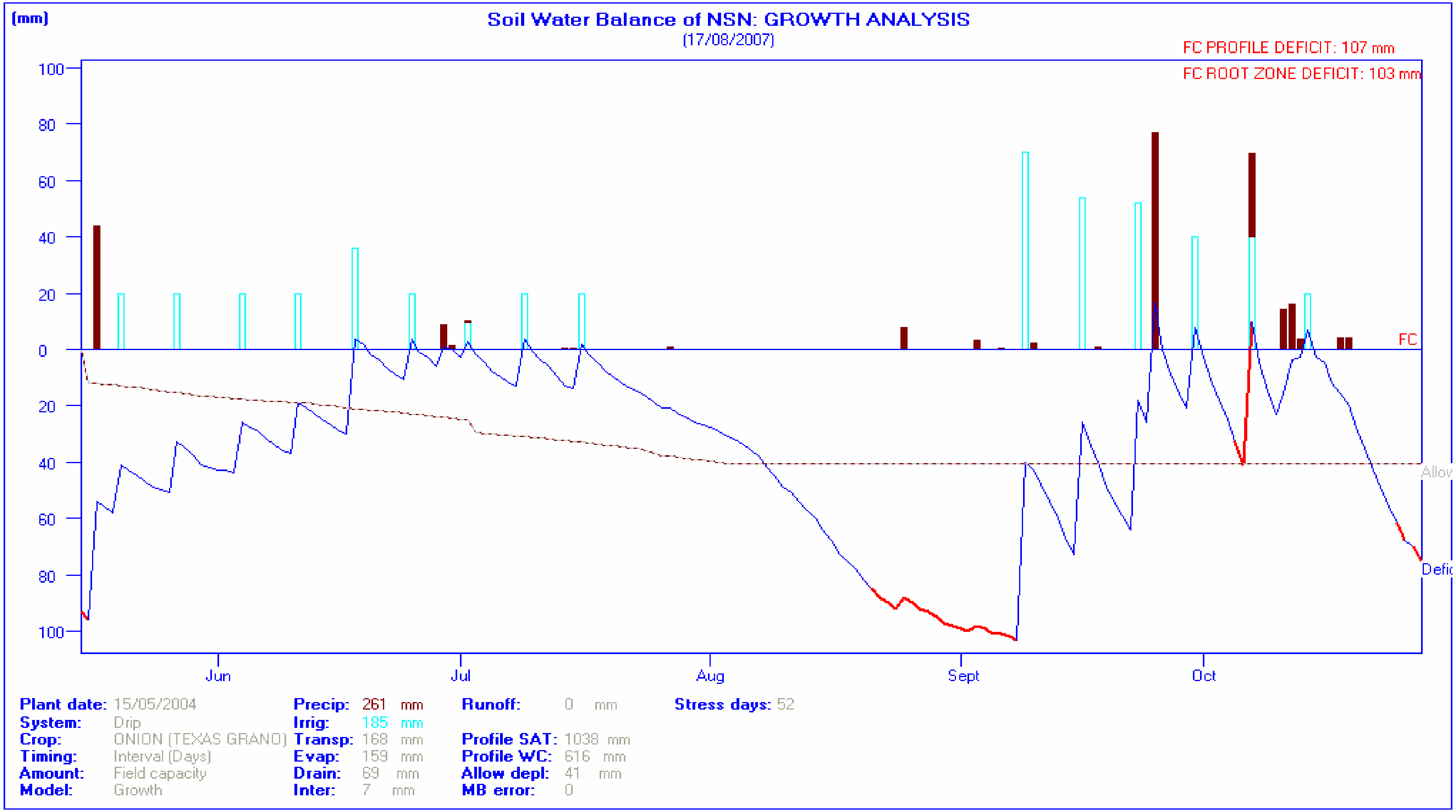

Figure A11 Irrigation, rainfall and the soil water balance during the growing period of onion (NSN) treatment

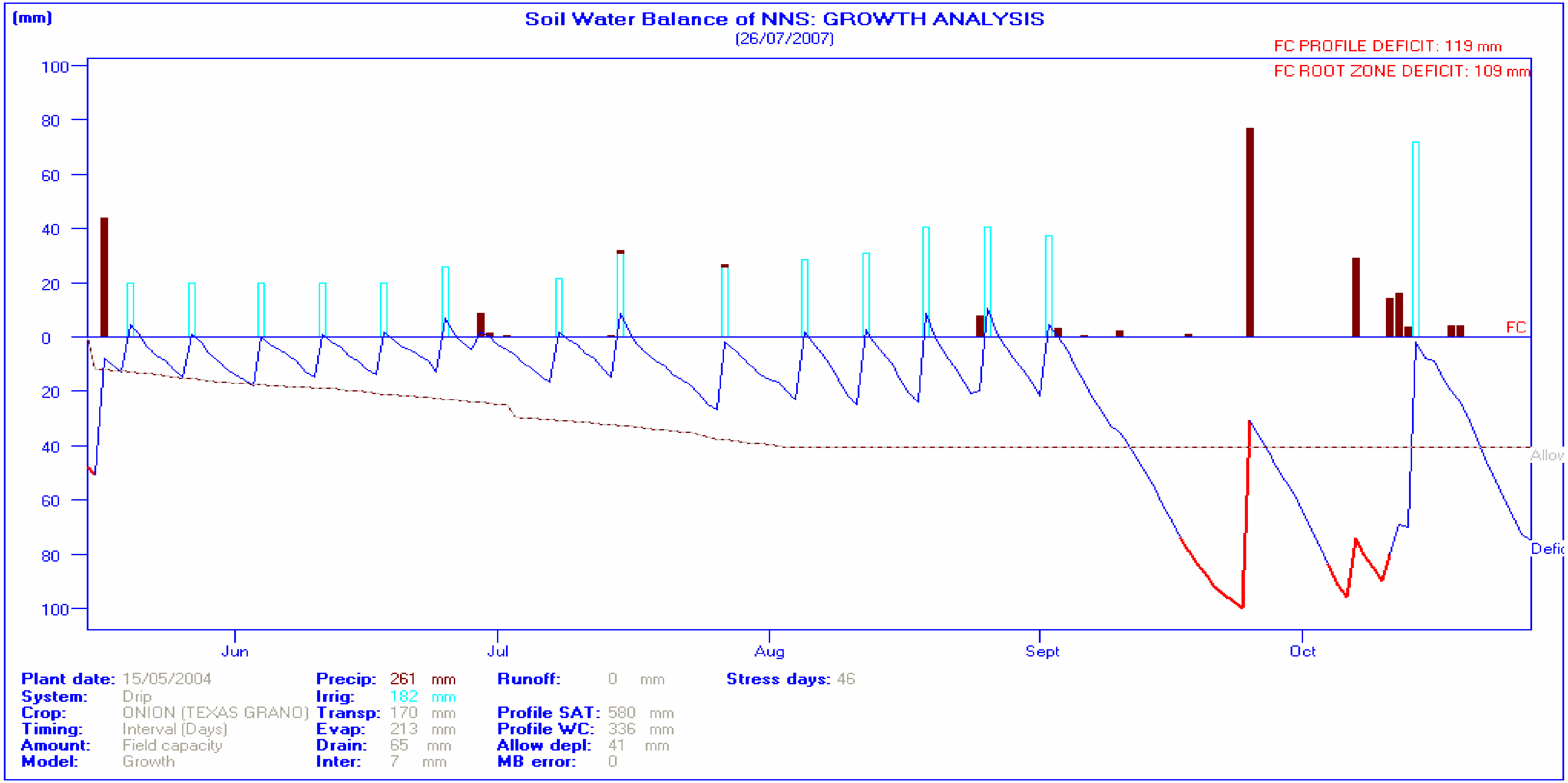

Figure A12 Irrigation, rainfall and the soil water balance during the growing period of onion (NNS) treatment