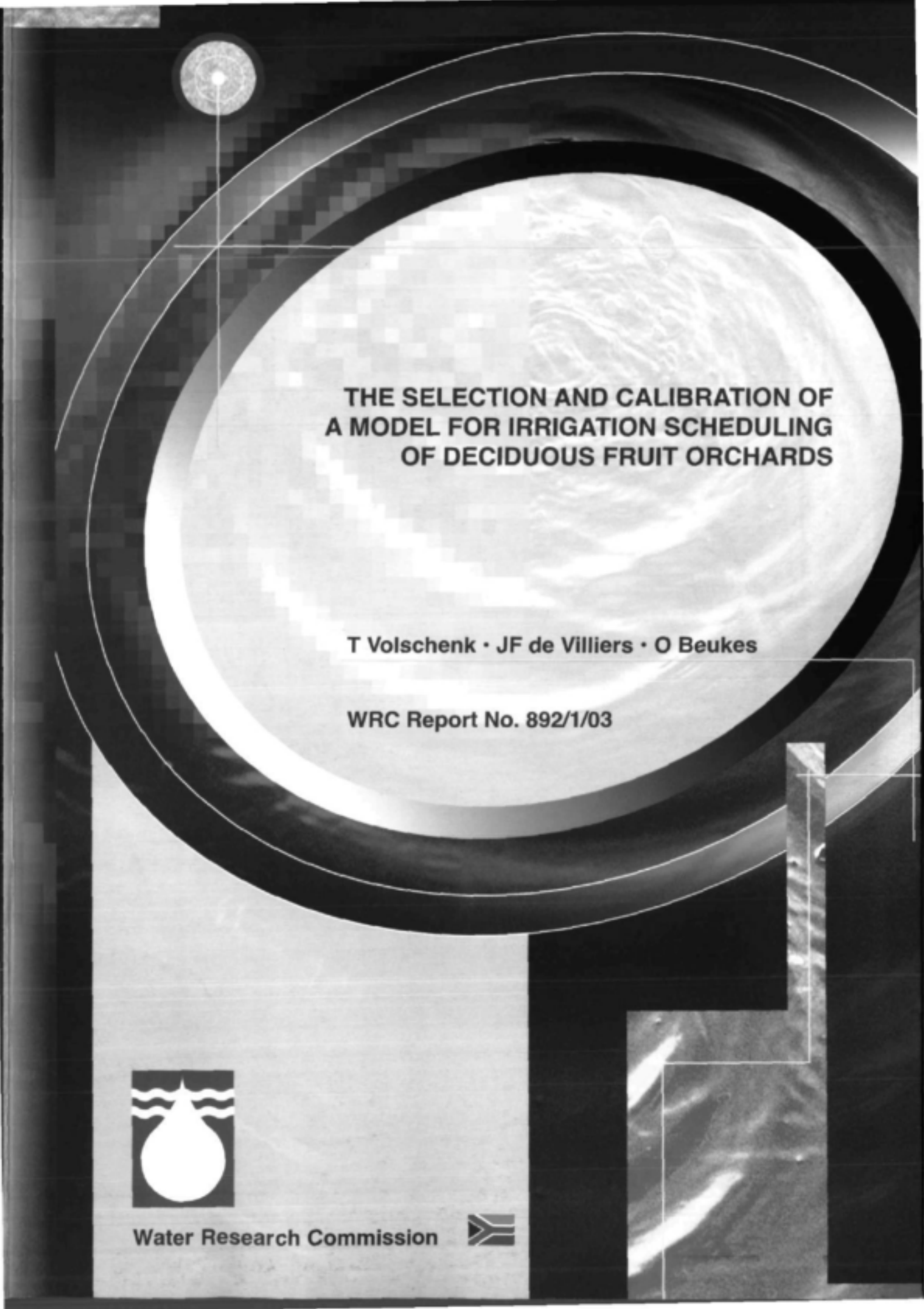

THE SELECTION AND CALIBRATION OF A MODEL FOR IRRIGATION SCHEDULING OF DECIDUOUS FRUIT ORCHARDS

T Volschenk • JF de Villiers • O Beukes

WRC Report No. 892/1/03

Water Research Commission

THE SELECTION AND CALIBRATION OF A MODEL FOR IRRIGATION SCHEDULING OF DECIDUOUS FRUIT ORCHARDS

by

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Report to the Water Research Commission

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August 2003

WRC Project No. 892/1/03
ISBN No. 1-77005-093-0
ISBN Set No. 1-77005-099-X

Printed by Silowa Printers: 012 804 7565

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Introduction

Water is the most limiting natural resource in terms of development in South Africa and indications are that present resources will be near maximum utilization within the next 8 years. The revised Water Law Principles state that ecological and basic domestic needs should enjoy first priority in the use of available water. However, fruit production in the Western Cape is only possible under irrigation and there is pressure on the sector to optimize its future water use.

The fruit industry is a major source of employment and a very important earner of foreign exchange for South Africa. Severe water restrictions have detrimental effects on this industry. Improved irrigation management through a reliable model can save a substantial amount of water to the benefit of all. The quality of the crop can, however, because of its export nature, never be compromised.

A survey during 1997 in the Western Cape, revealed that about 80% of producers do not use scientific irrigation tools or programmes. This could explain the widespread tendency among irrigation farmers to over-irrigate. This results in wastage of water, high consumption of electricity, as well as leaching of fertilizers and pollution of groundwater. The adverse effect on crops and soils is often not immediately visible or readily linked to excess water. The quality of water resources is also declining rapidly and measures to stem this trend are urgently needed.

Improved irrigation scheduling could reduce the wastage of water. Procedures used to schedule irrigation in orchards include those utilising soil or plant measurements to determine irrigation timing and those based on a water budget to estimate both depth of application and timing. The water budget method requires an evapotranspiration (ET) estimation and since direct measurement is not always possible on a large scale, ET can be estimated by mathematical models from meteorological, soil and crop-related data.

Several models to estimate ET by means of meteorological data are already in use in South Africa. However, these models were developed for annual crops covering entire soil surface and under full surface irrigation. They are therefore not developed for orchard situations where partial or total wetting of the soil surface under irrigation occurs and tree dimension make estimation of water use from meteorological data more difficult. Evapotranspiration is also affected by soil type, soil water content, tree size, phenological growing phase, training system, planting densities, irrigation system, irrigation cycle and various other cultivation practices.

The existing automated weather station network in the Western Cape makes the implementation of a real-time irrigation scheduling service a very feasible proposition. A reliable irrigation scheduling model that is easy to use and which can be linked with automated irrigation systems should therefore find universal acceptance. If such a model is validated for deciduous fruit crops, it could apart from improving decision making for operational water management, be used as a tactical tool to apply deficit irrigation strategies that could decrease labour costs through controlled inhibition of vegetative growth and improvement of fruit quality parameters.

Objectives

I. To evaluate a mathematical model for prediction of water use of deciduous fruit trees from meteorological data.

II. To supply guidelines for irrigation scheduling of deciduous fruit trees.

Structure and summary of the report

The project on evaluation of a model for water use in deciduous fruit orchards and scheduling of irrigation with the aid of meteorological data resulted in the publication of two separate reports. This report addresses the evaluation of a mathematical model for prediction of water use of deciduous fruit trees from meteorological data. Guidelines for irrigation scheduling of deciduous fruit trees are discussed in a separate report, namely "*Deficit irrigation studies to improve irrigation scheduling of deciduous fruit trees*".

Approach

The Soil Water Balance (SWB) irrigation scheduling model was selected for further evaluation because the way in which evaporation and transpiration is simulated has the possibility to address the vast array of management practices and irrigation methods employed in the deciduous fruit industry.

The calibration of the SWB FAO-based crop factor model was approached in two ways. Firstly, to determine if sap flow derived transpiration coefficients (Kt) could be used instead of Kcb values in combination with measured soil water deficit to calibrate the model. Secondly, to perform SWB simulations and fit SWB predicted soil water deficit to measured soil water deficit from orchards, until the best statistical fit was obtained.

Results and conclusions

Comparison of Kt to SWB derived Kcb values indicated that the former cannot necessarily be used interchangebly with the latter for the SWB model. Statistical output parameters and/or visual fit indicated reasonable agreement of SWB predicted to measured soil water deficit for six of the eleven plots where the fitting procedure was used.

Comparison of seasonal transpiration and ET, indicated that the transpiration was underestimated for one specific plot and overestimated for another. It follows that the Kcb values determined by the fitting procedure for the two cultivars was too low and too high, respectively. It is important to note that the model could underestimate evaporation grossly for warmer areas where the canopy cover fraction exceeds the irrigated fraction of the soil.

The fitting procedure to obtain Kcb values did not work well. This complicated interpretation of statistical output parameters used to evaluate the reliability of the model prediction. Several reasons for poor fit of simulated to measured data were identified:

- Evaporation could be severely overestimated by the SWB model if the measured soil water content of the top soil layer is not used as initial soil water content input. Although this is considered a once-off error, overestimation could re-occur if soil water content is updated according to measured data.
- Evaporation is limited to the top soil layer and the model could underestimate evaporation if the simulated water content of the top soil layer is air-dry during periods of high reference ET (ET_o).
- The model could underestimate evaporation during periods of high ET_o where the canopy cover fraction exceeds the irrigated fraction of the soil surface, especially if the irrigation frequency is high.
- Since the effect of crop removal or limited leaf senescence after harvest cannot be accurately simulated, the model over- or underestimated the soil water deficit at several plots after harvest.
- Use of the linear Kcb approach of the Food and Agriculture Organisation (FAO) of the United Nations could cause over- or underestimation of soil water deficit because the leaf area (LA) development and therefore fractional interception (FI), is not linear, especially during the development stage.
- The model does not simulate separate water balances for trees and cover crop under full surface irrigation.
- The recommended assumption that the cover crop contribution would be similar to that of bare soil proved to be invalid where the cover crop was irrigated and frequently mowed. However, it did apply where tree roots extended beyond the wetted area and the non-irrigated cover crop was patchy and dry.
- The Kcb values will have to be adjusted if canopy management practices like pruning change the FI. This can be done by updating simulated FI of the model to measured FI.

Alternative ways to obtain Kcb values for other orchards were investigated, but it was not possible to obtain a reliable Kcb estimate from easily measurable tree parameters. It was, however, possible to estimate it from measured LA, leaf area density (LAD) or FI. It follows that producers will have to make use of expertise and specialised equipment to determine these variables for estimating Kcb.

Full bearing trees of early and midseason cultivars had higher water requirements than previously predicted from crop factors and long-term Class-A pan evaporation. Hence, producers should consider the higher seasonal irrigation requirement of these trees when managing irrigation water.

Recommendations for further research

The use of an irrigation scheduling model such as SWB, that utilizes the dual crop coefficient approach, has the potential to address some of the variability present in irrigation of orchards and to improve water management. Development of separate water balances for trees and cover crop under full surface irrigation in the SWB model could enable more realistic simulations for such orchards. Furthermore, the availability of Kcb values apart from those published by the FAO, is problematic and a simple and practical approach to determine Kcb is still a challenge. In this regard, estimation of Kcb from radiation interception determined through the recently developed two dimensional energy interception model for hedgerow tree crops, as well as indirect methods in the orchard, could be further investigated. Although models are available to estimate radiation interception with acceptable reliability, LA is generally needed as input. Future research could therefore provide much needed information for modelers and enhance the use of models for management purposes if it eliminates the use of LA as an input variable or finds a practical, less laborious way to determine it. The dual crop coefficient approach of the FAO and adjustment procedures for local conditions could be evaluated in parallel to such a study.

Our research has shown that Kt cannot necessarily be used interchangebly with Kcb. However, it was also demonstrated that sap flow could provide accurate information regarding water flow and therefore transpiration of trees. The dual crop coefficient approach states that it models transpiration and evaporation separately. It should therefore be ideal if transpiration, estimated from Kt values, is combined with a reliable soil water evaporation submodel. In this regard the detailed two-dimensional finite difference soil water balance model for hedgerow tree crops or other suitable evaporation models could be considered to be used either directly, or to determine evaporation coefficients for simpler models. It will be very valuable if an evaporation model is calibrated and validated for the main soil types in deciduous fruit producing areas, including gravelly soils.

Application in practice

With regard to practical use of the SWB model for real time irrigation scheduling on farms, trained professionals to collect input data and assist farmers in using the model, are perhaps needed. Fractional interception can be used to estimate basal crop coefficients for apple and peach, or leaf area for pear orchards for which those coeffcients are not available.

Lateral water movement into orchards on slopes and soil variability may limit the use of models for real time irrigation scheduling. In such cases direct measurement of soil water content, which is also prone to the soil variability problem, may become more important. However, where lateral water flow into orchards is not a concern, real time irrigation scheduling models, that are verified through measurements, could aid in improved water management and saving of limited water resources. Integration of such an irrigation scheduling model with other models in a GIS based, integrated, farm management system that communicates with fruit producers through a computer network could be valuable to promote environmentally friendly farming and possibly facilitate a real time irrigation scheduling service in the Western Cape.

Capacity building

Capacity building amongst farmers was achieved by means of an information day in the Elgin production area. This event was organized by the project team to introduce the project to producers/ farm managers and make them aware of the value of correct irrigation scheduling. The different methods of irrigation scheduling were discussed and the principles of the SWB model introduced. The results on calibration of SWB was on another occasion presented to a group of farming consultants at a "Fieldsmans'" meeting in Elgin. Lectures at a short course, presentations at symposiums and publications also contributed to capacity building. Ms Beukes obtained an MSc degree in Botany at the University of Stellenbosch through completion of the thesis titled "The effect of regulated deficit irrigation on the production and fruit quality of peaches." Valuable experience in research methodology and reporting was gained from the project and will be used in the PhD study of Ms Volschenk with the title "The effect of saline irrigation on selected soil properties and the plant physiology, vegetative and reproductive growth of apricot trees".

ACKNOWLEDGEMENTS

The research in this report emanated from a project funded by the Water Research Commission and entitled:

THE EVALUATION OF A MODEL FOR WATER USE IN DECIDUOUS FRUIT ORCHARDS AND SCHEDULING OF IRRIGATION WITH THE AID OF METEOROLOGICAL DATA

The Steering Committee responsible for this project, consisted of the following persons:

Dr G.R. Backeberg	:	Water Research Commission (Chairperson 1998 to 2000)
Dr S. Mkhize	:	Water Research Commission (Chairperson 2001 to 2003)
Prof J.G. Annandale	:	University of Pretoria
Mr H.M. du Plessis	:	Water Research Commission
Dr J.E. Hoffman	:	University of Stellenbosch
Mr J.J.N Lambrechts	:	University of Stellenbosch
Mr E.C. Molteno	:	Deciduous Fruit Producers Trust
Mr R. Müller	:	Deciduous Fruit Producers Trust
Dr P. Myburgh	:	Agricultural Research Council
Prof S. Walker	:	University of the Free State

The financing of the project by the Water Research Commission and the contribution of the members of the Steering Committee is acknowledged gratefully.

This project was only possible with the co-operation of many individuals and institutions. The authors therefore wish to record their sincere thanks to the following:

Institutions:
Agricultural Research Council Infruitec-Nietvoorbij
Deciduous Fruit Producers Trust

Participating producers:
Bergendal (A. Kuiper) for potted trees provided for sap flow calibration studies.
Ashton Canning (E. Carsten & A. Rossouw) for experimental plots in commercial orchards and availability of orchard management and meteorological data.
De Rust (P. Cluver Jr. & W. and K. Voigt) for experimental plots in commercial orchards and availability of orchard management and meteorological data.
Molteno Brothers (G. Parkins) for experimental plots in commercial orchards, availability of orchard management and meteorological data and installation of drainage.
Oak Valley Estates (E. Heydenrich & P. Visser) for experimental plots in commercial orchards and availability of orchard management data.

Other:
Dr N.Z. Jovanovic for invaluable assistance regarding the set-up, running and calibration of the SWB model.
Mr N. du Sautoy for assistance with evaluation of the model.
Technical staff (Miss J.F. de Villiers, Mr F.Coetzee), assistants (Mr J. de Koker, Mr T. Harris) and colleagues of the Soil Science Division at ARC Infruitec-Nietvoorbij assisting in collection and processing of data.

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS, ACRONYMS AND SYMBOLS

ASH	Ashton
BR	Bon Rouge pear cultivar
D	Drainage (mm)
ρ_f	Bulk density of the fine-earth fraction (Mg m^{-3})
ρ_s	Bulk density of the stones (Mg m^{-3})
DR	De Rust
ET	Evapotranspiration (mm)
ETo	Reference evapotranspiration (mm)
FI	The fractional proportion of available solar radiation intercepted by the trees
F_{max}	The proportion of solar radiation which would be intercepted if the trees were solid
FOR	Forelle pear cultivar
GD	Golden Delicious apple cultivar
GDGP2001	Simulation field name for the Golden Delicious apple tree plot at Grabouw Farms during the 2000/2001 season
GDMG2001	Simulation field name for the Golden Delicious apple tree plot at Molteno Glen during the 2000/2001 season
GDOV2001	Simulation field name for the Golden Delicious apple tree plot at Oak Valley during the 2000/2001 season
GP	Grabouw farms
GS	Granny Smith apple cultivar
GSGP2001	Simulation field name for the Granny Smith apple tree plot at Grabouw Farms during the 2000/2001 season
I	Irrigation (mm)
K	Radiation extinction coefficient
Kc	Crop coefficient
Kcb	Basal crop coefficient
Kt	Transpiration coefficient
L'	Leaf area index divided by the mean daily shadow area
LA	Leaf area (m^2)
LAI	Leaf area index (m^2 m^{-2})
LAD	Leaf area density (m^2 m^{-3} or m^{-1})
MG	Molteno Glen
NEETH	Neethling peach cultivar
OV	Oak Valley
P	Precipitation (mm)
P-BR2001FS	Simulation field name for the Bon Rouge pear plot at De Rust during the 2000/2001 season
P-F2001FS	Simulation field name for the Forelle pear plot at Oak Valley during the 2000/2001 season
P-RM2001FS	Simulation field name for the Rosemary pear plot at De Rust during the 2000/2001 season
PCA	Plant canopy analyzer
PCHAK2001	Simulation field name for the Keisie peach plot at Ashton during the 2000/2001 season
PCHAN2001	Simulation field name for the Neethling peach plot at Ashton during the 2000/2001 season
PCHRN2001	Simulation field name for the Neethling peach plot at Robertson during the 2000/2001 season

PEACH(KS)	Peach tree plot, variety Keisie
PEACH(N)	Peach tree plot, variety Neethling
PEARPT2001	Simulation field name for the Packhams' Truimph pear plot at Molteno Glen during the 2000/2001 season; soil water deficit from clean cultivated area for simulation
PET	Potential evapotranspiration
PT	Packhams' Truimph pear cultivar
PT2001FS	Simulation field name for the Packhams' Truimph pear plot at Molteno Glen during the 2000/2001 season; soil water deficit from total area for simulation
Quasi-2D	Quasi-two dimensional
R	Runoff (mm)
RFI	Relative fractional interception of solar radiation
RM	Rosemary pear cultivar
ROB	Robertson
SWB	Soil Water Balance
SWC	Soil water content (mm)
SWC_b	Soil water content at beginning of period (mm)
SWC_e	Soil water content at end of period (mm)
$SWC_{w\ cc}$	Weighted soil water content of the cover crop area
$SWC_{w\ strip}$	Weighted soil water content of clean cultivated soil surface
$SWC_{w\ total}$	Weighted volumetric soil water content of total soil surface
W_{cc}	Weight assigned to neutron water meter access tubes in the cover crop area
W_{strip}	Weight assigned to neutron water meter access tubes in the clean cultivated surface
$W_{strip\ T1\ to\ T4}$	Weight assigned to neutron water meter access tubes T1 to T4 in the clean cultivated surface
$W_{strip\ T5\ \&\ T7}$	Weight assigned to neutron water meter access tubes T5 and T7 in the clean cultivated surface
W_{total}	Weight assigned to neutron water meter access tubes in the total surface.
$W_{total\ T1\ to\ T4}$	Weight assigned to neutron water meter access tubes T1 to T4 in the total surface
$W_{total\ T5\ \&\ T7}$	Weight assigned to neutron water meter access tubes T5 and T7 in the total surface
$W_{total\ T6\ \&\ T8}$	Weight assigned to neutron water meter access tubes T6 and T8 in the total surface
ZAND	Zandvliet peach cultivar

δT	The elapsed time to temperature equilibration between two temperature probe sets after initiation of a heat pulse (s)
θ_v	Volumetric soil water content ($m^3\ m^{-3}$)
$\theta_{v\ T}$	Volumetric water content in the percentage of total soil volume including stones
$\theta_{v\ M\%\ stone\ corrected}$	Volumetric water content corrected for mass percentage stones
$\theta_{v\ N}$	Volumetric water content in the percentage net soil volume excluding stones
τ	The amount of solar radiation transmitted to the orchard floor
τ_f	The amount of solar radiation transmitted to the orchard floor even if the trees were totally opaque
τ_c	The amount of solar radiation reaching the ground only after passing through the orchard canopy

FAO	Food and Agriculture Organization of the United Nations
MORECS	Meteorological Office Rainfall and Evapotranspiration Calculation System

CHAPTER 1

INTRODUCTION

1.1 Background

Water is the most limiting natural resource in terms of development in South Africa and indications are that present resources will be near maximum utilization within the next 8 years (Liebenberg & Uys, 1995). The revised Water Law Principles state that ecological and basic domestic needs should enjoy first priority in the use of available water. However, fruit production in the Western Cape is only possible under irrigation and pressure on this sector is expected to optimize its future water use.

A survey during 1997 in the Western Cape though, revealed that about 80% of producers do not use scientific irrigation tools or programmes (Murray, Biesenbach & Badenhorst Consulting Engineers Incorporated, 1997). This could explain the widespread tendency among irrigation farmers to over-irrigate. This results in wastage of water, high consumption of electricity, as well as leaching of fertilizers and pollution of ground water. The adverse effect on crops and soils is often not immediately visible or readily linked to excess water. The quality of water resources is already deteriorating rapidly and measures to stem this trend are urgently needed.

Irrigation scheduling is the process to decide when to irrigate crops and how much water to apply. Procedures used to schedule irrigation in orchards include those utilising soil or plant measurements to determine irrigation timing and those based on a water budget to estimate both depth of application and timing (Goldhamer & Snyder, 1989). The water budget method requires evapotranspiration (ET) estimation and since direct measurement thereof is not always possible on a large scale, ET can be estimated by mathematical models from meteorological, soil and crop-related data.

Several models to estimate ET by means of meteorological data are already in use in South Africa. However, these models were developed for annual crops covering the full soil surface and under full surface irrigation. It is therefore not applicable to orchard situations where strip irrigation is practiced and crop architecture makes estimation of water use from meteorological data more difficult. Evapotranspiration is also affected by soil type, soil water content, tree size, phenological growing phase, training system, planting densities, irrigation system, irrigation cycle and various other cultivation practices.

The fruit industry is a major source of employment and of foreign exchange (National Department of Agriculture, 1998). Severe water restrictions superimposed on the announced price increases of water will have a detrimental effect on this industry. Improved irrigation management through a reliable model can save a substantial amount of water to the benefit of all. Quality of the crop can, however, because of its export nature, never be compromised. Systems with different degrees of sophistication will have to be applied for producers who have, and those who do not have access to their own weather stations. The existing automated weather station network makes the implementation of a real-time irrigation scheduling service a very feasible proposition. A reliable irrigation scheduling model that is easy to use and which can be linked to automated irrigation systems should therefore find universal acceptance.

1.2 Objective(s)

To evaluate a mathematical model for prediction of water use of deciduous fruit trees from meteorological data.

1.3 Structure of the report

The first approach of the study was to do a survey of available models and analyse and identify relevant models. One model that could generate the proposed objectives was to be selected and parameters needed to employ the model identified. The selection of an appropriate model is described in section 3 and detailed model descriptions for one national and one international model are attatched (Appendices A & B). The collection of data for calibration of the selected model and estimation of basal crop coefficients (Kcb) is presented in section 4. The model was calibrated for apple, pear and peach trees. Estimation of Kcb for other orchards from easily measurable orchard parameters is discussed in section 5.

Data of the 1999/2000 season was supposed to be used to evaluate the model if the Kcb values could be successfully estimated for the orchards. Evaluation of the model, however, was not possible, because the specific dates of all irrigation events were not available and concerns regarding excessive leaching were raised by steering committee members.

CHAPTER 2

LITERATURE

The horticulture production process can be characterized as a highly complex system and computer technology and models can be applied to support farm management (Lenz, 1998). However, to find a model that can accommodate the large variability found on deciduous fruit farms is exceptionally difficult. Orchards differ with regard to fruit kind (pome and stone fruit); orchard composition (more than one cultivar per orchard; presence or absence of cover crops), canopy management practices, irrigation systems (sprinkler / micro irrigation) and management (fraction of soil wetted, irrigation frequencies applied), topography, soil type as well as climate.

Growth, productivity and quality of horticultural crops are closely linked to water status (Jones & Tardieu, 1998) and management of water status of trees is therefore important to achieve optimal production and the high fruit quality standard demanded by consumer markets. Timeous irrigation decision making relies on the measurement or estimation of ET that is used as input for water balance calculations. The irrigation manager can use equipment to monitor changes in water content in the soil or plant water status to aid in decision making and/or rely on a model of the system for this purpose. Such a model can be based on statistics applied to a set of experimental data or on physical laws (Gary, Jones & Tchamitchian, 1998).

Computerized calculation of ET from water balance models could enhance irrigation scheduling management. Basically two approaches for calculation of ET were identified namely, the use of simple crop coefficient irrigation scheduling models or that of crop growth models (Howell, 1996). Crop growth models often compute soil water evaporation and crop transpiration separately (Ritchie, 1972) for daily periods using leaf area index (LAI) to partition ET in evaporation and transpiration components. Such an approach would be preferable to accommodate simulations for the variable crop, soil and management scenarios present in orchards.

However, a limited number of growth models for deciduous fruit crops have been developed and validated. This could be attributed to the complex physiology of perennial crops due to the following complicating factors: [a)] physiologically inert biomass accumulates in trees due to some biomass that dies; [b)] growth in perennial trees often reflects interactions with a previous environment, for example biennial bearing and [c)] deciduous trees have unique physiological processes such as development of winter hardiness, the process leading to physiological rest, breaking of rest and the need to accumulate stored reserve material to initiate growth following dormancy (Seem & Elfving, 1986). Despite these difficulties, growth models were developed for apple (Lakso *et al.*, 1999) and peach (Grossman & DeJong, 1994) trees, but neither was linked to a tree water balance model. Some of the input data needed for the models are furthermore considered too laborious to be determined by farm managers in a farming system. The leaf area (LA) development submodel for apple trees, for example, needs the total number of shoots per tree as an input (Lakso & Johnson, 1990).

Light interception and distribution through the canopy has a major effect on transpiration via energy effects on leaf and air temperatures and leaf-air humidity gradients and is thus a very important factor that influences tree productivity and water use (Johnson & Lakso, 1991). Approaches to modelling light interception in orchards includes canopy section models (Charles-Edwards & Thornley, 1973; Charles-Edwards & Thorpe, 1976), canopy layer models (DeJong & Goudriaan, 1989) as well as whole canopy models (Jackson & Palmer, 1979), with the latter being the simplest. Although the more complicated canopy section model was validated to estimate photosynthesis and transpiration of a small apple tree (Thorpe *et al.*, 1978), the whole canopy model of Jackson and Palmer (1979) is considered to be able to simulate reality with reasonable accuracy (Johnson & Lakso, 1991). Preliminary data for peach trees from a weighing lisimeter indicated that light interception predicted by the model was a better predictor of tree water use than total LA. The only inputs needed for the model are canopy and tree spacing dimensions and total LA (Johnson & Lakso, 1991). The direct determination of the total LA for deciduous fruit trees, however, is a time-consuming task demanding many man-hours and, as indicated above, the input needed for daily estimation thereof by growth models is also problematic.

The less demanding and simpler crop coefficient irrigation scheduling model approach is therefore preferred in practice for irrigation scheduling of deciduous fruit crops, especially where automatic weather station network services provide real time weather data, for example CIMIS in California (Eching, Moellenberndt & Brainard, 1995) and AGROMET in Washington State (Ley, 1994). Crop ET is calculated by multiplying reference crop ET (ETo) by a crop coefficient (Kc) (Allen *et al.*, 1998). The ETo is the ET rate from a reference surface, a hypothetical grass reference crop with specific characteristics, not short of water and is calculated from weather data using the FAO Penman-Monteith equation. Crop ET differs from the ETo and the effects of ground cover, canopy properties and aerodynamic resistance of the crop are integrated into the crop coefficient (Kc). The Kc can furthermore be separated into two coefficients, a Kcb and a soil evaporation coefficient (Ke). This enables one to predict the effect of specific wetting events on soil evaporation separately from transpiration.

The Food and Agriculture Organisation (FAO) of the United Nations recommend the use of averaged single crop coefficients for normal irrigation planning and management purposes, the development of basic irrigation scheduling and most hydrologic water balance studies (Allen *et al.*, 1998). However, when daily values for Kc are needed for specific fields and crops, a separate transpiration and evaporation coefficient should be considered. The separate estimation of transpiration and evaporation by the dual crop coefficient approach or the approach of Myburgh (1998) has potential to address the problem for estimation of ET for variable orchards. Myburgh (1998) developed and validated a water consumption model that accommodates transpiration and evaporation submodels for vineyards with the transpiration submodel being developed from sap flow and LA data. The ideal would be to supply farmers with an irrigation scheduling model that requires reasonable input data and provides output information that enables decision making to improve their water management. Means to determine input information such as transpiration coefficient (Kt) values for different fruits and varieties, as well as soil evaporation coefficients for different soil types and irrigation system/management combinations should also be determined.

CHAPTER 3

SELECTION OF AN APPROPRIATE MODEL

3.1 Introduction

Various local and international crop growth (Grossman & DeJong, 1994; Lakso & Johnson, 1990) and irrigation scheduling models (SWB or Soil Water Balance, Putu, MORECS or Meteorological Office Rainfall and Evapotranspiration Calculation System of the United Kingdom) were theoretically evaluated, from which a suitable model for water consumption of deciduous fruit trees could be selected. The selected model was then evaluated further by collection of minimum data sets from orchards. However, due to the complicated nature of crop growth models for deciduous fruit trees and the limited research period available, it was decided to evaluate only irrigation scheduling models which used real-time weather data. One local and one international model was selected for theoretical evaluation.

The ideal model for estimation of water consumption of deciduous fruit trees should be able to predict water consumption for orchards of different crop and management combinations accurately from daily meteorological data and facilitate timeous irrigation scheduling to ensure optimal yield and fruit quality. Management variables include different combinations of planting density, tree training systems, summer pruning, clean cultivation, cover crops, mulching, ridging, terraces, wind breaks and crop density. Irrigation systems wet full surface (flood, sprinkler) or only part of the soil surface (micro, drip). Currently traditional Kc values for use with Class A-pan evaporation are in use by the deciduous fruit industry in the Western Cape. The performance of the Class A-pan evaporation has been described as "erratic" if used for estimation of evaporation for periods less than ten days. The use of Penman-Monteith (Allen *et al.*, 1998) was therefore the best option for estimation of reference ET. It was therefore necessary that the selected model employs Penman-Monteith reference ET for estimation of the atmospheric evaporative demand.

3.2 Model description

3.2.1 Soil Water Balance

Soil Water Balance (SWB) is a weather-data based, mechanistic, real time, generic crop, soil water balance, irrigation scheduling model (Annandale *et al.*, 1999). Water movement in the soil profile is simulated with a simple cascading model (Campbell & Diaz, 1988). Potential evapotranspiration (PET) is calculated adopting the internationally standardised FAO Penman-Monteith methodology. The two components of PET (potential evaporation and potential transpiration) are estimated using canopy cover (Ritchie, 1972). The SWB model gives a detailed description of the soil-plant-atmosphere continuum, making use of weather, soil and crop databases. Mechanistic crop growth parameters needed to run

SWB, are not available for all crops, and growth analyses data are required to determine them. In particular, growth analysis for trees is time consuming and expensive. For this reason, an alternative soil water balance has been developed based on the Kcb approach of the FAO (Jovanovic & Annandale, 1999). This approach requires Kcb factors and length of crop stages as crop specific input. Kcb factors and length of stages are available from the FAO database (Allen *et al.*, 1998), but these may change for different locations.

SWB was recently further developed to combine the FAO-based crop factor model with a quasi-2D cascading soil water balance model to predict crop water requirements on a daily time step for hedgerow tree crops from limited input data. An FAO-based crop factor procedure has been developed and combined with the mechanistic SWB model, thereby still allowing evaporation and transpiration to be modelled separately as supply or demand limited processes. This model includes a semi-empirical approach for partitioning of above-ground energy, a cascading soil water redistribution that separates the wetted and non-wetted portion of the ground, as well as prediction of crop yields. The crop factor model does not grow the canopy mechanistically and therefore the effect of water stress on canopy size is not simulated. The crop factor model should, however, still perform satisfactorily if the estimated canopy cover closely resembles that found in the field. Improvements made to the mechanistic SWB model included an FAO-type crop factor modification, a soil water balance with localised (micro- or drip) irrigation and yield predictions with the FAO model (Annandale *et al.*, 2002). The input parameters required to run the FAO-type crop factor model are as follows: planting date, latitude, altitude, maximum and minimum daily air temperatures, FAO crop factors and duration of crop stages. The input data required to run the two-dimensional cascading model are rainfall and irrigation amounts, volumetric soil water content at field capacity and permanent wilting point and initial volumetric soil water content for each soil layer. Row spacing, wetted diameter, distance between emitters and the fraction of roots in the wetted volume of soil are also required. A more detailed description of the model is included in Appendix A.

3.2.2 MORECS

A previous publication of the FAO (Smith, 1992) outlined a two-step and a one-step method for estimation of crop ET by means of the Penman-Monteith equation. According to the two-step method ET is calculated from a Kc and ETo. The one-step method entails adjusting the albedo and the aerodynamic and canopy surface resistance to the growing characteristics of the growing crop, in order to estimate the ET rate directly. The MORECS model employs the one-step method (Thompson, Barrie & Ayles, 1981).

The Penman-Monteith equation is used to estimate ET for a variety of surface types and locations. The system relies on routinely observed daily meteorological data as its input. An important feature of MORECS is a scheme designed to determine potential and actual ET over a variety of different surface types. Using MORECS such estimates can be obtained for open water, bare soil, grass, cereals, potatoes, deciduous trees, conifers, orchards and pastures.

The British MORECS has been modified and validated for use in the north-eastern United States. Presently historical and real-time estimates of PET from grass, evaporation from bare soil and standard evaporation pans, as well as actual ET from grass and deciduous tree-covered surfaces are available for the region. In addition, soil water deficits can be calculated under grass, bare soil and deciduous trees. Evapotranspiration and soil moisture estimates can also be obtained for a variety of other crops, however, the unavailability of reliable verification data for other surface covers has precluded validation of the model for other surface cover types. The description of the model that is available includes information on evaporation, precipitation and dew deposition, runoff and water budget calculations. The basic information regarding the model is shortly summarised in Appendix B.

3.3 Discussion and conclusions

The latest FAO guidelines for computing crop water requirements recommended that the FAO Penman-Monteith method is used only for estimating ETo. The reason for this was that albedo and resistances are difficult to estimate accurately, as they will vary continuously during the growing season as climatic conditions change, as the crop develops and with wetness of the soil surface. Canopy resistance will further be influenced by the soil water availability, and it increases strongly if the crop is subjected to water stress. There is furthermore still a lack of consolidated information on the aerodynamic and canopy resistance for the various cropped surfaces. It is unclear if and in which way MORECS overcomes these problems.

The mechanistic SWB irrigation scheduling model was selected for evaluation because the way in which evaporation and transpiration are simulated has the possibility to address the vast array of management practices and irrigation methods employed in the deciduous fruit industry (Annandale *et al.*, 1999). The developers of the model were also already involved in research on deciduous tree crops. The model has since the start of this project been further developed to include a FAO-based crop factor model with a quasi-2D cascading soil water balance model which is more suitable than the original model for the estimation of ET from orchards (Annandale *et al.*, 2002). However, no locally determined Kc or Kcb factors for use with Penman-Monteith ETo are available for the deciduous fruit trees in the Western Cape and they had to be determined.

CHAPTER 4

CALIBRATION OF THE SWB FAO-BASED CROP FACTOR MODEL

Data collected during the 2000/2001 season was used for calibration of the cascading two-dimensional version of the SWB model.

4.1 Materials and methods

Calibration of the model was approached in two ways. The first approach was to determine a statistical function for estimation of transpiration and to calculate Kt values for the initial, mid and late growth stages. The SWB model estimates transpiration and evaporation separately. It should therefore be possible to use Kt values instead of Kcb values in the model to estimate the transpiration component of ET. Neutron water meter determined soil water content values could then be used to calibrate the model.

The second approach was to perform simulations and visually fit SWB predicted soil water deficit to soil water deficit calculated from neutron water meter measured soil water content data from orchards, until the best statistical fit was obtained.

Experimental plots: Experimental sites that represented variation in planting density, tree size, crop load and soil type were selected for calibration of the SWB model during the 2000/2001 growing season for apple, pear and peach trees. The position of plots in orchards was selected to avoid border effects. An experimental plot comprised five trees. A prerequisite for sites to qualify was that no lateral subsurface inflow of water from adjacent areas would occur. Soil profiles for all the experimental plots were described and classified according to the South African Soil classification system (Soil Classification Working Group, 1991).

Meteorological parameters: Air temperature, wet-bulb and dry-bulb temperature, solar radiation, wind speed at 2 m height and precipitation were measured hourly by automatic weather stations from August/October to May. The temperature sensors were enclosed in standard Stevenson screens. Daily Penman-Monteith ETo was calculated according to Allen *et al.* (1998) from data recorded by the automatic weather station located nearest to a specific plot. Missing weather data were, where needed, obtained from other automatic weather stations representative of the specific plots.

Irrigation scheduling: Irrigation scheduling for specific farms was performed by farm managers or irrigation scheduling consultants. Irrigation dates were predicted from crop factors and Class-A pan evaporation and precipitation data and adjusted according to weekly soil water content measurements using a neutron water meter. Some farm managers used profile wetting patterns in combination with the neutron water meter measurements and irrigation was applied when water extraction decreased in the deeper soil layers. The recommended profile refill point was the laboratory determined soil water content at a soil matric potential of –100 kPa. Farm managers were advised to adjust their irrigation if over-irrigation or under-irrigation was detected through weekly soil water content measurements by the project team.

Soil water content: Soil water content was monitored weekly at 200, 300, 600 and 900 mm depths by means of a neutron water meter (CPN 503DR Hydroprobe® Moisture gauge, Boart Longyear Company, California, USA). Calibration curves to convert neutron water meter counts to volumetric soil water content (θ_v) for different soils were predicted from soil clay and silt content according to the method of Karsten, Deist and De Waal (1975). Separate calibration curves were obtained for depths shallower than 300 mm (Karsten & Van der Vyver, 1979). A bulk density of 1.5 Mg m^{-3} was used for all plots. Volumetric soil water content (m m^{-1}) was converted to soil water content (SWC) in millimeters for 600 mm and 900 mm deep soils as follows:

$$SWC_{0\text{-}600\ mm} = (0.2 \times (\theta_{v\ 200mm} + \theta_{v\ 300\ mm} + \theta_{v\ 600\ mm})) \times 1000 \qquad (4.1)$$

$$SWC_{0\text{-}900\ mm} = (0.2 \times \theta_{v\ 200mm}) + (0.2 \times \theta_{v\ 300\ mm}) + (0.3 \times \theta_{v\ 600\ mm}) + (0.2\ m \times \theta_{v\ 900\ mm}) \times 1000 \qquad (4.2)$$

where 0.2 and 0.3 are depth increments in metres and 1000 is for conversion from metres to millimeters.

In order to evaluate the original one-dimensional version of SWB (Version 1) it was necessary to obtain representative estimations of soil water in the total area allocated to the tree. Eight access tubes for the neutron water meter were installed in two concentric ellipses at one tree per plot. Neutron water meter access tubes were distributed according to a double-ellipsoid pattern that represented the full surface area allotted per tree (Fig. 1). At the end of October 2000, however, the steering committee recommended that the project team evaluate the cascading-2D version of SWB. It was decided that the contribution of the different neutron water meter access tubes (T1 to T8) should be weighted by the fraction of the total profile it represents. At some plots the clean cultivated strip, while at others, the total surface was irrigated. Different weights were therefore assigned to access tubes in the clean cultivated strip (W_{strip}), cover crop area (W_{cc}) and total surface (W_{total}). Weights were calculated as follows:

For the clean cultivated strip:

$W_{strip\ T5\ \&\ T7}$ = [(half the distance of access $tubes_{T1\ \&\ T2}$ perpendicular to the tree row) + (half the distance of access $tubes_{T3\ \&\ T4}$ perpendicular to the tree row)] / clean cultivated width. (4.3)

$W_{strip\ T1\ to\ T4}$ = 1 - $W_{strip\ T5\ \&\ T7}$ (4.4)

A weight of 1 was assigned to access tubes in the cover crop surface, the two access tubes representing the area (T6 & T8) being installed in the same position on both sides of the tree row.

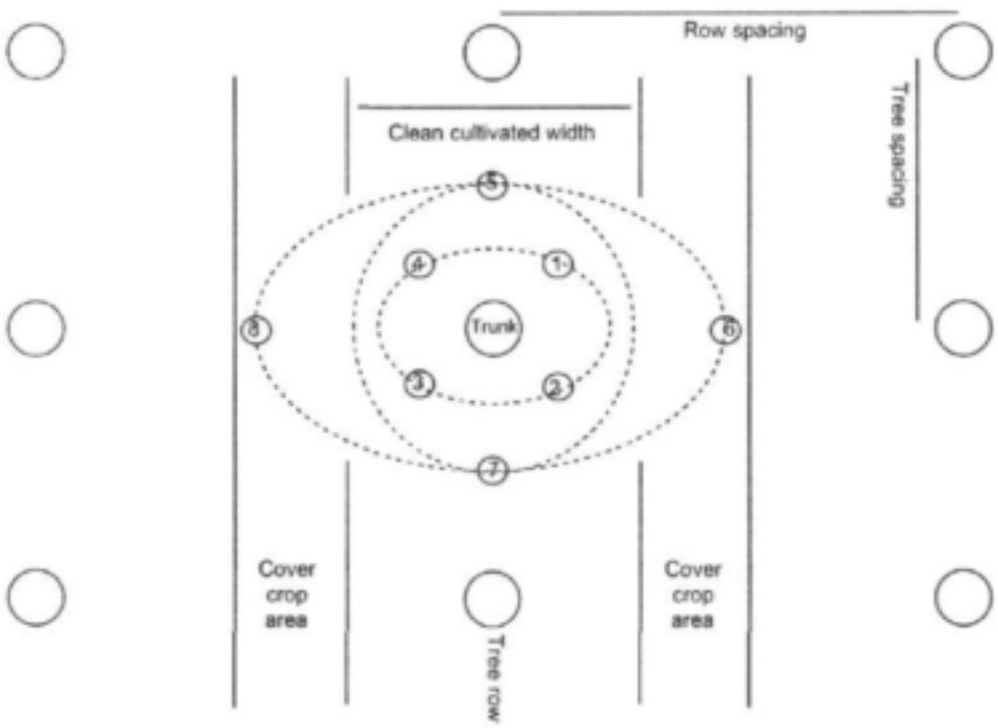


Figure 1. Positions of neutron probe access tubes used in the double-ellipsoid configuration for estimation of total profile volumetric soil content in experimental plots during the 2000/2001 season.

For the total surface:

$$W_{\text{total T5 \& T7}} = [(\text{half the distance of access tubes}_{\text{T1 \& T2}} \text{ perpendicular to the tree row}) + (\text{half the distance of access tubes}_{\text{T3 \& T4}} \text{ perpendicular to the tree row})] / \text{row width} \tag{4.5}$$

$$W_{\text{total T6 \& T8}} = (\text{Row width} - \text{clean cultivated width})/\text{Row width} \tag{4.6}$$

$$W_{\text{total T1 to T4}} = 1 - (W_{\text{total T5 \& T7}} + W_{\text{total T6 \& T8}}) \tag{4.7}$$

Weighted soil water content was calculated for the clean cultivated soil surface ($SWC_{\text{w strip}}$), the non-irrigated soil surface or cover crop area ($SWC_{\text{w cc}}$) and the total soil surface ($SWC_{\text{w total}}$).

$$SWC_{\text{w strip}} = (\text{average SWC}_{\text{T1 to T4}} \times W_{\text{strip T1 to T4}}) + (\text{average SWC}_{\text{T5 \& T7}} \times W_{\text{strip T5 \& T7}}) \tag{4.8}$$

$$SWC_{\text{w cc}} = \text{average SWC}_{\text{T6 \& T8}} \tag{4.9}$$

$$SWC_{\text{w total}} = (\text{average SWC}_{\text{T1 to T4}} \times W_{\text{total T1 to T4}}) + (\text{average SWC}_{\text{T5 \& T7}} \times W_{\text{total T5 \& T7}}) + (\text{average SWC}_{\text{T6 \& T8}} \times W_{\text{total T6 \& T8}}) \tag{4.10}$$

Soil water retention: Soils were sampled at all positions where neutron water meter access tubes were installed at 0 mm to 300 mm, 300 mm to 600 mm and 600 mm to 900 mm depths. For each plot samples were pooled per depth. The soil samples were analysed for water-holding capacities according to the method of De Kock *et al.* (1977), as well as particle size distribution (De Kock, undated). Percentage stone of dried soil samples was calculated as: Stone Mass% = [(Total soil sample mass – mass of soil particles <2 mm)/Total soil sample mass].

Laboratory determined soil water retention curves are not always a true reflection of the retention curve under field conditions. *In situ* soil matric potential curves were therefore determined to compare the estimated SWC values at field capacity (-5 kPa, -10 kPa) and refill point (-100 kPa) with the laboratory determined values and neutron probe measured SWC values of a full profile at the start of the season. Soil matric potential curves were determined *in situ* at Grabouw Farms for the Golden Delicious and Granny Smith plots, at De Rust for the Rosemary and Bon Rouge plots, at Molteno Glen for the young Golden Delicious and Packhams' Truimph plots and at Oak Valley for the Forelle and Golden Delicious plots. Mercury manometer tensiometers were installed in the plant row *ca.* 300 mm from the neutron water meter access tube in the plant row and *ca.* 200 mm from the tree trunk, at depths of 200, 300, 600 and 900 mm. The volumetric soil water content at this specific access tube and soil matric potential were determined once a week by means of the neutron water meter and tensiometers, respectively. Volumetric water content of soils at permanent wilting point (–1500 kPa) was estimated from clay and silt content by means of the Texture tool in SWB and empirically corrected for mass percentage stone content by the following equation (Knight,1992):

$$\theta_{\text{v Mass\% Stone corrected}} = \theta_{\text{v (-1500 kPa)}} \times 0.9907 - 0.004 \times \text{Mass\% Stone} - 0.0000584 \times \text{Mass\% Stone}^2 \tag{4.11}$$

For modelling purposes, however, a mechanistic approach is preferred, and θ_v can be corrected more mechanistically for stones by calculating the water content in the percentage of total soil volume ($\theta_{v\,T}$) including stones, from the water content in the percentage net soil volume ($\theta_{v\,N}$), excluding stones, according to Reinhart (1961) as follows:

$$\theta_{v\,T} \quad = \quad \theta_{v\,N} \times (100 - \text{volume percent stones}) / 100 \qquad (4.12)$$

The percentage stones by mass can be converted to volume percentage stones using the formula of Avery & Rascomb (1974):

$$\text{Volume \% stone} = (\text{mass\%} \times \rho_f)/[(100 - \text{mass\%})\rho_s + \text{mass\%} \times \rho_f] \times 100 \qquad (4.13)$$

where

ρ_f = bulk density of the fine-earth fraction (Mg m^{-3})

ρ_s = bulk density of the stones (Mg m^{-3})

Avery & Rascomb (1974) recommended a value of 2.7 Mg m^{-3} for ρ_s and a value of 1.5 Mg m^{-3} was used for ρ_f.

The empirical and more mechanistic method for stone correction of laboratory determined or SWB Texture tool-estimated volumetric soil water content was compared to ascertain the validity of the empirical approach.

Soil water balance: Water use was calculated at each plot using the universal soil water balance equation as follows:

$$ET = SWC_b - SWC_e + P + I - R - D \qquad (4.14)$$

Where:

ET = Evapotranspiration over period (mm)

SWC_b = Soil water content at beginning of period (mm)

SWC_e = Soil water content at end of period (mm)

P = Precipitation (mm)

I = Irrigation (mm)

R = Runoff

D = Drainage

Precipitation data was obtained from the automatic weather stations. Precipitation was also measured by means of a rain gauge installed at each plot. Irrigation volumes were monitored by means of water meters. **Irrigation volumes** applied to the wetted area **were expressed as mm based on the wetted strip width** and corrected for an application efficiency of microsprinkler irrigation systems of 0.85 (Clemens, 2000). The application efficiency indicates how effectively water reached the soil surface after being released from emitters. Precipitation was assumed to be 100% effective and runoff to be negligible. Drainage was considered to be instantaneous and estimated from the soil water deficit of the soil profile of the previous week to a full profile at the start of the season, irrigation applied and precipitation received ($\text{Drainage}_{\text{week } n}$ = $\text{Soil water deficit}_{\text{week } n\text{-}1}$ + $\text{Irrigation}_{\text{week } n}$ + $\text{Precipitation}_{\text{week } n}$). It was assumed that no drainage occurred if the calculation resulted in negative numbers. Separate soil water balances were calculated for the irrigated and non-irrigated areas. A monthly crop coefficient was calculated from monthly averaged ET per day, expressed as equivalent evapotranspiration over the whole area, and monthly averaged daily ETo.

Leaf area index and density: LAI was measured by means of the LAI2000 plant canopy analyzer (PCA) (Li-Cor Inc., Lincoln, Nebraska, USA). A calibration curve was developed to convert PCA readings to actual LA for pome and stone fruit. LAI of five pear, twenty-nine apple and fifteen peach trees varying in size and leaf density was measured after sunset. Measurements were made 20 mm above the soil surface. Field of view was restricted to 270°. The restricted view area was directed to the trunk of the tree and the operator. Leaves were stripped from trees the day after PCA measurements and the total LA determined by means of a Licor 3100 LA meter (Li-Cor Inc., Lincoln, Nebraska, USA). PCA measurements were done with all five detector rings activated. The two outer rings (rings 4 and 5) were masked by means of the Li-Cor C2000 software to eliminate effects of open spaces and adjacent trees on LAI values. Data were collected during May and June 1999, April 2000 and February and April 2001. Tree dimensions and LAI of trees at the experimental plots were measured approximately once a month during the 2000/2001 season. LAI measurements started approximately two and a half hours before sunset to allow measurements at all plots. PCA LAI measurements were converted to LA by means of the calibration equation.

Canopy diameter, tree height and canopy height above the ground was used to calculate tree volume. An inverted cone tree form was used (Fig. 2) and tree volume was calculated as $^1/_3\pi r^2 h$ with r as radius and h as canopy height. The r was calculated as (diameter over the work row + diameter within the tree row)/4 and h as tree height minus the height of the canopy above the ground. Data were integrated to provide values for dates when LAI measurements were done. Leaf area density (LAD) was calculated as (LA/Tree volume).

Sap flow calibration:

A laboratory calibration of the heat pulse sap flow system was done according to a method described by Green and Clothier (1988). Water was forced by a pressurized system through a stem section (200 mm – 250 mm) and the volumetric flow of water determined simultaneously to heat pulse measurements. A calibration curve was established to estimate sap flux per unit trunk cross section area ($cm^3\ cm^{-2}\ h^{-1}$) from δT values. Calibrations were performed on 1) three stem sections each of increasing diameter for nine year-old Golden Delicious, Royal Gala and Granny Smith apple trees and eleven-year-old Packhams' Truimph pear trees and 2) one stem section each for five year-old Zandvliet, Neethling and Keisie peach trees.

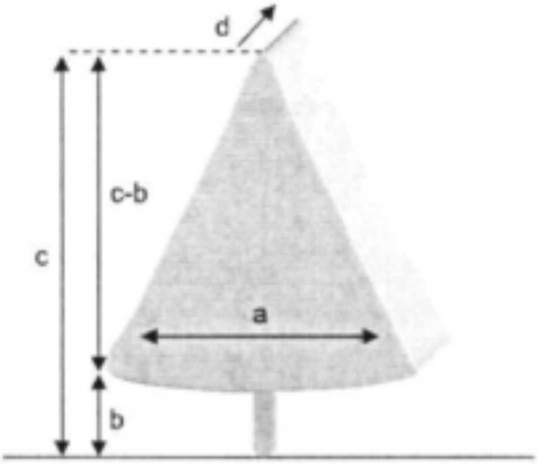


Figure 2. Schematic representation of canopy dimensions measured. Canopy dimensions included diameter over the work row (a), height of the canopy above the ground (b), tree height (c) and canopy diameter within the tree row (d). Canopy height was calculated as c-b.

Actual sap flow was determined *in situ* for two year-old Royal Gala apple trees. The trees were grown outdoors in 20 L plastic containers in coconut peat and irrigated frequently with fertilizer enriched water. The trees were removed from the orchard and placed in a glasshouse for the duration of the experiment. A tree and the sap flow equipment were placed on an electronic balance. A cardboard cover, which fitted closely around the tree trunk, was used to minimize evaporation losses. Heat pulse measurements were monitored and registered every thirty minutes. Water loss was determined by recording the change in mass.

Sap flow: Transpiration was quantified by means of a heat pulse sap flow method (Green, 1988) at all plots, except the Packhams' Truimph plot at Molteno Glen, during the development stage, mid stage before harvest and after four to six weeks post harvest. Two temperature probe sets were installed in the trunk of a tree at least 150 mm from the soil surface. One set of probes was installed in the northern and the other in the eastern side of the tree trunk. The vertical distance between the two probe sets was *ca.* 50 mm. A CR10X logger (Campbell Scientific, INC., Logan, Utah) and necessary software initiated a heat pulse every thirty minutes and the time to temperature equilibration (δT) was monitored and registered. The trunk circumference and depth of bark was measured. Sap flux of experimental trees was estimated from the average δT of 8 sensors per tree and the laboratory calibration equation. Sap flow was estimated by multiplying the sap flux by the trunk cross-sectional area. The depth of the bark was subtracted from the trunk diameter before calculation of the trunk cross-sectional area. Total daily sap flow was estimated as the sum of the half-hourly sap flow from 00h00 to 24h00.

Estimating seasonal variation in transpiration: Leaf area was expressed as a function of time where day one was the 1st of July 2000 for peach plots and the 1st of September 2000 for apple and pear plots (trees dormant). This function was used to estimate the LA for periods during which sap flow was monitored, but LAI measurements were prevented by poor weather conditions. Sap flow as a function of LA and daily Penman-Monteith ETo of measured periods was calculated by means of multiple regression for apple, pear and peach trees.

For each plot, the LA for the middle of each month from September/October until May was estimated using the function of LA against time. Sap flow was estimated for the middle of each month using the appropriate average LA per plot and monthly mean ETo in the multiple regression equation as discussed above. Sap flow was converted to mm based on the total soil area. Monthly Kt values were calculated as the ratio of estimated transpiration (sap flow) to monthly mean ETo.

Fractional intercepion: Fractional interception of solar radiation (FI) was used to calculate relative fractional interception (RFI) to identify the stage of growth development for SWB simulations. Relative fractional interception is the FI measured at any stage during a season divided by the maximum FI attained during that specific season. FI was estimated according to the method of Jackson (1997). The amount of solar radiation transmitted to the orchard floor (τ) consists of two components – that which would reach the orchard floor even if the trees were totally opaque (τ_f) and that which reaches the ground only after passing through the orchard canopy (τ_c). The latter depends on L', which is the leaf area per unit orchard area divided by the mean daily shadow area, and radiation extinction coefficient (K). The relevant equations are:

$$\tau = \tau_f + \tau_c \qquad (4.15)$$

$$\tau_c = (1-\tau_f)e^{-KL'} \qquad (4.16)$$

The fractional proportion of available solar radiation intercepted therefore can be described as:

$$FI = F_{max}(1 - e^{-KL'}) \qquad (4.17)$$

where F_{max} is the proportion of radiation which would be intercepted if the trees were solid (Jackson, 1980). F_{max} is the cast shadow area as a proportion of the total ground surface integrated over a chosen period of time. At any one time, it depends for a hedgerow orchard, on height of the hedge in relation to the width of the alley, hedge orientation and geometry and solar altitude and azimuth. F_{max} was estimated according to the FAO56-procedure for rectangular canopies (Allen et. al, 1998). A value of 0.5, representing a spherical leaf-angle distribution, was used for K (Goudriaan, 1988; Wagenmakers, 1994).

Model calibration: The appropriate weather, irrigation, field, soil and crop input information was entered in the model for each cultivar/plot combination. The irrigation amounts were corrected for an application efficiency of 0.85 (Clemens, 2000) and entered as mm applied to the wetted area. The FAO model parameters were determined according to SWB guidelines (SWB User's guide and Technical manual). RFI was used to identify the stage of growth development where initial, development, mid and late growth stages were defined respectively as follows: $RFI < 0.1$, $0.1 \leq RFI < 0.9$, $RFI \geq 0.9$, $RFI < 0.9$. The lengths of the growth stages were determined for each cultivar from RFI values expressed as a function of time.

Profile-weighted volumetric soil water content values for the start of the season, field capacity and permanent wilting point (200, 300, 600 and 900 mm depths) were divided into eleven soil layers to represent the total root depth. Profile soil water deficit to field capacity was calculated for each plot/cultivar combination from weighted profile soil water content values for the season. The appropriate area for calculation was determined by the root width of the tree. SWB simulations were performed and the Kcb's for the FAO model in SWB (two-dimensional cascading water balance) were determined for the initial growth stage, mid-season growth stage and end of the season by selecting the best statistical fit of SWB predicted soil water deficit to measured soil water deficit from orchards. Predicted soil water deficit was updated to equal measured soil water deficit of the wetted soil volume where specific irrigation problems were identified.

4.2 Results and discussion

4.2.1 Experimental plots

Ten plots were identified at six suitable sites (Fig. 3) and to introduce additional variation, two cultivars of apples and pears were measured in two of the plots. Plot, plant, soil and irrigation system information for the 2000/2001 season is summarized for plots of apple, pear and peach trees (Tables 1, 2 & 3).

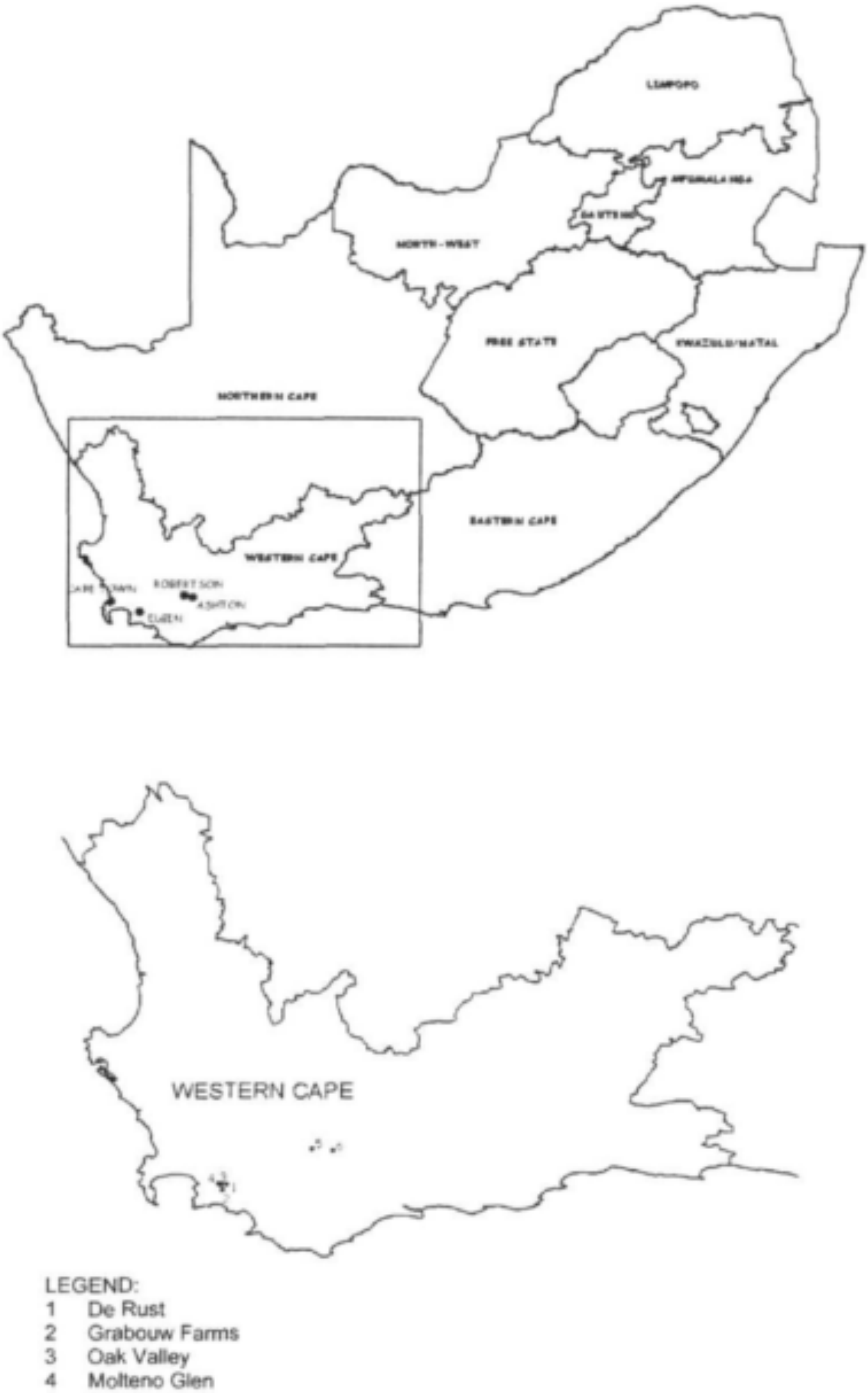


Figure 3. Map of the Republic of South Africa and the Western Cape (insert) illustrating the locality of the experimental plots. The positions of plots are represented by their respective automatic weather station co-ordinates (see Tables 1, 2 & 3).

Table 1. Plant, soil and irrigation system characteristics and automatic weather station information of plots in the Elgin area *used for determination of transpiration and a soil water balance of apple trees.*

Location	Molteno Glen	Grabouw Farms	Oak Valley
Block identification number	53	124	G17
Season(s) measured	1999/2000 2000/2001	1999/2000 2000/2001	- 2000/2001
Cultivar/rootstock	Golden Delicious/M793	Golden Delicious/M793 Granny Smith/M793	Golden Delicious/ M793
Plant spacing	3.5 x 2.0	4.0 x 1.5	4.25 x 2.0
Year planted	1996	1993	1992
Training system	Central leader	Central leader	Central leader
Young/ full bearing	Young	Full bearing	Full bearing
Soil texture	Loam	Sandy clay loam	Clay loam
Soil depth (m)	0.6	0.9	0.9
Restricting soil layers	Clay/ wetness	Clay	Clay
Measured root depth (m)	0.6	0.9	0.9
Measured root system width (m)	3.0	3.0	4.25
Emitter spacing (m)	3.5 x 2.0	4.0 x 1.5	4.25 x 2.0
Irrigation system pressure (kPa)	110	110	100
Micro sprinkler flow rate (L h^{-1})	32	32	50
Wetted strip (m)	3.0	3.0	4.25
Subsurface drains/ drainage channel	No	Yes	Yes
Plant row direction	E-W	N-S	N-S
Automatic weather station			
ID	Old Nursery	Grabouw farms	Infruitec
Latitude	34°09'	34°13'	34°10'
Longitude	19°03'	19°05'	19°04'
Altitude (m)	290	210	330

Table 2. Plant, soil and irrigation system characteristics and automatic weather station information of plots in the Elgin area used for determination of transpiration and/or a soil water balance of pear trees.

Location	De Rust	Molteno Glen	Oak Valley
Block identification number	6E2	23	A22
Season(s) measured	1999/2000 2000/2001	1999/2000 2000/2001	- 2000/2001
Cultivar/rootstock	Rosemary/BP1 Bon Rouge/BP1	Packham's Truimph/ Bon Chretien seedling	Forelle/BP1
Plant spacing (m)	3.5 x 1	4.5 x 2.5	4.0 x 1.2
Year planted	1996	1981	1995
Training system	Central leader	Central leader	Central leader
Young/ full bearing	Young	Full bearing	Full bearing
Soil texture	Clay loam	Sandy loam	Clay loam
Soil depth (m)	0.9	0.9	0.9
Restricting soil layers	Clay	None	Clay
Measured root depth (m)	0.9	0.9	0.9
Measured root system width (m)	2.8	4.5	2.5
Emitter spacing (m)	3.5 x 1.0	4.5 x 1.25	4.0 x 1.2
Irrigation system pressure (kPa)	100	100	100
Micro sprinkler flow rate (L h^{-1})	20	32	30
Wetted strip (m)	2.8	3.0	4.0
Subsurface drains/drainage channel	Yes	Yes	No
Plant row direction	N-S	N-S	N-S
Automatic weather station			
ID	De Rust	Old Nursery	Infruitec
Latitude	34°10'	34°09'	34°10'
Longitude	19°07'	19°03'	19°04'
Altitude (m)	330	290	330

Table 3. Plant, soil and irrigation system characteristics and automatic weather station information of plots in the Robertson and Ashton area used for determination of transpiration and a soil water balance of peach trees.

Location	ARC Experiment farm – Robertson		Ashton Canning Experiment farm – Ashton	
Block identification number	B2	B8	357	352
Season(s) measured	1999/2000 2000/2001	- 2000/2001	- 2000/2001	- 2000/2001
Cultivar/rootstock	Neethling/ Kakamas seedling	Zandvliet/ Kakamas seedling	Keisie/ GF677	Neethling/ Kakamas seedling
Plant spacing (m)	5.0 x 3.0	5.0 x 2.5	4.5 x 2.0	5.0 x 2.5
Year planted	1987	1992	1998	1995
Training system	Closed vase	Closed vase	Central leader	Closed vase
Young/ full bearing	Full bearing	Full bearing	Young	Full bearing
Soil texture	Sand loam	Loam sand	Sand clay	Sand loam
Soil depth (m)	0.9	0.9	0.9	0.9
Restricting soil layers	None	None	None	None
Measured root depth (m)	0.9	0.9	0.9	0.9
Measured root system width (m)	3.2	2.8	3.0	3.0
Emitter spacing (m)	5.0 x 2.5	5.0 x 2.2	4.5 x 2.0	5.0 x 2.5
Irrigation system pressure (kPa)	100	100	110	100
Micro sprinkler flow rate (L h^{-1})	32	31.2	32	50
Wetted strip (m)	3.2	2.8	3.0	3.0
Subsurface drains/drainage channel	No	No	No	No
Plant row direction	N-S	N-S	N-S	NW/SE
Automatic weather station				
ID	Robertson		Zandvliet	
Latitude	33°50'		33°51'	
Longitude	19°53'		20°04'	
Altitude (m)	156		170	

Subsurface cutoff drains were installed in 1999/2000 in the orchard two rows up-slope to the Golden Delicious and Granny Smith apple (block 124, Grabouw farms) and one row upslope of the Packhams' Truimph pear (block 23, Molteno Glen) experimental plots. An existing drainage channel was deepened in 1999/2000 at the Rosemary and Bon Rouge pear tree experimental plot (block 6E2, De Rust). Subsurface drains were present in the Golden Delicious orchard (block G17) selected at Oak Valley.

Classification and descriptions of soil profiles for the experimental plots are attached as Appendix C. Soil texture and laboratory determined soil water retention characteristics of soils at plots are summarized for apple, pear and peach trees (Tables 4, 5 & 6). Both young and full bearing trees were selected as well as high and lower planting densities (Tables 1, 2 & 3).

4.2.2 Meteorological data

Data from September to May of the 2000/2001 season for the apple and pear tree plots are summarized in Figure 4(A,B,C&D) and Figure 5(A,B&C) and for peach tree plots in Figure 6(A,B,C&D) and Figure 7 (A,B&C). Data from the Old Nursery automatic weather station were used for both the young Golden Delicious apple (block 53) and Packhams' Truimph pear (block 23) plots at Molteno Glen. Long-term data from Elgin (average of 35 years) (Figs. 4&5) and Robertson (average of 36 years) (Figs. 6&7) weather stations were also included in the graphs for comparison purposes.

4.2.3 Soil parameters

***In situ* soil water retention:** The soil water retention curves for apple, pear and peach plots are shown in Figures 8, 9 and 10 (A,B,C&D). Data collected at the 900 mm soil depth from the Granny Smith plot at Grabouw farms and the Zandvliet plot at Robertson were limited to the wet range and a reliable soil water retention curve could not be fitted. A dry soil profile at the Bon Rouge pear plot (900 mm depth) at De Rust and at the Forelle pear plot (600 mm and 900 mm depths) at Oak Valley frequently caused the soil to reach soil matric potentials lower than the measurable range of the tensiometers. During weekly visits for the purpose of soil water measurement, tensiometers were serviced, but the water columns ran dry before the next soil water measurement was due. Data for soil water retention curves for the abovementioned depths at these plots were therefore not available. The soil matric potential curve for the 900 mm depth from the Rosemary plot at De Rust (Fig. 9A) was used to estimate volumetric soil water content at field capacity for the Bon Rouge plot. Soil texture at the Oak Valley plot was fairly uniform for the soil profile (Table 5) and the soil water retention curve for the 300 mm depth (Fig. 9C) was used for both the 600 mm and 900 mm depths.

The empirical correction of θ_v for percentage stones by mass compared favourably to the more mechanistic correction using volume percentage stones (Fig. 11). Laboratory-determined SWC of disturbed soil samples at field capacity (-10 kPa) was corrected for stone content according to the empirical method and compared to that estimated from *in situ* determined soil water retention curves at –5 kPa and –10 kPa and the neutron probe measured "full point" for the different plots as measured during the 2000/2001 season (Fig. 12A). Overall the laboratory-determined SWC at field capacity compared poorly to the *in situ* determined values at –5 kPa ($R^2 = 0.47$) and –10 kPa ($R^2 = 0.43$). No clear pattern of over- or underestimation could be determined.

Table 4. Soil texture, soil water retention characteristics as well as readily available water (RAW) between – 10 kPa and – 100 kPa of soils from the different apple plots as determined in the laboratory. The volumetric water content was empirically corrected for mass percentage stone content.

Plot	Block	Cultivar	Soil depth (mm)	Particle size < 2 mm (%)					Stone (%)	Water content (θ_v)		RAW (mm/m)
				Clay	Silt	Fine sand	Medium sand	Coarse sand		- 10 kPa	- 100 kPa	
MG[1]	53	GD[4]	0-300	32.2	30.6	28.4	2.6	6.2	59.4	26.7	18.4	83.6
			300-600	35.2	27.0	24.2	2.8	10.8	62.4	25.2	18.9	63.2
			600-900	34.4	29.6	21.2	2.6	12.2	63.9	25.4	19.6	57.7
GP[2]	124	GD	0-300	11.5	7.1	22.6	24.2	34.6	49.4	16.2	10.3	59.4
			300-600	19.4	7.4	18.3	20.4	34.5	62.8	12.9	9.9	30.8
			600-900	22.9	7.9	16.3	21.6	31.3	64.7	15.3	10.0	53.2
		GS[5]	0-300	9.4	7.0	29.2	19.3	35.1	39.4	25.3	13.9	114.3
			300-600	19.2	12.4	18.4	13.8	36.2	48.7	22.3	16.1	62.6
			600-900	21.6	20.4	14.4	5.8	37.8	29.6	35.2	27.9	72.7
OV[3]	G17	GD	0-300	23.2	20.4	46.4	1.4	8.6	72.0	17.0	11.0	60.0
			300-600	31.0	22.0	34.0	1.6	11.4	76.6	14.3	10.2	40.5
			600-900	48.8	24.8	20.8	1.0	4.6	61.3	25.9	19.8	60.6

[1] Molteno Glen
[2] Grabouw farms
[3] Oak Valley
[4] Golden Delicious
[5] Granny Smith

Table 5. Soil texture, soil water retention characteristics as well as readily available water (RAW) between – 10 kPa and – 100 kPa of soils from the different pear plots as determined in the laboratory. The volumetric water content was empirically corrected for mass percentage stone content.

Plot	Block	Cultivar	Soil depth (mm)	Particle size <2 mm (%)					Stone	Water content (θ_v)		RAW
				Clay	Silt	Fine sand	Medium sand	Coarse sand	(%)	- 10 kPa	- 100 kPa	(mm/m)
DR[1]	6E2	RM[4]	0-300	30.4	19.6	40.2	3.6	6.2	35.8	35.2	23.6	115.9
			300-600	33.0	18.6	33.0	3.6	11.8	49.9	26.3	18.1	82.7
			600-900	43.2	24.2	28.4	1.0	3.2	14.9	49.6	36.6	130.0
		BR[5]	0-300	26.8	17.6	44.4	4.2	7.0	41.1	31.9	20.0	119.2
			300-600	33.2	17.4	34.8	4.0	10.6	47.0	26.4	18.6	78.2
			600-900	43.0	28.2	26.6	1.0	1.2	6.1	39.8	43.0	108.8
OV[2]	A22	FOR[6]	0-300	27.2	23.4	42.6	2.8	4.0	48.8	29.0	19.5	95.1
			300-600	33.4	23.6	36.6	3.2	3.2	48.5	28.6	21.6	70.0
			600-900	28.8	22.8	43.8	2.8	1.8	44.4	29.9	23.8	60.3
MG[3]	23	PT[7]	0-300	13.0	18.0	46.0	21.6	1.4	1.2	43.5	22.4	211.0
			300-600	18.4	14.2	42.2	23.6	1.6	5.4	35.4	18.1	173.0
			600-900	20.2	14.2	38.8	21.2	5.6	25.0	32.3	16.6	157.3

1 De Rust
2 Oak Valley
3 Molteno Glen
4 Rosemary
5 Bon Rouge
6 Forelle
7 Packhams' Truimph

Table 6. Soil texture, soil water retention characteristics as well as readily available water (RAW) between – 10 kPa and – 100 kPa of soils from the different peach plots as determined in the laboratory. The volumetric water content was empirically corrected for mass percentage stone content.

Plot	Block	Cultivar	Soil depth (mm)	Particle size < 2 mm (%)					Stone (%)	Water content (θ_v)		RAW (mm/m)
				Clay	Silt	Fine sand	Medium sand	Coarse sand		- 10 kPa	- 100 kPa	
ROB[1]	B2	NEETH[3]	0-300	18.1	9.8	49.7	17.6	4.8	1.7	36.0	15.8	202.1
			300-600	21.4	10.0	45.9	17.5	5.2	4.8	39.6	22.1	175.1
			600-900	22.0	10.0	43.3	17.9	6.8	16.5	39.0	21.5	174.7
ROB	B8	ZAND[4]	0-300	10.2	5.4	58.8	21.8	3.8	15.8	25.4	11.2	142.0
			300-600	12.4	4.6	57.2	20.4	5.4	38.8	19.8	9.7	101.0
			600-900	17.0	6.4	51.0	16.0	9.6	43.8	18.7	11.2	74.0
ASH[2]	357	KEISIE	0-300	33.4	7.6	33.2	17.8	8.0	19.0	30.5	19.3	112.2
			300-600	35.0	6.4	34.2	16.6	7.8	16.0	33.3	21.3	120.0
			600-900	36.0	7.8	31.6	16.0	8.6	18.2	32.5	21.1	113.7
ASH	352	NEETH	0-300	13.6	9.8	45.6	21.4	9.6	5.7	27.3	13.6	137.0
			300-600	15.0	11.2	48.0	19.0	6.8	6.9	28.3	13.9	143.9
			600-900	13.0	14.0	51.2	16.4	5.4	9.5	30.8	13.6	172.1

1 Robertson
2 Ashton
3 Neethling
4 Zandvliet

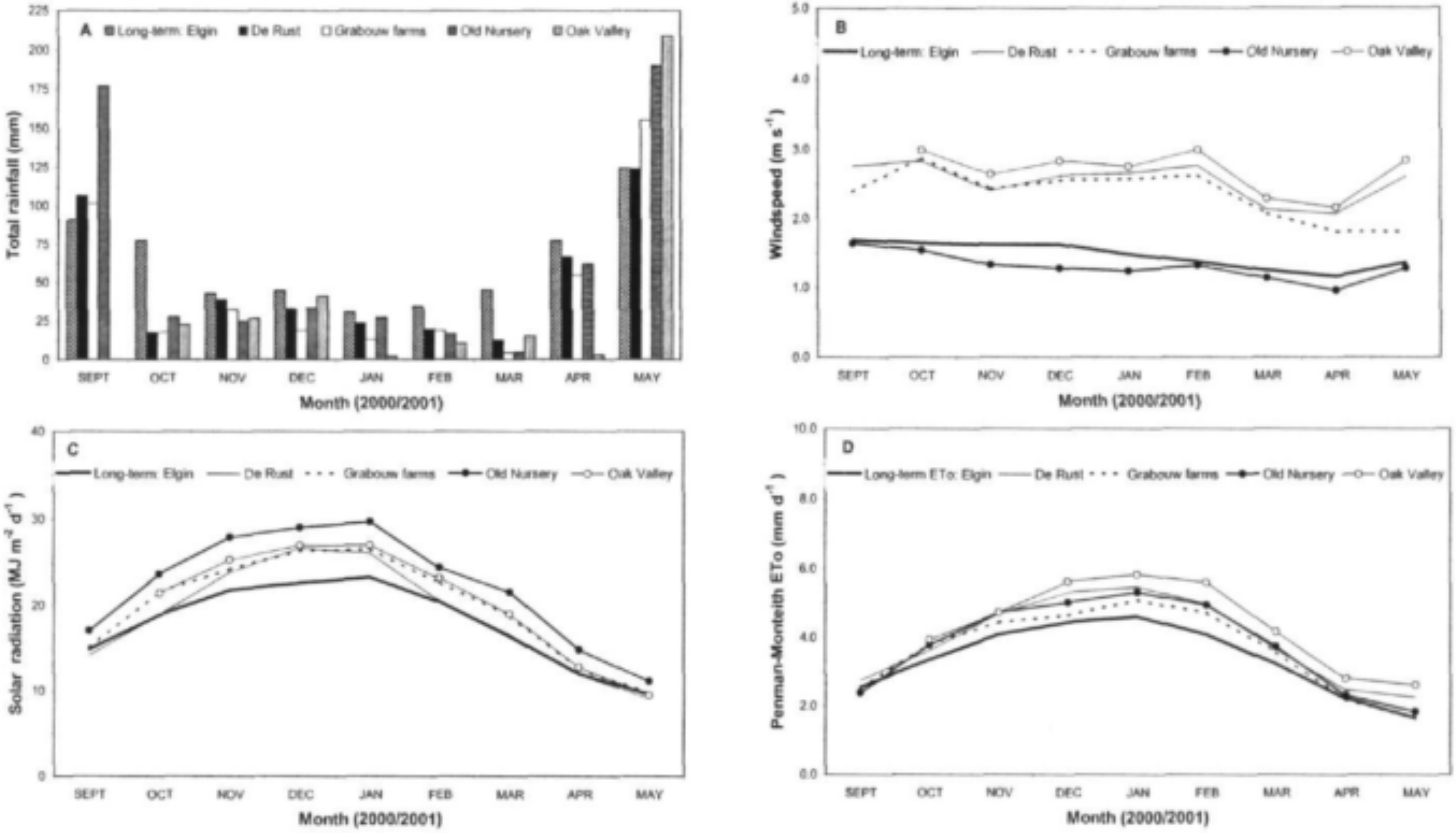


Figure 4. Total monthly rainfall (A), average daily windspeed (B), total daily solar radiation (C) and total daily Penman-Monteith reference evapotranspiration (ET_o) (D) obtained from automatic weather stations at De Rust, Grabouw farms, Molteno Glen (Old Nursery) and Oak Valley. Long-term data (average of 35 years) from Elgin weather station (longitude 19°02', latitude 34°08', altitude 305 m) were compared to the 2000/2001 season data.

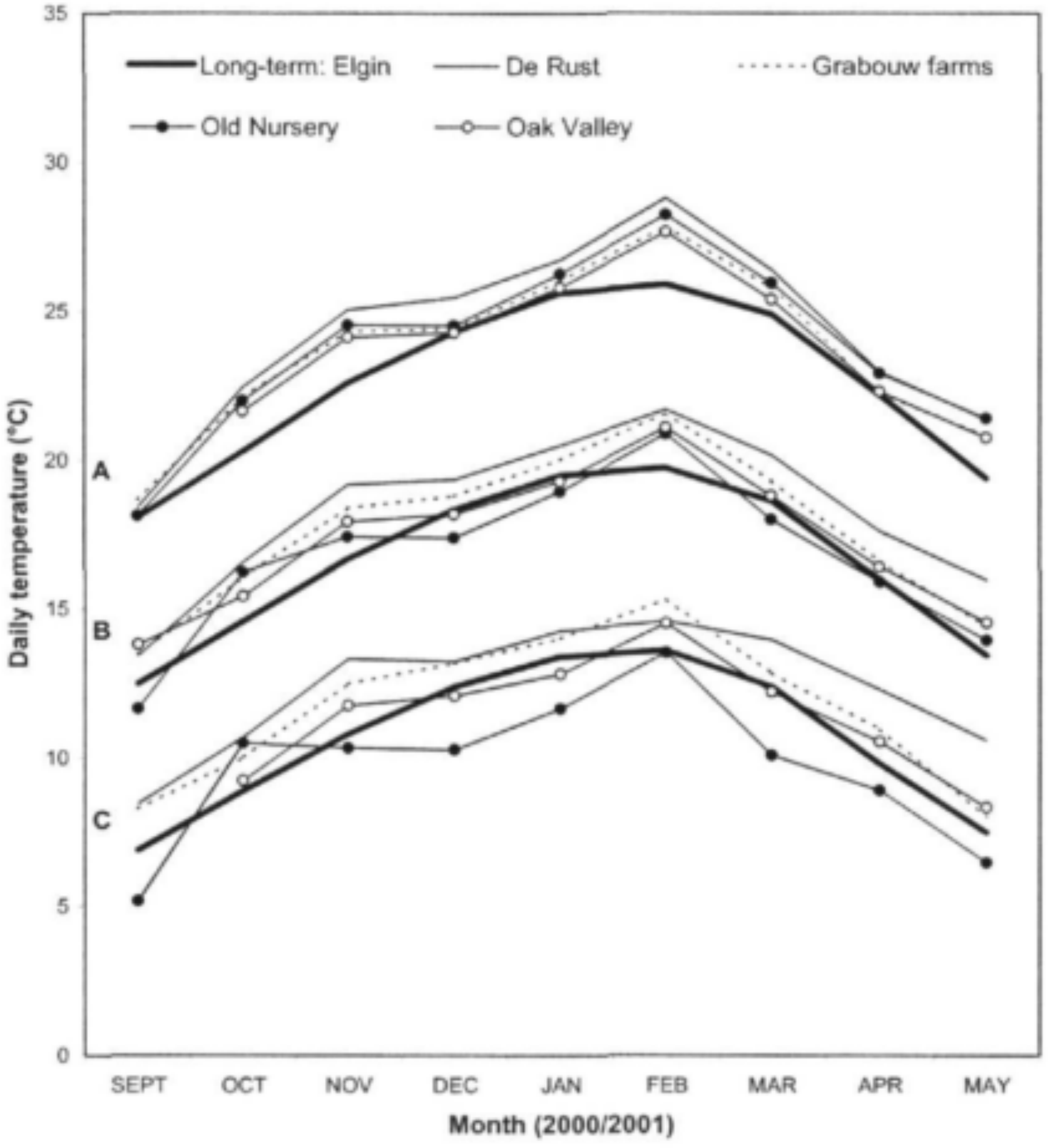


Figure 5. Daily maximum temperature (A), daily average temperature (B) and daily minimum temperature (C) obtained from automatic weather stations at De Rust, Grabouw farms, Molteno Glen (Old Nursery) and Oak Valley. Long-term data (average of 35 years) from Elgin weather station (longitude 19°02', latitude 34°08', altitude 305m) were compared to the 2000/2001 season data.

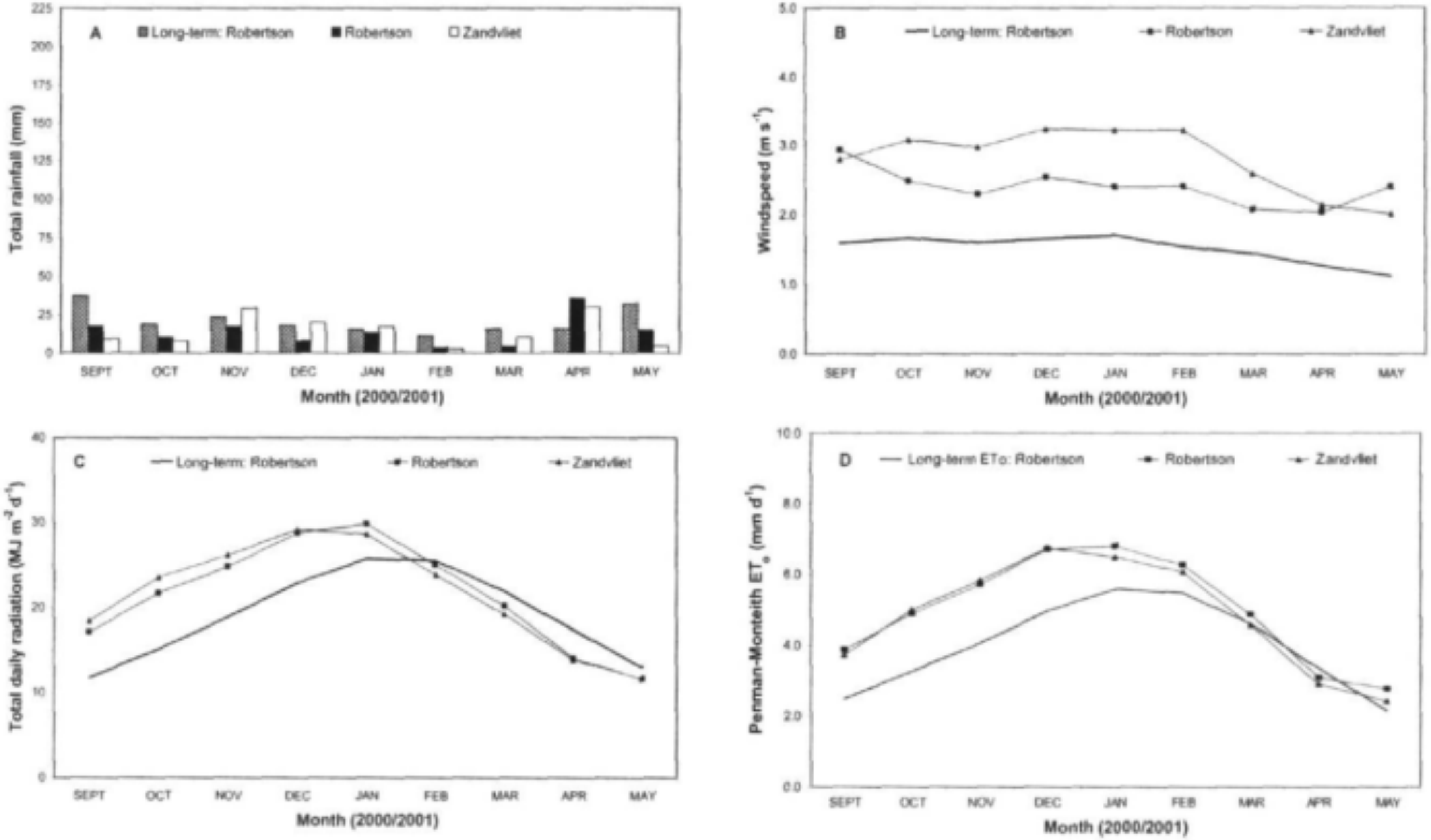


Figure 6. Total monthly rainfall (A), average daily windspeed (B), total daily solar radiation (C) and total daily Penman-Monteith reference evapotranspiration (ET_o) (D) obtained from automatic weather stations at Robertson and Ashton (Zandvliet). Long-term data (average of 36 years) from Robertson weather station were compared to the 2000/2001 season data.

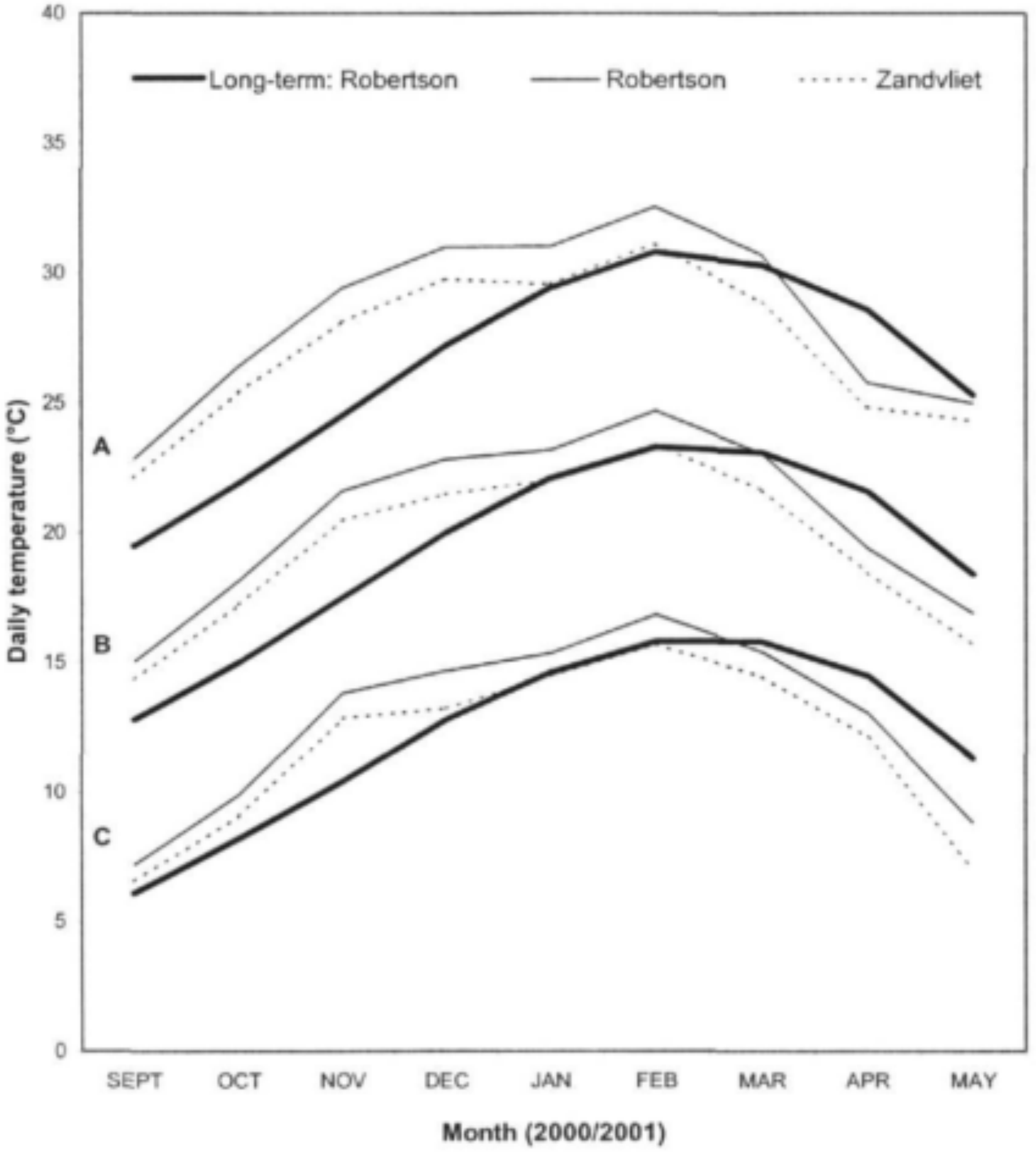


Figure 7. Daily maximum temperature (A), daily average temperature (B) and daily minimum temperature (C) obtained from automatic weather stations at Robertson and Ashton (Zandvliet). Long-term data (average of 36 years) from Robertson weather station were *compared to the 2000/2001 season data.*

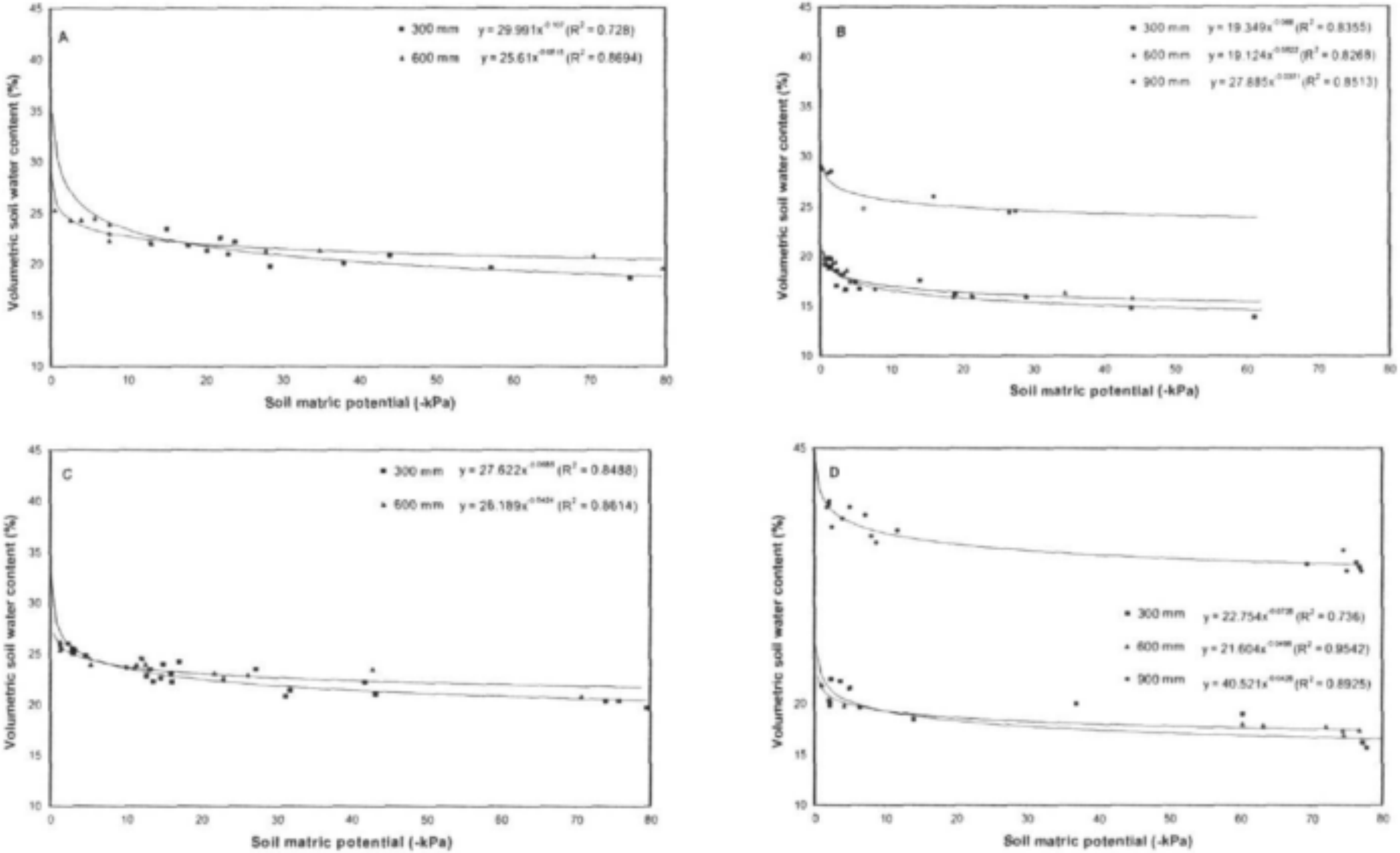


Figure 8. *In situ* determined soil water retention curves for apple plots at Molteno Glen (A), Grabouw farms (B & C) and Oak valley (D) measured at 300 mm, 600 mm and 900 mm depths. B is for the Golden Delicious plot and C for the Granny Smith plot at Grabouw farms.

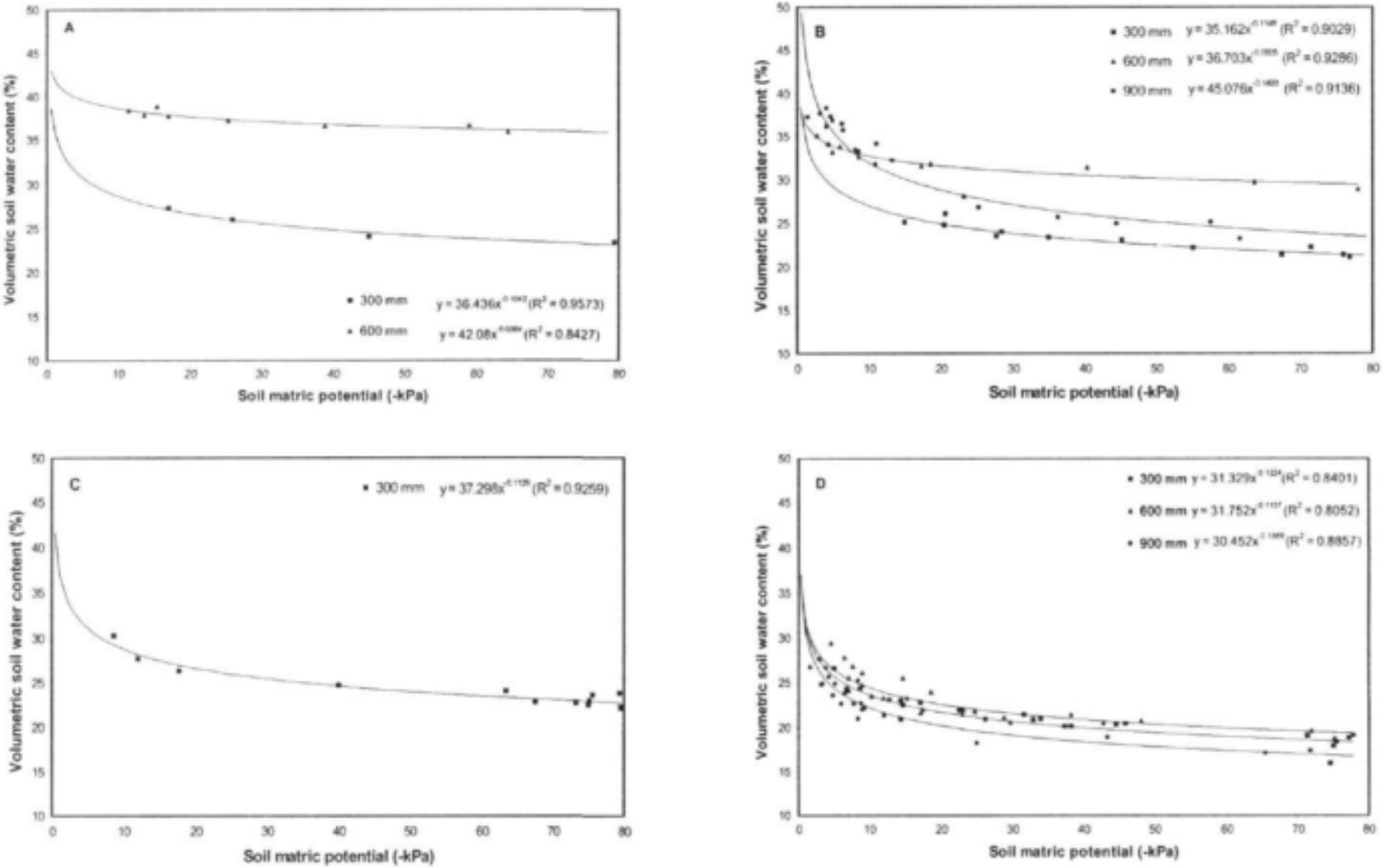


Figure 9. *In situ* determined soil water retention curves for pear plots at De Rust (A & B), Oak Valley (C) and Molteno Glen (D) measured at 300 mm, 600 mm and 900 mm depths. A is for the Rosemary plot and B for the Bon Rouge plot at De Rust.

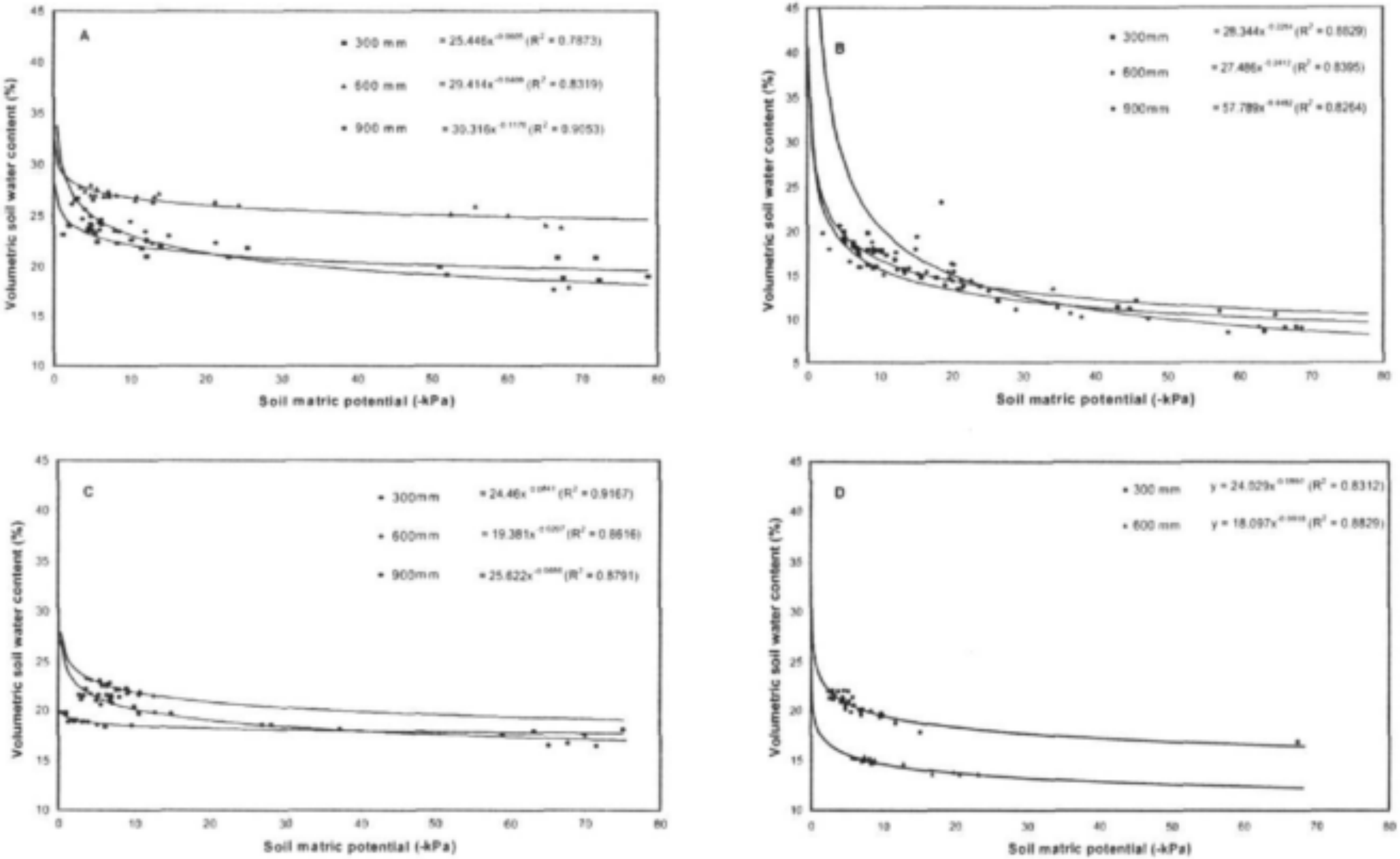


Figure 10. *In situ* determined soil water retention curves for peach plots at Ashton (A & B) and Robertson (C & D) measured at 300 mm, 600 mm and 900 mm depths. A is for the Keisie, B &C for the Neethling and D for the Zandvliet peaches.

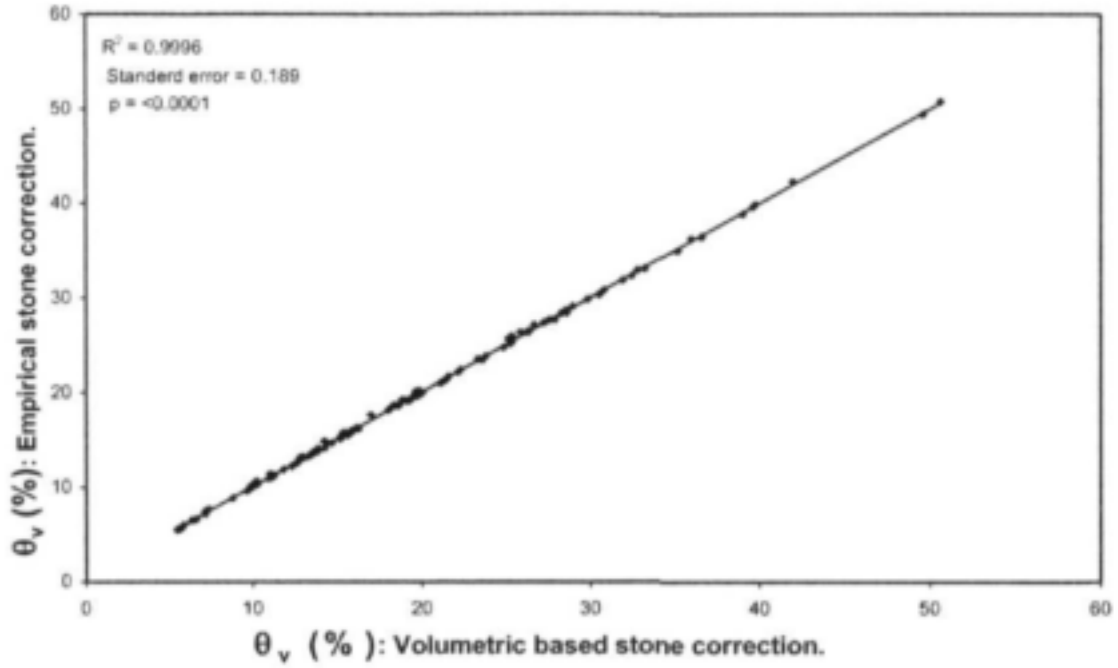


Figure 11. Comparison of laboratory determined volumetric soil water content (θ_v) corrected for stones by an empirical equation to θ_v corrected by a volumetric based approach.

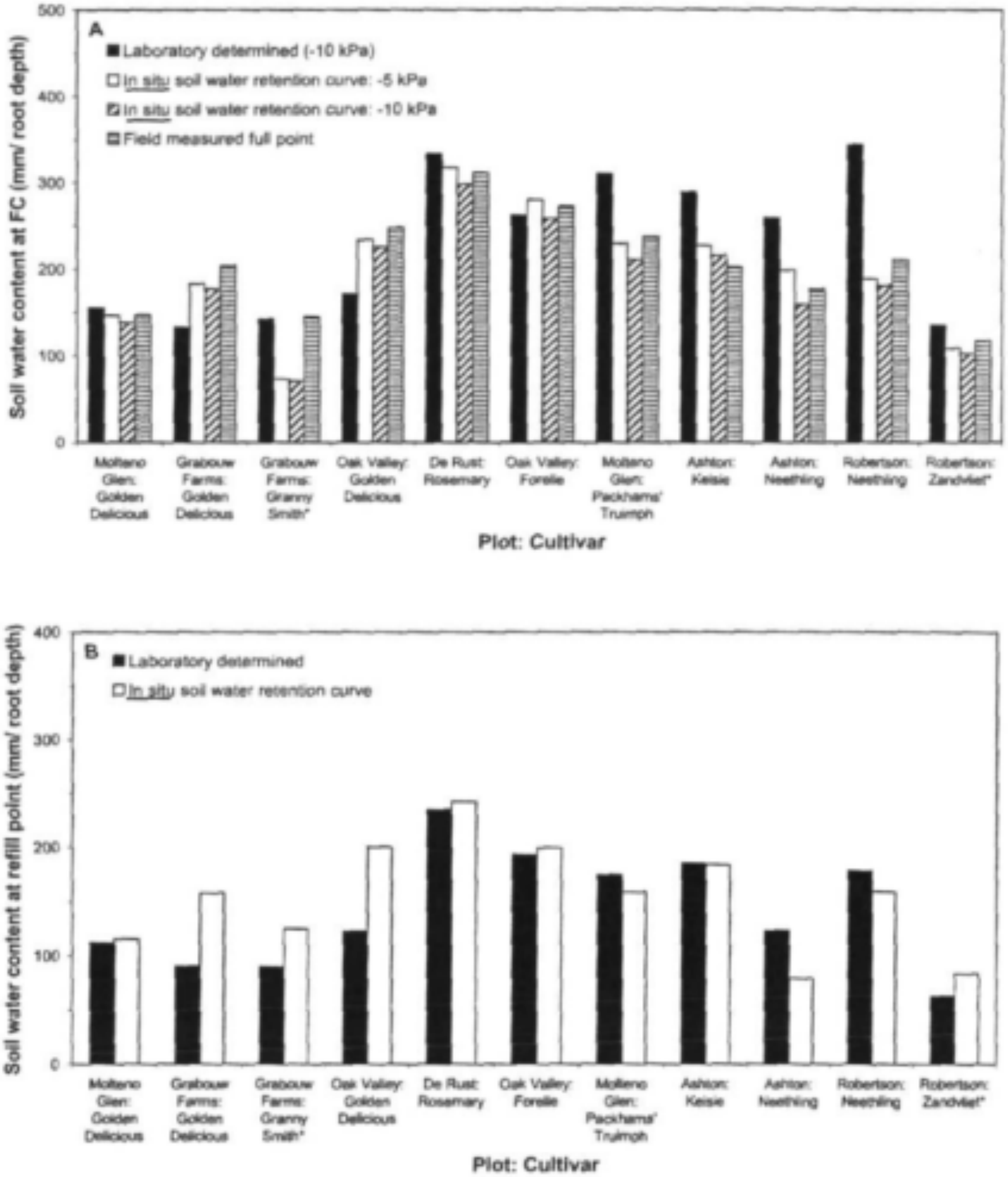


Figure 12. Comparison of profile soil water content (mm per root depth) at A. Field capacity as 1) determined from disturbed samples in the laboratory at –10 kPa and empirically corrected for mass percentage stones, 2) estimated from *in situ* determined soil water retention curves at –5 kPa and –10 kPa and 3) neutron probe measured "full point" for the different plots as measured during the 2000/2001 season and B. Soil water content at refill point as 1) determined from disturbed samples in the laboratory at –100 kPa and empirically corrected for mass percentage stones and 2) estimated from *in situ* determined soil water retention curves at –100 kPa. Plot:Cultivar combinations followed by an asterisk do not represent the soil water content of the full root depth.

Similarly, SWC at refill point as determined from disturbed samples in the laboratory at –100 kPa was compared to that estimated from *in situ* determined soil water retention curves extrapolated to –100 kPa (Fig. 12B). The SWC at refill point (-100 kPa) determined in the laboratory and with *in situ* methods, in contrast to the comparisons made for field capacity, agreed better (R^2 = 0.74).

The appropriate field capacity for the different plots was selected by comparing the laboratory-determined, stone-corrected SWC at field capacity (-10 kPa), *in situ* determined SWC at –5 kPa and –10 kPa and the neutron water meter measured "full point" to SWC measurements of the 2000/2001 season. Soil water content at -5 kPa as determined from *in situ* determined soil water retention curves was used in the soil water balance for all plots except Granny Smith at Grabouw Farms and the Neethling and Zandvliet peaches at Robertson, where the neutron water meter measured "full point" was selected.

Soil water content: Coordinates of access tubes used in the double-ellipsoid configuration for estimation of total profile volumetric soil water content by means of the neutron water meter as well as the weights assigned to neutron water meter access tubes (T1 to T8) for calculation of SWC_w per root depth for the different plots are summarized as Appendix D. Coordinates of the inner ellipse refer to positions of access tubes 1 to 4, while X- and Y-coordinates of the outer ellipse refer to access tubes 5 and 7 and 6 and 8, respectively (Fig. 1). Weighted soil water content was used in the soil water balance calculations as well as estimation of soil water deficit to field capacity for calibration of the SWB model.

Soil water balance and single crop coefficients: ET for the apple, pear and peach plots for the 2000/2001 season is displayed in Figures 13, 14 and 15 respectively. The data from the Zandvliet plot were omitted due to a prolonged period of excessive wet conditions in the orchard. One of the subsurface irrigation mainlines of the farm, located in the orchard near the experimental plot, burst and probably caused an inflow of water. Suboptimal soil water conditions could reduce water use and cause lower crop coefficients. During the harvest period for pears, it is practice to withhold irrigation, while peach trees are irrigated more frequently to prevent any excessive water deficit. Evapotranspiration was estimated by means of interpolation at pear and peach plots for months where excessive wet or dry soil profiles could have caused water stress. Graphs of LA development and ETo over time were used to decide if interpolated values were reasonable.

Crop coefficients for apple, pear and peach plots for the 2000/2001 season are displayed in Figures 16, 17 and 18, respectively. The crop coefficient curves did not follow the typical decreasing trend of FAO crop coefficient curves to the end of the season, but increased instead. This could be the result of ET decreasing at a lower rate than anticipated, while ETo decreased according to its annual pattern. In the Northern hemisphere colder conditions at the end of the growing season probably enhance the rate of leaf aging and defoliation and the FAO determined crop coefficient curves apply to their conditions.

4.2.4 Plant parameters

PCA calibration: The relationship between actual LA and PCA LAI of pome (apple and pear) and stone (peach) fruit is displayed in Figure 19. The relationship where the outer two rings of the LAI

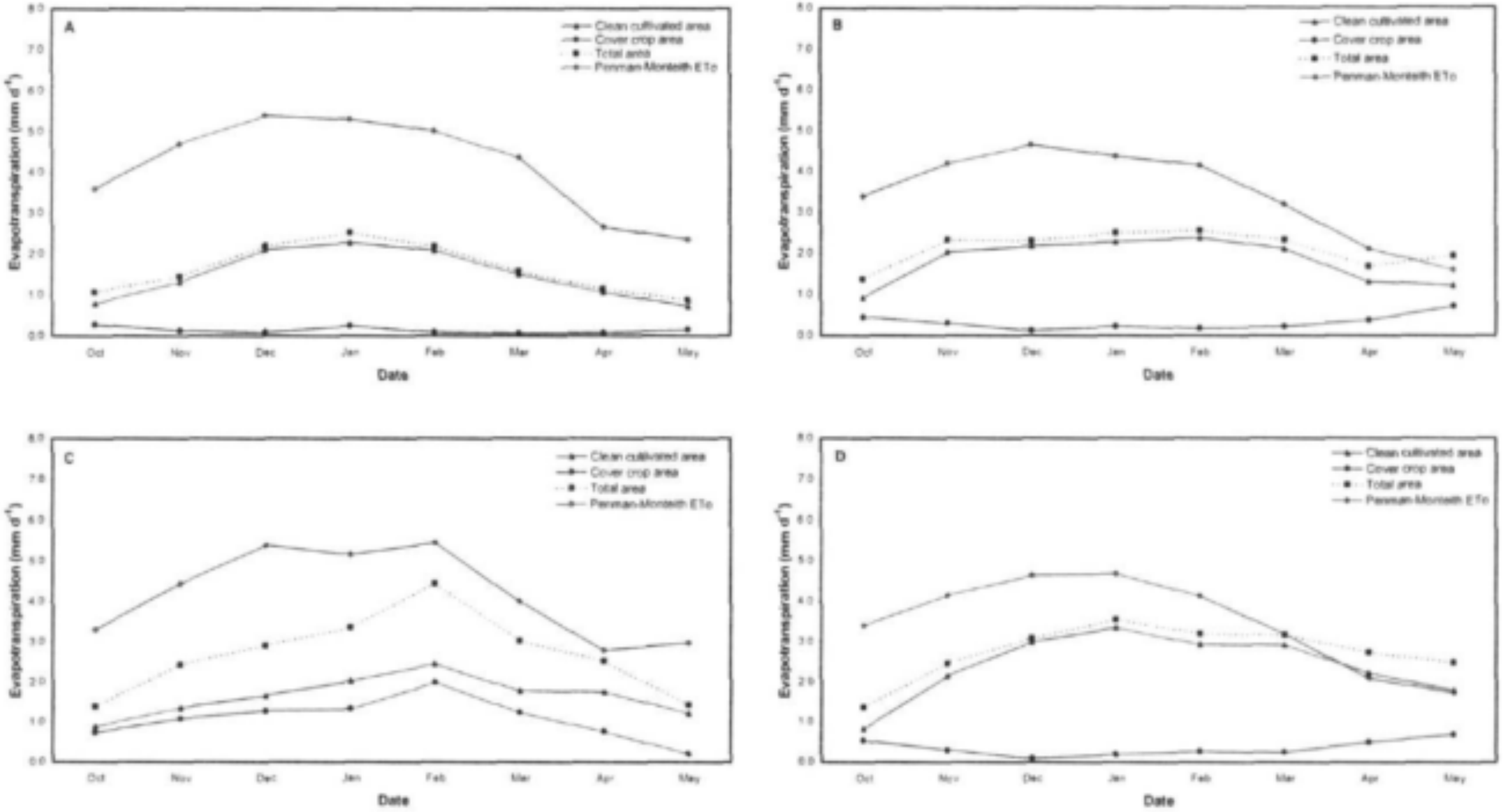


Figure 13. Evapotranspiration for (A) young Golden Delicious, (B & C) full bearing Golden Delicious and (D) full bearing Granny Smith apple trees as estimated from a water balance during the 2000/2001 growing season. Irrigation was applied on the clean cultivated area for A, B and D and on the full surface area for C. B is for the Grabouw Farms plot and C for the Oak Valley plot. Penman-Monteith reference evapotranspiration (ETo) is also indicated on the graphs.

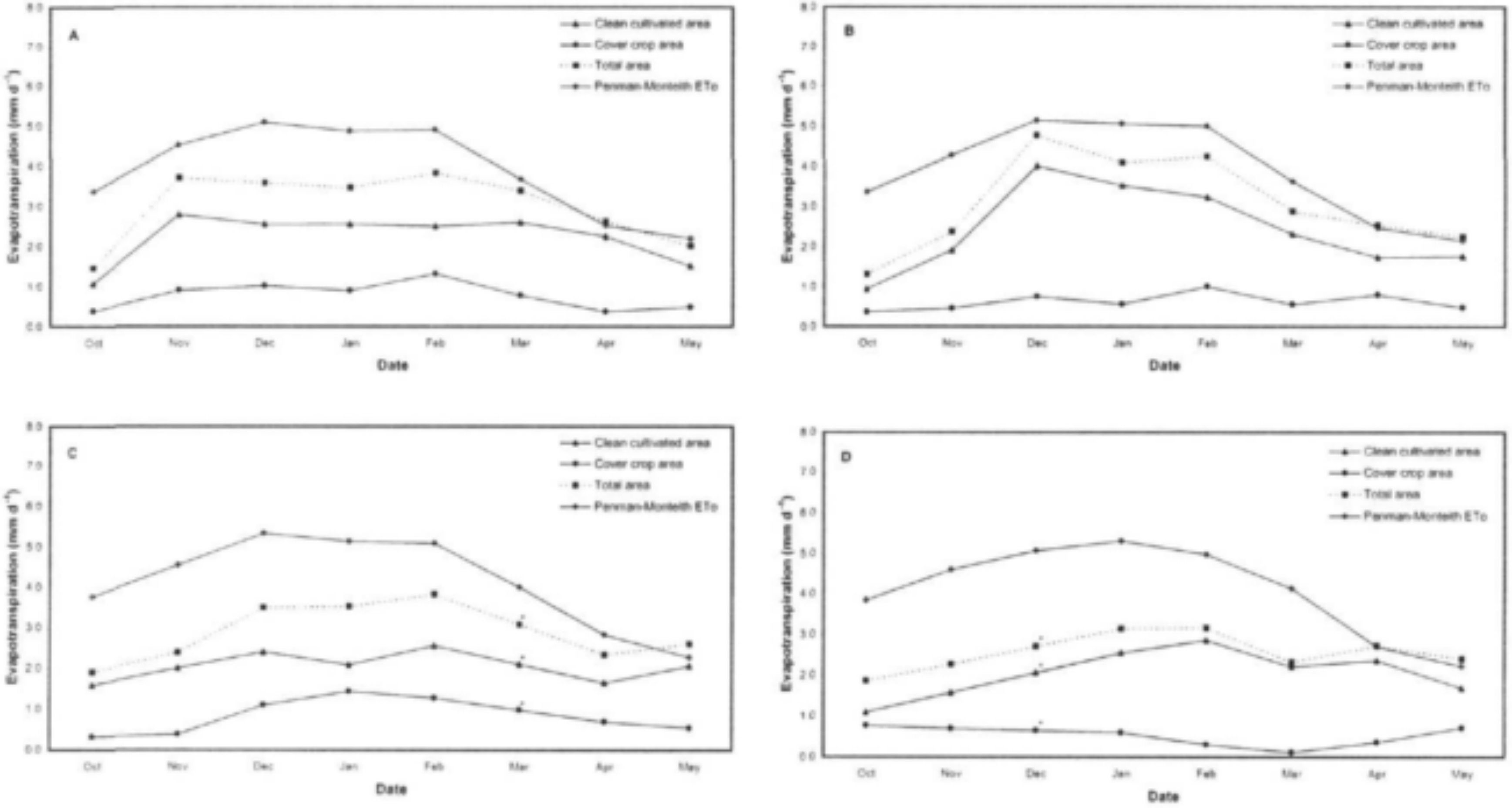


Figure 14. Evapotranspiration for young Rosemary (A) and Bon Rouge (B) and full bearing Forelle (C) and Packhams' Truimph (D) pear trees as estimated from a water balance during the 2000/2001 growing season. Irrigation was applied only to the clean cultivated area for A, B and D and on the full surface area for C. Tree roots were present in the non-irrigated area for D. Penman-Monteith reference evapotranspiration (ETo) is also indicated on the graph. Estimated values are indicated by markers followed by an asterisk.

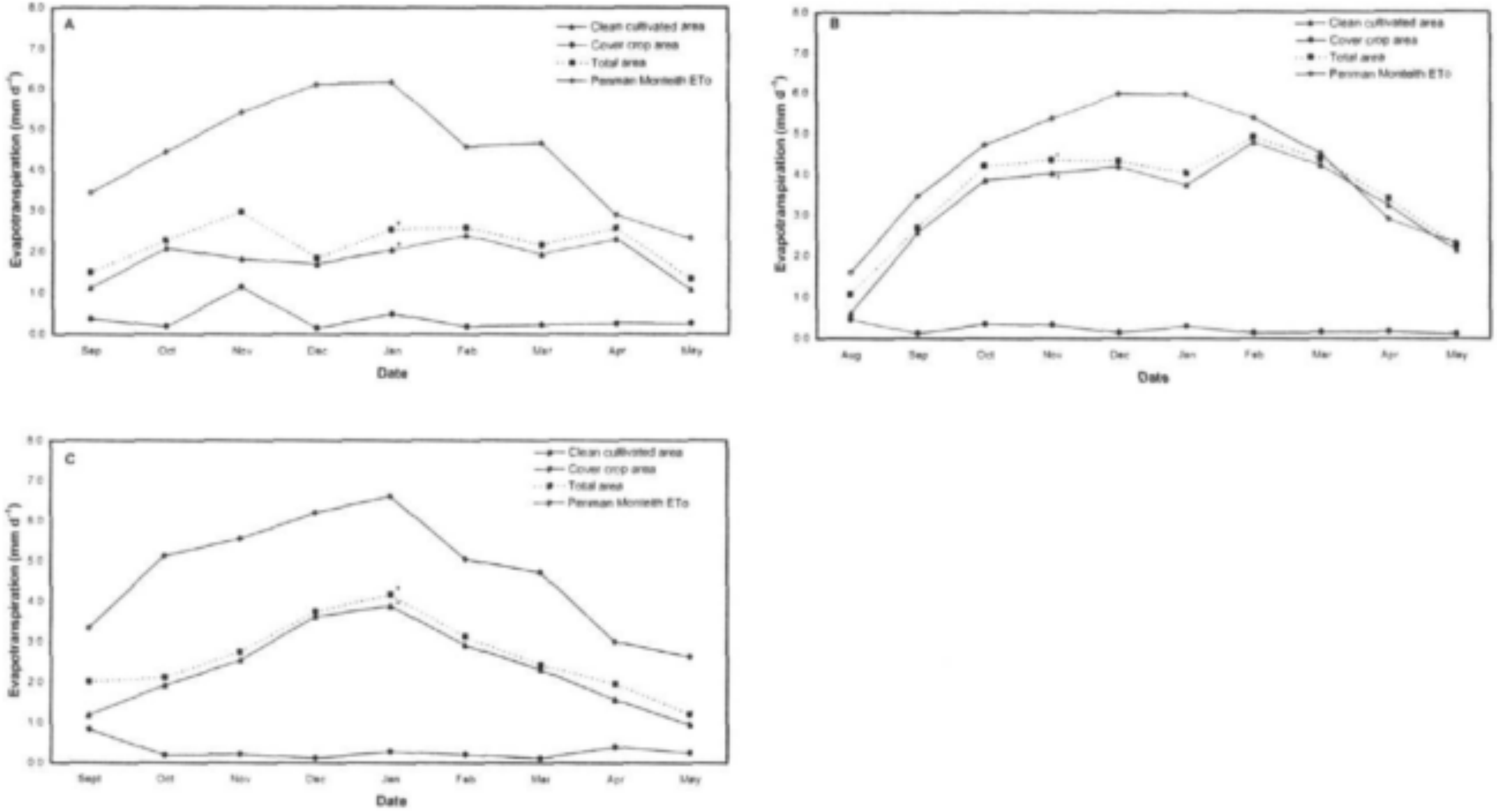


Figure 15. Evapotranspiration for (A) young Keisie and (B & C) full bearing Neethling peach trees as estimated from a water balance during the 2000/2001 growing season. Irrigation was applied only on the clean cultivated area. B is for the Ashton plot and C for the Robertson plot. Penman-Monteith reference evapotranspiration (ETo) is also indicated on the plot. Estimated values are indicated by markers followed by an asterisk.

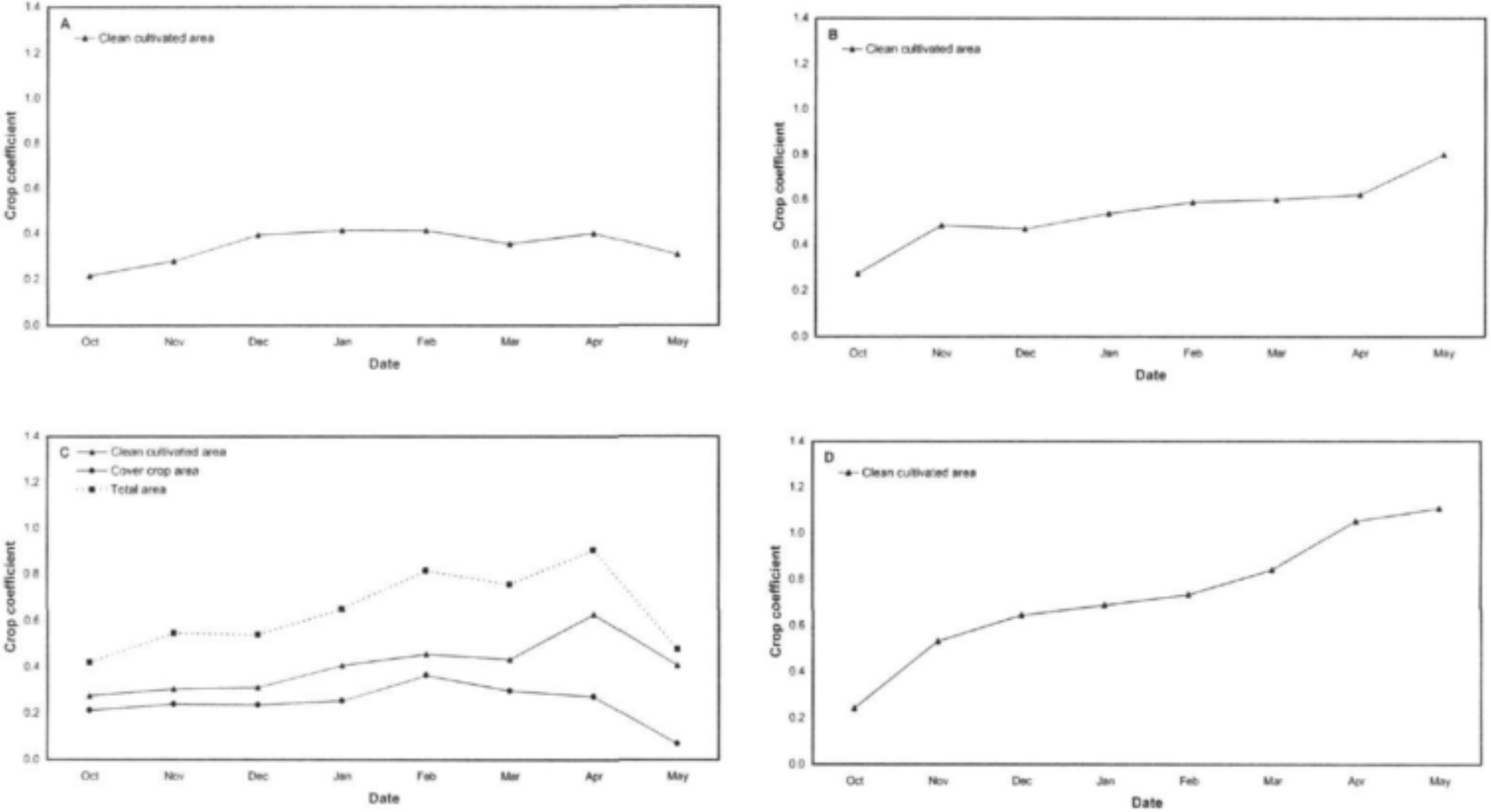


Figure 16. Single crop coefficients (Kc) for (A) young Golden Delicious, (B & C) full bearing Golden Delicious and (D) full bearing Granny Smith apple trees as estimated from a water balance during the 2000/2001 growing season. Irrigation was applied on the clean cultivated area for A, B and D and on the full surface area for C. B is for the Grabouw Farms plot and C for the Oak Valley plot.

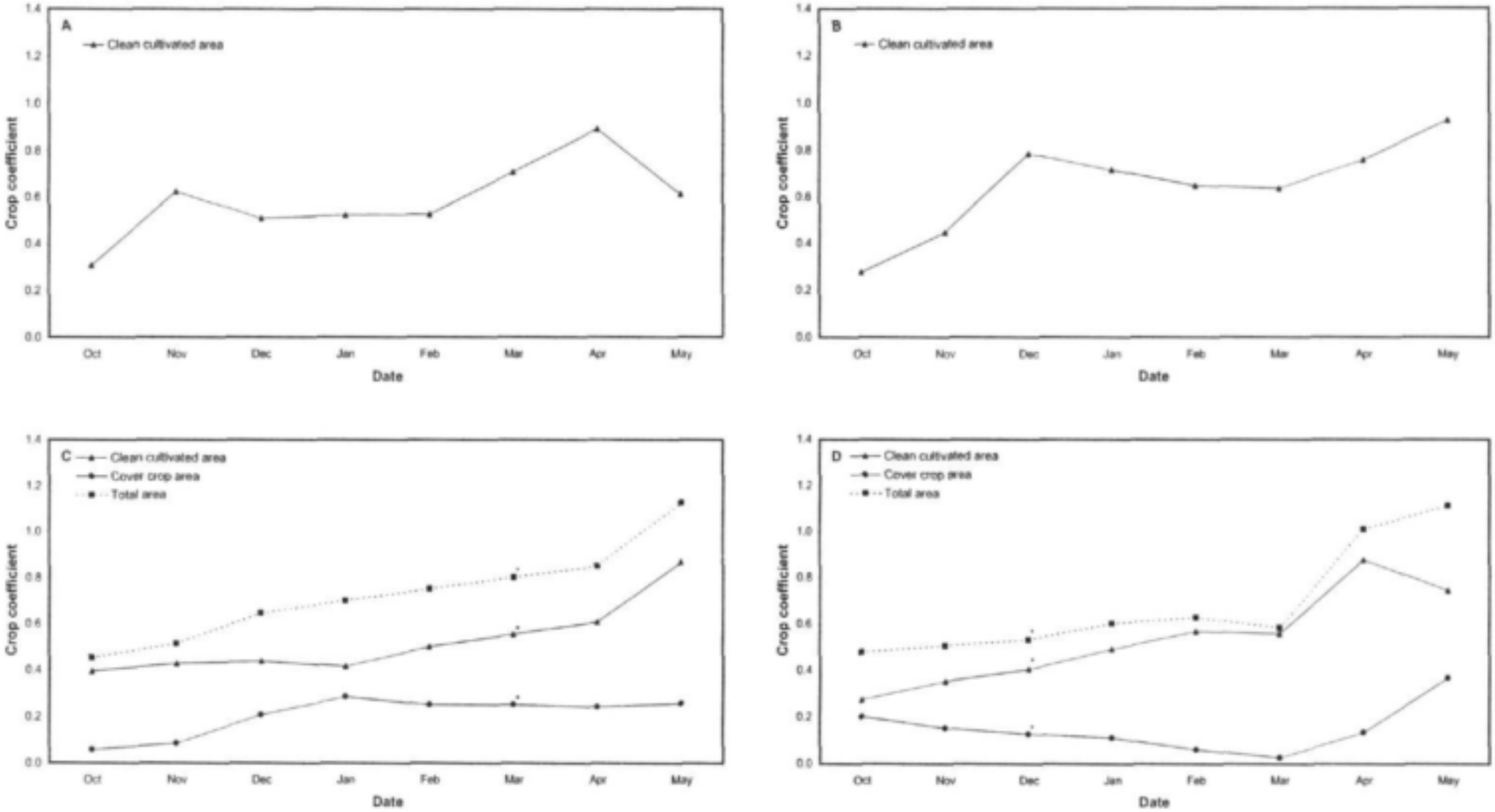


Figure 17. Single crop coefficients (Kc) for young Rosemary (A) and Bon Rouge (B), full bearing Forelle (C) and Packhams' Truimph (D) pear trees as estimated from a water balance during the 2000/2001 growing season. Irrigation was applied to the full surface area for C and only on the clean cultivated area for A, B and D. Tree roots were present in the non-irrigated area for D. Estimated values are indicated by markers followed by an asterisk.

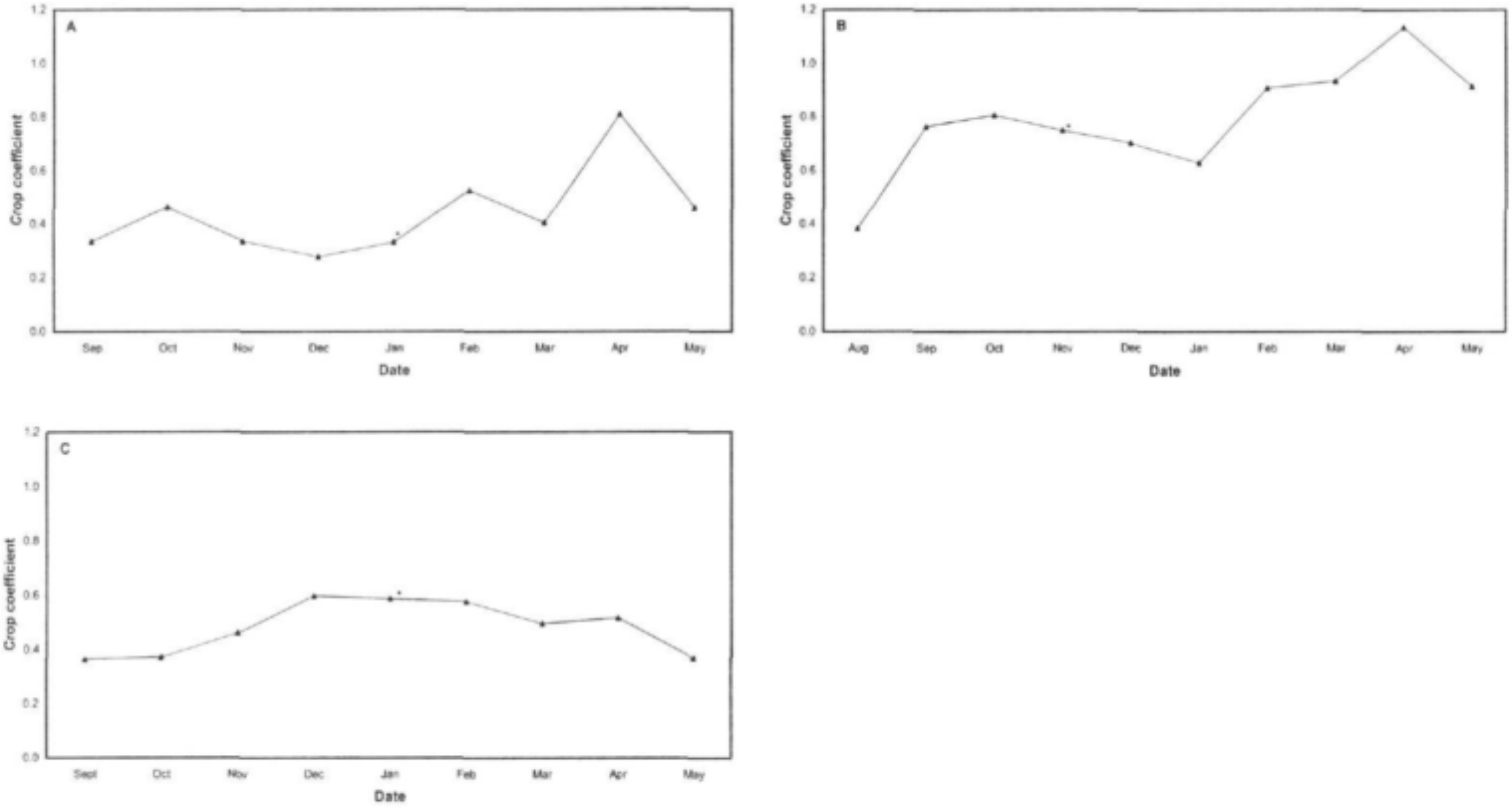


Figure 18. Single crop coefficients (Kc) for (A) young Keisie and (B & C) full bearing Neethling peach trees as estimated from a water balance during the 2000/2001 growing season. Irrigation was applied on the clean cultivated area. B is for the Ashton plot and C for the Robertson plot. Estimated values are indicated by markers followed by an asterisk.

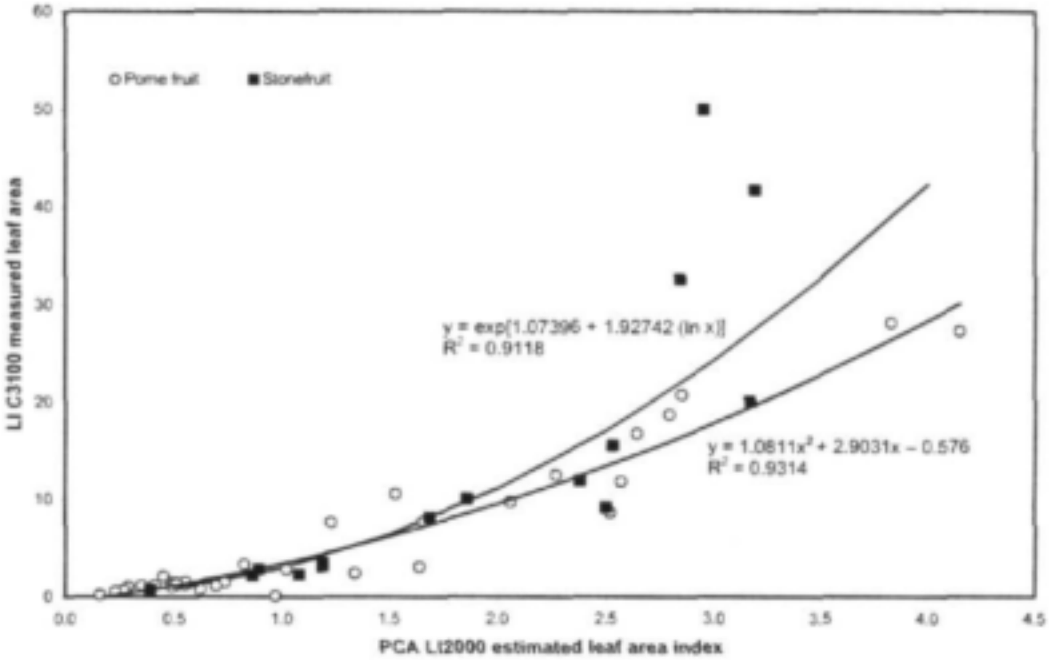


Figure 19. Relationship between LAI2000 Plant Canopy Analyser estimated leaf area index and leaf area of pome (apple and pear) and stone (peach) fruit trees. The two outer rings were masked.

values were masked rendered the best coefficient of determination. For apple trees, a quadratic, and peach trees an exponential function gave the best coefficient of determination. The need for different functions for pome and stone fruit could be due to differences in tree form and LAD. Lower branches of peach trees were generally more spreading and leaves more densely distributed in the canopy. The higher LAI values for pome fruit trees at comparable peach LA values could be due to tree frame components that the PCA "sees" in apple and pear trees, with less dense leaf distributions compared to the peaches.

Leaf area index and density: Canopy dimensions measured during midseason used for calculation of tree volume for the apple, pear and peach tree plots are displayed in Figure 20. The average of the LA and LAD of trees on different days after dormancy during the 2000/2001 season is presented for apple, pear and peach trees in Figure 21(A,B,C&D), Figure 22(A,B,C&D) and Figure 23(A,B,C&D), respectively. These patterns did not represent natural LA development for the young Rosemary pear (Fig. 22A) and Keisie peach (Fig. 23A) trees. Summer pruning was applied to the pear trees and tree manipulation was performed on the peach trees at different stages of the season. Tree manipulation resulted in a dense column of leaves in the centre of the tree. Estimated LA for the Keisie peach trees was higher than expected if compared to field observations of canopies from the other peach tree plots. The reason for this could be that the PCA was calibrated for peach trees with normal LAD values and that the calibration function did not apply to these trees. The LAD of the Keisie trees attained a seasonal maximum value of *ca.* 10 m^{-1} compared to maximum values between 2.5 m^{-1} and 7 m^{-1} for the other peach trees (Fig. 23). Maximum seasonal LAD ranged between *ca.* 2 and 12 for apple (Fig. 21) and *ca.* 4 and 9 for pear trees (Fig. 22). Fourth-order polynomial relationships established between the LA of single trees at each plot and day of season are summarized for apple, pear and peach trees in Tables 7, 8 and 9, respectively. Functions for single trees over day of season were preferred above that for average LA per plot over day of season, because it resulted in better coefficients of determination.

Sap flow calibration: Laboratory determined calibration curves for the heat pulse sap flow method (A) and the relation between the sap flux predicted from the laboratory calibration of apple and pear and the actual sap flux (B) are presented in Figure 24. There was good agreement between the average δT of the heat pulse method and the actual water flow through stem sections (Fig. 24A). Calibration curves of the four apple cultivars and Packhams' Truimph pear trees were not significantly different and they were combined into one calibration equation to estimate the sap flux for apples and pears. A good agreement was obtained between the sap flux predicted from the laboratory calibration and the actual sap flux measured in intact apple trees (Fig. 24B).

Sap flow: Multiple regression on data of the 1999/2000 season showed that actual sap flow of apples and pears could be predicted from LA and ETo (refer 1999/2000 progress report). The data set used, however, was limited and thirty-five additional sap flow data sets (5 sets at 7 plots each) were collected during the 2000/2001 season on a range of tree sizes, including large apple and medium to large sized pear trees during all growth stages to improve the prediction of the multiple regression relationship (data not shown). Leaf area and sap flow data prone to experimental error were omitted from the statistical analysis. The data set of the Granny Smith apple trees was omitted because the possibility existed that

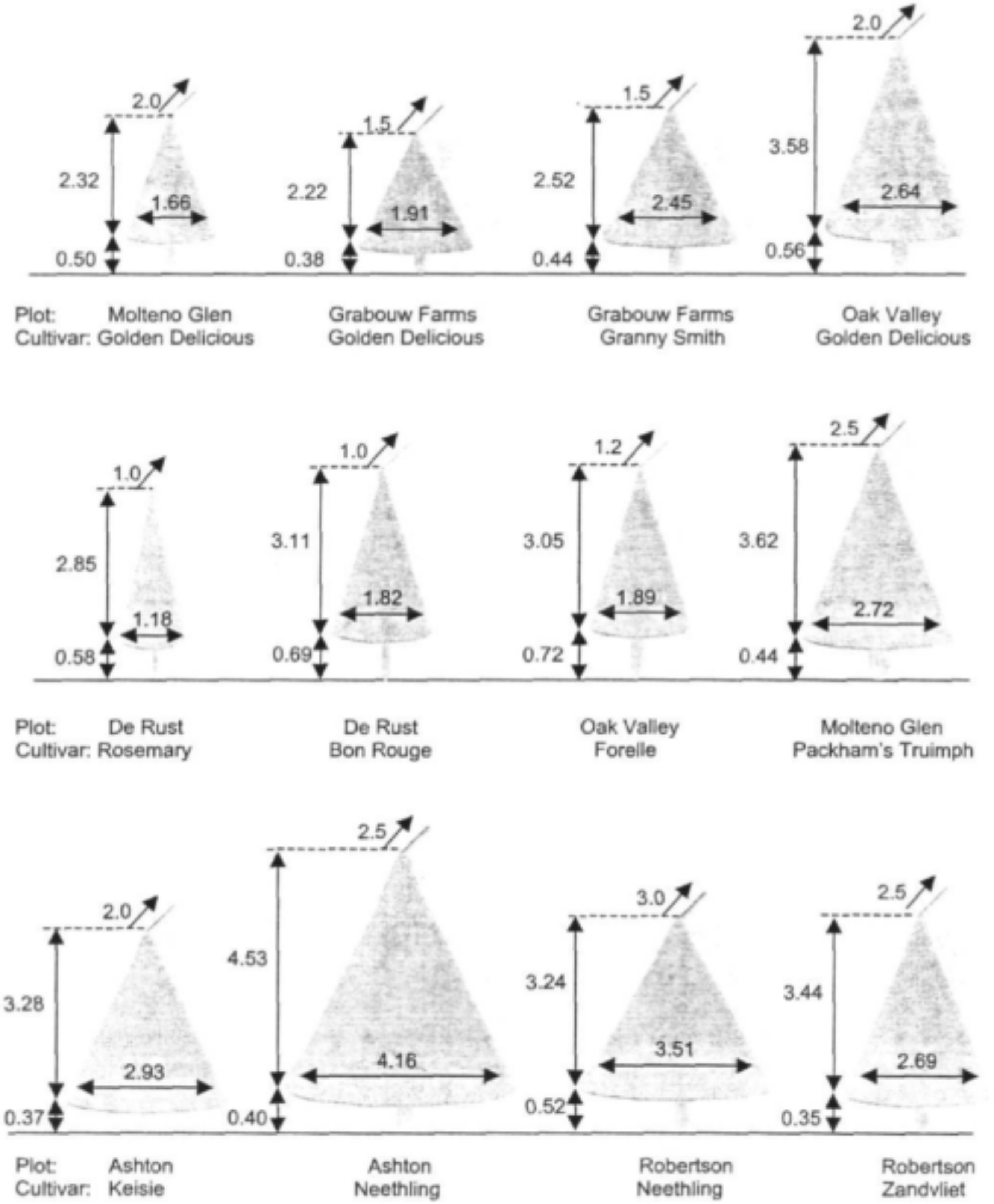


Figure 20. Schematic representation of measured tree dimensions in meter during midseason 2000/2001 for apple, pear and peach tree plots. Canopy dimensions included diameter over the work row, height of the canopy above the ground , tree height and canopy diameter within the tree row. Canopy height was calculated as tree height minus the height of the canopy above the ground.

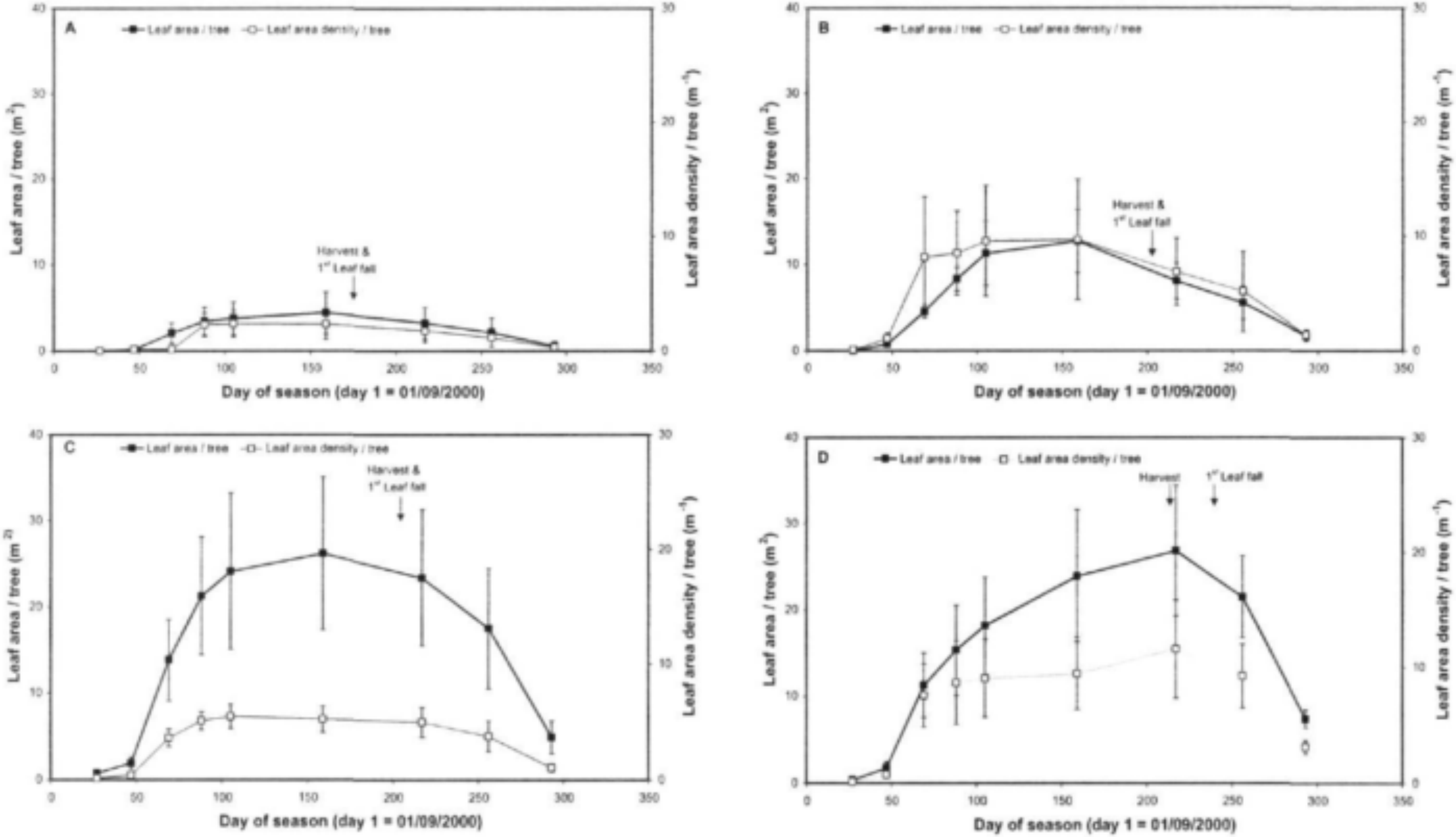


Figure 21. The leaf area and leaf area density of (A) young and (B & C) full bearing Golden Delicious and (D) full bearing Granny Smith apple trees as measured during the 2000/2001 season. B is for the Grabouw farms plot and C for the Oak Valley plot.

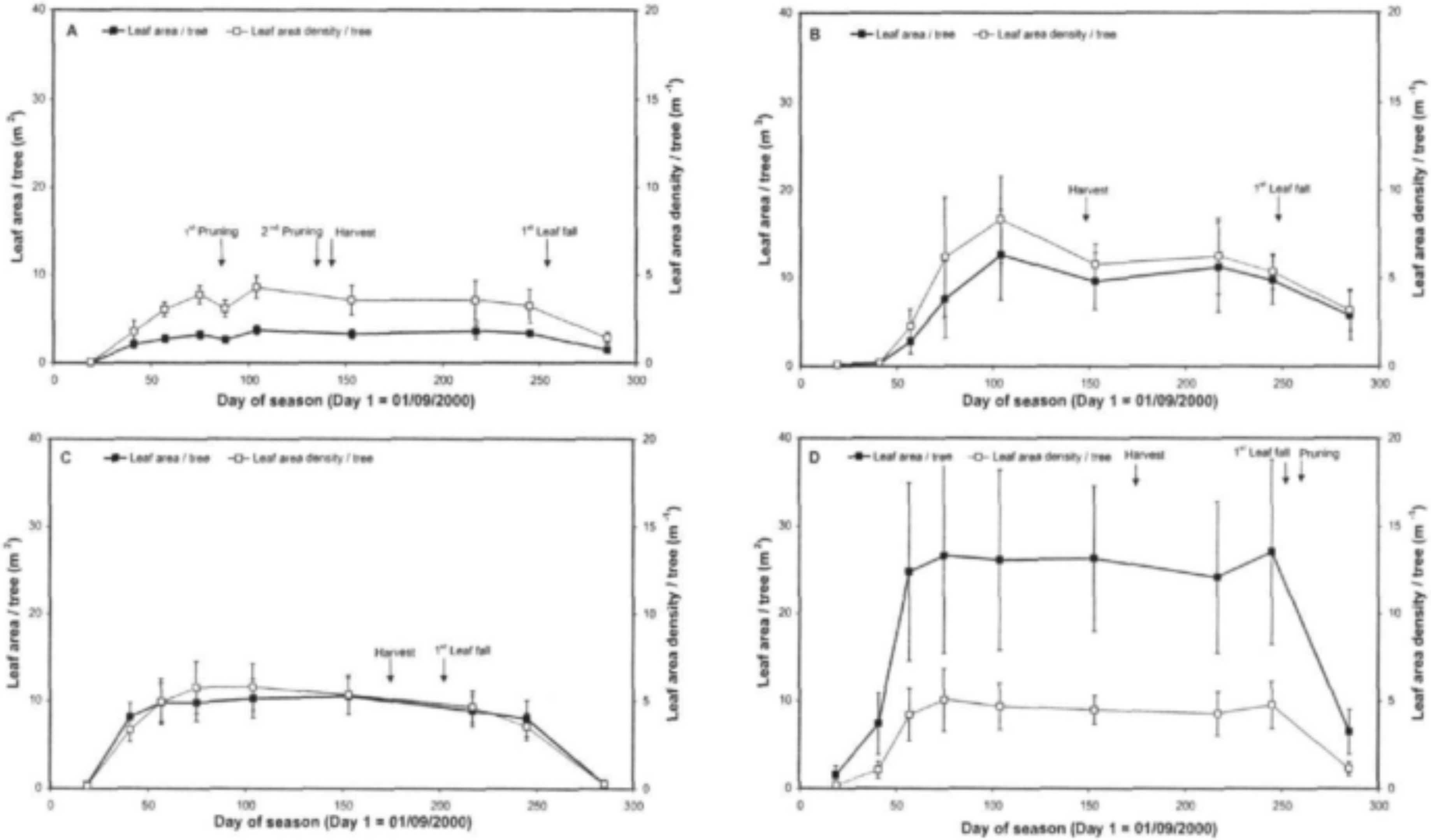


Figure 22. The leaf area and leaf area density of young Rosemary (A) and Bon Rouge (B) and full bearing Forelle (C) and Packhams' Truimph (D) pear trees as measured during the 2000/2001 season.

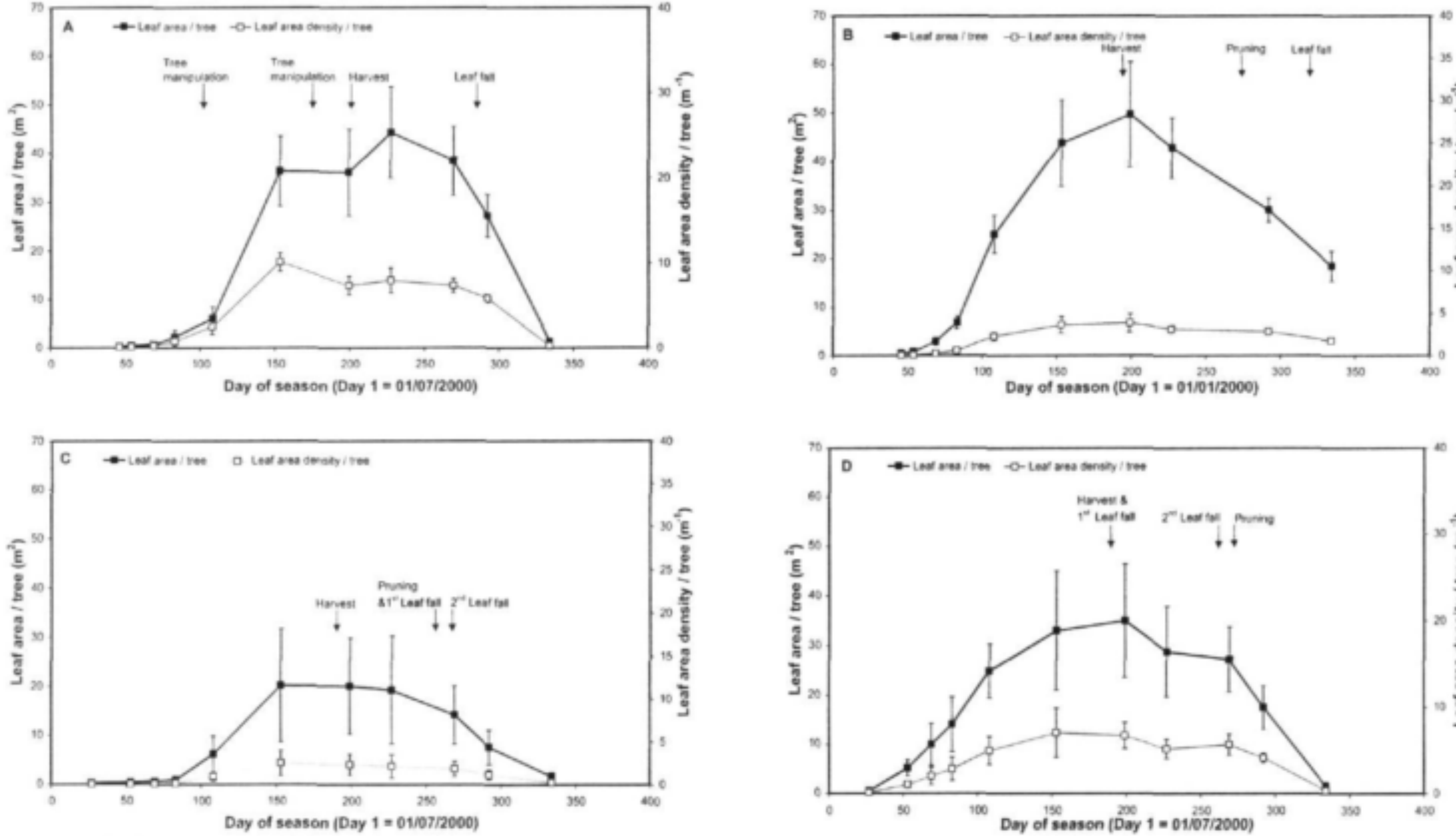


Figure 23. The leaf area and leaf area density of young Keisie (A) and full bearing Neethling (B & C) and Zandvliet (D) peach trees as measured during the 2000/2001 season. B is for the Ashton plot and C for the Robertson plot.

Table 7. Fourth order polynomial relationships ($y = a + bx + cx^2 + dx^3 + ex^4$) of leaf area of single apple trees over day of season for the 2000/2001 season.

Plot	Cultivar	Tree	Pr > F	R^2	a	b	c	d	e
MG	GD	1	0.009	0.95	-3.055765	0.117328	-0.000565	0.000001130	-1.3697690E-9
		2	0.012	0.94	-3.310271	0.099658	0.000174	-0.000003251	5.7083775E-9
		3	0.022	0.91	-0.668654	0.010450	0.000345	-0.000002446	4.0155589E-9
		4	0.024	0.91	-0.664875	0.008102	0.000422	-0.000003173	5.7177965E-9
		5	0.004	0.97	-1.519255	0.017596	0.001038	-0.000007261	1.2304937E-8
GP	GD	1	0.006	0.96	-3.665743	0.103021	0.000603	-0.000006678	1.2346890E-8
		2	0.001	0.99	0.224136	-0.105401	0.003993	-0.000023614	3.8545621E-8
		3	0.008	0.95	-4.494924	0.118465	0.000793	-0.000008104	1.4643904E-8
		4	0.017	0.92	-17.645181	0.621239	-0.001231	-0.000006189	1.3728198E-8
		5	0.033	0.89	-1.335597	-0.107741	0.004908	-0.000029506	4.8306143E-8
	GS	1	0.007	0.95	-20.279598	0.879537	-0.007856	0.000035070	-5.9195480E-8
		2	0.002	0.97	-10.777766	0.493347	-0.004763	0.000022822	-3.9658320E-8
		3	0.002	0.97	-13.092933	0.458508	-0.000756	0.000000143	-7.0225720E-9
		4	0.001	0.98	-0.677776	-0.106413	0.004970	-0.000025454	3.4320213E-8
		5	0.001	0.98	-9.257897	0.320655	-0.001020	0.000004638	-1.4545170E-8
OV	GD	1	0.005	0.96	-18.863847	0.687922	-0.002097	0.000000312	-6.4102900E-10
		2	0.015	0.93	-15.331204	0.593055	-0.003787	0.000012557	-1.9595370E-8
		3	0.001	0.98	-4.285649	0.060986	0.003538	-0.000023110	3.6286290E-8
		4	0.012	0.93	-12.685145	0.486053	-0.002425	0.000004634	-4.5959650E-9
		5	0.022	0.91	-22.837116	0.833883	-0.003297	0.000003476	-2.2353990E-9

Table 8. Fourth order polynomial relationships ($y = a + bx + cx^2 + dx^3 + ex^4$) of leaf area of single pear trees over day of season for the 2000/2001 season.

Plot	Cultivar	Tree	Pr > F	R^2	a	b	c	d	e
DR	RM	1	0.088	0.89	-3.019275	0.197307	-0.002106000	0.000009352	-1.4709450E-8
		2	0.039	0.83	-2.094509	0.128318	-0.001192000	0.000004927	-7.6244870E-9
		3	0.003	0.94	-2.400758	0.161117	-0.001710000	0.000007433	-1.1369920E-9
		4	0.001	0.96	-2.054544	0.154624	-0.001530000	0.000006757	-1.1369920E-8
		5	0.003	0.94	-2.607696	0.194990	-0.002288000	0.000011089	-1.1048210E-8
	BR	1	0.055	0.86	-4.326094	0.185083	-0.000467000	-0.000000584	1.4879342E-9
		2	0.061	0.85	-2.499564	0.079894	0.000477000	-0.000004401	7.0079937E-9
		3	0.046	0.87	-1.964613	0.056362	0.000748000	-0.000005599	8.9833270E-9
		4	0.053	0.86	-3.736458	0.144640	0.000089129	-0.000003208	5.3643356E-9
		5	0.098	0.81	-7.51367	0.301012	-0.000171000	-0.000005784	1.2127007E-8
OV	FOR	1	0.008	0.95	-5.193142	0.403946	-0.004303000	0.000019021	-3.0396230E-8
		2	0.002	0.98	-8.932498	0.633587	-0.006672000	0.000029179	-4.6166230E-8
		3	0.003	0.97	-10.996978	0.771935	-0.008513000	0.000038412	-6.1457070E-8
		4	0.001	0.98	-6.918399	0.485197	-0.005231000	0.000023391	-3.7461470E-8
		5	0.004	0.96	-8.319078	0.629667	-0.006781000	0.000029980	-4.7626040E-8
MG	PT	1	0.044	0.87	-25.790971	1.548205	-0.015412000	0.000069276	-1.1500000E-7
		2	0.027	0.90	-7.250986	0.439735	-0.003802000	0.000015378	-2.4532150E-8
		3	0.031	0.90	-24.267369	1.473498	-0.015133000	0.000066160	-1.0500000E-7
		4	0.032	0.89	-24.517797	1.525005	-0.016308000	0.000074300	-1.2100000E-7
		5	0.043	0.88	-37.190922	2.354182	-0.025449000	0.000112000	-1.7300000E-7

Table 9. Fourth order polynomial relationships ($y = a + bx + cx^2 + dx^3 + ex^4$) of leaf area of single peach trees over day of season for the 2000/2001 season.

Plot	Cultivar	Tree	Pr > F	R^2	a	b	c	d	e
ASH	KEISIE	1	0.0001	0.99	40.034974	-1.482696	0.016550000	-0.000055417	5.4203428E-8
		2	0.0002	0.96	25.315980	-1.111804	0.014278000	-0.000051412	5.3927701E-8
		3	0.0005	0.95	29.125458	-1.142159	0.013337000	-0.000047127	4.9967147E-8
		4	0.0002	0.97	46.958062	-1.797258	0.020668000	-0.000074450	8.2265120E-8
		5	0.0003	0.96	14.851767	-0.635652	0.007847000	-0.000026180	2.4025458E-8
	NEETH	1	0.0033	0.94	-6.496165	-0.270449	0.009554000	-0.000048047	6.7391611E-8
		2	0.0001	0.99	5.616479	-0.469372	0.008835000	-0.000036988	4.5181336E-8
		3	0.0002	0.98	5.249303	-0.546067	0.010672000	-0.000046976	6.1138185E-8
		4	0.0026	0.94	27.023049	-1.356653	0.020116000	-0.000085552	1.1100000E-7
		5	0.0001	0.99	25.896612	-1.408172	0.022144000	-0.000096959	1.2900000E-7
ROB	NEETH	1	0.0001	0.98	12.850757	-0.648251	0.008670000	-0.000033220	3.8206499E-8
		2	0.0001	0.97	6.373256	-0.336176	0.004821000	-0.000020021	2.5303239E-8
		3	0.0002	0.96	23.548423	-1.269778	0.018471000	-0.000079793	1.0600000E-7
		4	0.0001	0.98	8.576351	-0.449703	0.006359000	-0.000025731	3.1559154E-8
		5	0.0032	0.90	4.306188	-0.265383	0.004342000	-0.000019116	2.5204943E-8
	ZAND	1	0.0001	0.98	-5.193855	0.058633	0.005766000	-0.000031653	4.2172843E-8
		2	0.0011	0.93	-8.372963	0.309341	-0.000825000	0.000001231	-3.7796090E-9
		3	0.0018	0.92	-3.512344	-0.036291	0.005342000	-0.000028970	4.0258280E-8
		4	0.0001	0.99	-2.517591	0.023798	0.002852000	-0.000011848	9.6125039E-9
		5	0.0003	0.96	-8.150317	0.263447	-0.000007632	-0.000002515	1.2802069E-9

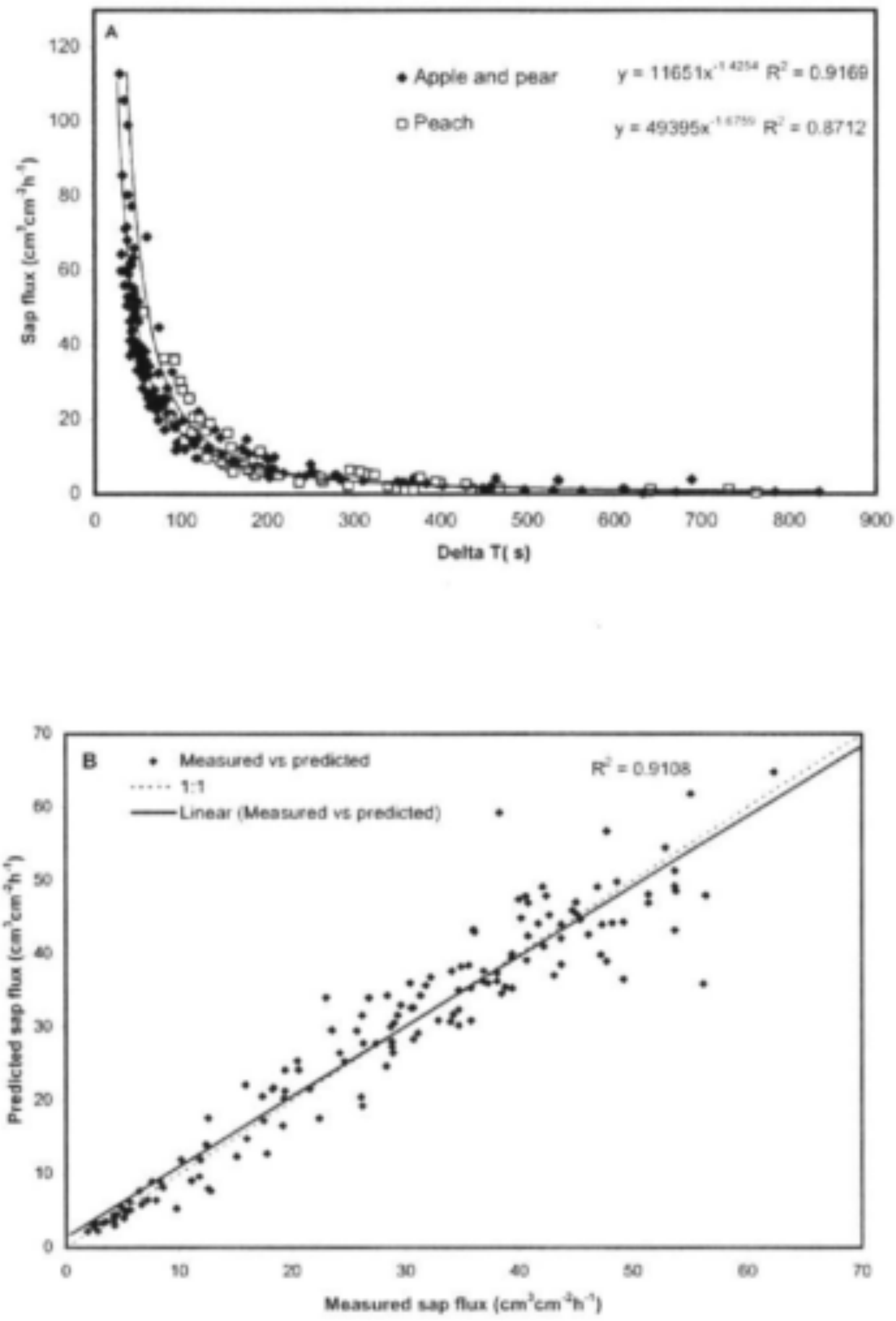


Figure 24. The relation between (A) delta T of the heat pulse based sap flux method and the actual sap flux of apple and pear stem sections as determined in the laboratory and (B) the sap flux predicted from the laboratory calibration and the actual sap flux as determined *in situ* for an apple tree.

tension wood was present in non-uniform tree trunks. Sap flow measurements done in less dense wood sections of the tree trunk could cause overestimation and measurements done in cellulose-rich tension wood, could underestimate sap flow of the tree. Multiple regression on the combined data set of the two seasons confirmed that actual sap flow of apples and pears could be predicted from LA and ETo (Fig. 25A&B).

Twenty additional sap flow data sets (5 sets at 4 plots each) were collected during the 2000/2001 season on a range of peach tree sizes. The data sets from the Zandvliet peaches were omitted due to suboptimal soil water conditions that occured for a large part of the season in the plot. Sap flow of Neethling peaches could be predicted from LA and ETo (Fig. 25C). The relationship was significant (Pr>F=0.001), but poor when data from the Keisie peach trees were included ($R^2 = 0.23$). The reason for the poor correlation with the other data points could be excessively high LA values from the Keisie trees (see Leaf area index).

4.2.5 Transpiration and single crop coefficients

ETo, estimated LA, estimated sap flow, crop Kt and Kc values with and/or without cover crop were summarized for apple, pear and peach trees (Tables 10, 11 &12). Transpiration coefficients were not estimated for Granny Smith apple (Table 10), Packham's Truimph pear (Table 11) and Keisie peach (Table 12) trees. Pear Kt values were higher than the Kc's (excluding the values for Forelle pears from February to May) (Table 11). Sap flow predicted for pear trees from LA and ETo was much higher than that of the apple trees at comparable leaf areas. The sap flow calibration included only stems of Packhams' Truimph pear trees and the calibration was not verified for pears by measurements in intact trees. It is concluded that the Kt values for pears are not reliable.

4.2.6 Monthly and seasonal transpiration and evapotranspiration

Monthly and seasonal transpiration and/or ET are summarized for apple, pear and peach trees in Table 13, Table 14 and Table 15, respectively. Evapotranspiration was compared to that estimated by Green (1985) from long-term daily Class-A pan evaporation and a set of crop factors for deciduous fruit trees for early, mid-season and late cultivars for Elgin and for early cultivars for the Robertson area. The growing season starts on 1 August, 1 September and 1 October for early, mid-season and late cultivars, respectively. The Keisie and Neethling peach and Forelle pear trees can be considered as early (1 August), Granny Smith apple, Rosemary, Bon Rouge and Packhams' Truimph pear trees as mid-season (1 September) and Golden Delicous apple trees as late (1 October).

Granny Smith trees used approximately 1000 $m^3 ha^{-1}$ more water per season compared to that estimated from the Class A-pan crop-factors (Table 13). It was assumed by Green (1985) that periods of active growth end approximately April. Granny Smith, however, still used a lot of water in May. Cover crop also increased water consumption where the full surface was irrigated (full bearing Golden Delicious trees, Oak Valley). Forelle evapotranspirated nearly 2000 $m^3 ha^{-1}$ and Packhams' Truimph 876 $m^3 ha^{-1}$ more

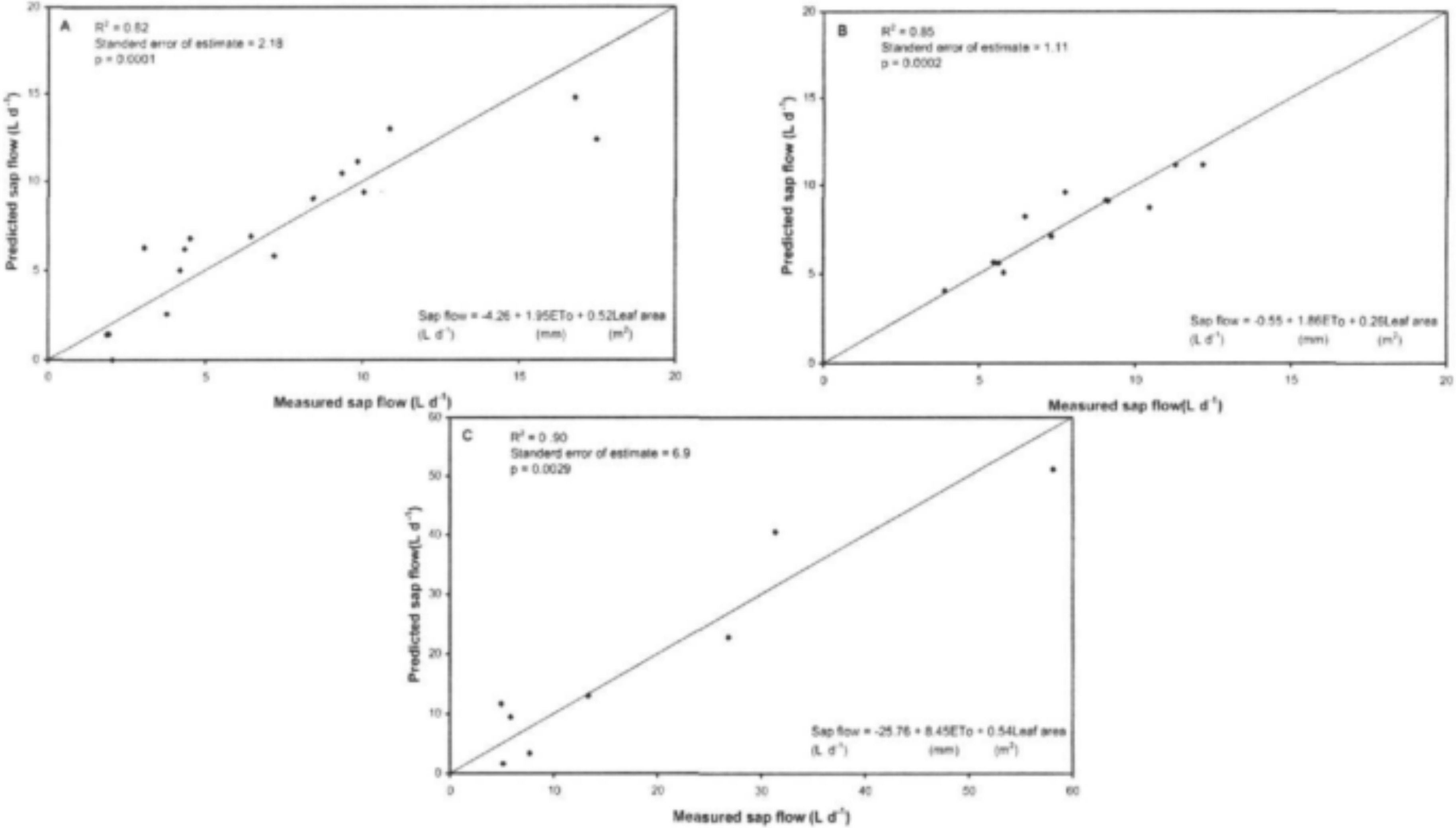


Figure 25. Comparison of measured sap flow values to sap flow values predicted from a multiple regression equation with leaf area and Penman-Monteith reference evapotranspiration (ETo) as independent variables for Golden Delicious apple (A), pear (B) and Neethling peach (C) trees.

Table 10. Monthly average of daily Penman-Monteith reference evapotranspiration (ET_o), estimated leaf area, estimated sap flow and crop transpiration coefficients (Kt) as well as single crop coefficients for apple trees of selected plots without (Kc Tree) and with covercrop (Kc Tree & CC) as determined for the 2000/2001 season.

Plot	Cultivar	Month	ET_o (mm d^{-1})	Estimated leaf area (m^2 $tree^{-1}$)	Sap flow (L d^{-1} $tree^{-1}$)	Kt	Kc Tree
Molteno Glen	Golden Delicious (Young)	Oct	3.75	0.76	3.42	0.13	0.22
		Nov	4.73	2.50	6.20	0.19	0.28
		Dec	5.02	3.79	7.42	0.21	0.39
		Jan	5.31	4.54	8.36	0.22	0.41
		Feb	4.95	4.62	7.69	0.22	0.41
		Mar	3.74	4.14	5.10	0.19	0.35
		Apr	2.31	3.13	1.81	0.11	0.40
		May	1.84	1.93	0.29	0.02	0.31
Grabouw Farms	Golden Delicious (Full bearing)	Oct	3.81	2.71	4.52	0.20	0.20
		Nov	4.44	9.01	8.90	0.33	0.37
		Dec	4.65	13.91	11.77	0.42	0.40
		Jan	5.08	16.78	14.05	0.46	0.51
		Feb	4.71	17.01	13.44	0.48	0.60
		Mar	3.57	15.03	10.23	0.48	0.55
		Apr	2.18	11.05	5.53	0.42	0.72
		May	1.62	6.51	2.16	0.22	0.41

Table 10. (Continued)

Plot	Cultivar	Month	ET_o (mm d^{-1})	Estimated leaf area (m^2)	Sap flow (L d^{-1} tree^{-1})	Kt	Kc Tree	Kc Tree & CC
Grabouw Farms	Granny Smith (Full bearing)	Oct	3.81	4.38	-	-	0.24	-
		Nov	4.44	12.08	-	-	0.53	-
		Dec	4.65	18.06	-	-	0.65	-
		Jan	5.08	22.93	-	-	0.69	-
		Feb	4.71	26.29	-	-	0.73	-
		Mar	3.57	27.59	-	-	0.84	-
		Apr	2.18	26.27	-	-	1.05	-
		May	1.62	21.06	-	-	1.11	-
Oak Valley	Golden Delicious (Full bearing)	Oct	3.94	5.86	6.35	0.19	0.20	0.31
		Nov	4.73	16.21	13.08	0.33	0.37	0.47
		Dec	5.63	23.23	18.35	0.38	0.40	0.52
		Jan	5.83	27.40	20.84	0.42	0.51	0.60
		Feb	5.6	28.54	20.96	0.44	0.60	0.71
		Mar	4.17	27.07	17.44	0.49	0.55	0.62
		Apr	2.81	22.81	12.66	0.53	0.72	0.78
		May	2.62	16.25	9.00	0.40	0.41	0.45

Table 11. Monthly average of daily Penman-Monteith reference evapotranspiration (ET$_o$), estimated leaf area, estimated sap flow and crop transpiration coefficients (Kt) as well as single crop coefficients for pear trees of selected plots without (Kc Tree) and with covercrop (Kc Tree & CC) as determined for the 2000/2001 season.

Plot	Cultivar	Month	ET$_o$ (mm d^{-1})	Estimated Leaf area (m^2 tree^{-1})	Sap flow (L d^{-1} tree^{-1})	Kt	Kc Tree	Kc Tree & CC
De Rust	Rosemary (Young)	Oct	3.63	2.19	6.76	0.53	0.31	-
		Nov	4.70	3.13	9.00	0.55	0.62	-
		Dec	5.31	3.29	10.17	0.55	0.51	-
		Jan	5.47	3.23	10.45	0.55	0.52	-
		Feb	4.98	3.27	9.55	0.55	0.52	-
		Mar	3.66	3.42	7.14	0.56	0.71	-
		Apr	2.47	3.50	4.95	0.57	0.89	-
		May	2.26	3.02	4.44	0.56	0.61	-
	Bon Rouge (Young)	Oct	3.63	2.84	6.93	0.55	0.28	-
		Nov	4.70	6.95	9.99	0.61	0.45	-
		Dec	5.31	9.99	11.92	0.64	0.79	-
		Jan	5.47	11.94	12.73	0.66	0.71	-
		Feb	4.98	12.59	11.99	0.69	0.65	-
		Mar	3.66	12.10	9.41	0.73	0.64	-
		Apr	2.47	10.56	6.80	0.79	0.76	-
		May	2.26	8.40	5.85	0.74	0.93	-

Table11. (Continued)

Plot	Cultivar	Month	ET_o (mm d^{-1})	Estimated leaf area (m^2 $tree^{-1}$)	Sap flow (L d^{-1} $tree^{-1}$)	Kt	Kc Tree	Kc Tree & CC
Oak Valley	Forelle (Full bearing)	Oct	3.94	7.86	8.82	0.47	0.40	0.45
		Nov	4.73	10.79	11.06	0.49	0.43	0.51
		Dec	5.63	10.85	12.74	0.47	0.44	0.65
		Jan	5.83	10.08	12.91	0.46	0.42	0.70
		Feb	5.60	9.58	12.35	0.46	0.50	0.75
		Mar	4.17	9.49	9.68	0.48	0.55	0.80
		Apr	2.81	9.06	7.04	0.52	0.61	0.85
		May	2.62	6.70	6.07	0.48	0.87	1.13
Molteno Glen	Packhams' Truimph (Full bearing)	Oct	3.75	17.14	-	-	0.28	0.48
		Nov	4.73	25.86	-	-	0.35	0.51
		Dec	5.02	27.50	-	-	0.41[1]	0.53[1]
		Jan	5.31	27.08	-	-	0.49	0.60
		Feb	4.95	27.15	-	-	0.57	0.63
		Mar	3.74	27.94	-	-	0.56	0.58
		Apr	2.31	27.81	-	-	0.88	1.01
		May	1.84	22.79	-	-	0.75	1.11

1 Interpolated value

Table 12. Monthly average of daily Penman-Monteith reference evapotranspiration (ET_o), estimated leaf area, estimated sap flow and crop transpiration coefficients (k_t) as well as single crop coefficients (Kc Tree) for peach trees of selected plots as determined for the 2000/2001 season at Ashton and Robertson.

Month	Ashton						Robertson				
	ET_o (mm d^{-1})	Keisie (Young)	Neethling (Full bearing)				ET_o (mm d^{-1})	Neethling (Full bearing)			
		Kc Tree	Estimated leaf area (m^2 $tree^{-1}$)	Sapflow (L d^{-1} $tree^{-1}$)	Kt	Kc Tree		Estimated leaf area (m^2 $tree^{-1}$)	Sapflow (L d^{-1} $tree^{-1}$)	Kt	Kc Tree
Aug	2.75	-	-	-	-	0.38	-	-	-	-	-
Sep	3.72	0.34	7.84	9.93	0.21	0.76	3.86	1.34	7.58	0.13	0.37
Oct	5.00	0.46	21.87	28.38	0.45	0.81	4.89	7.63	19.70	0.27	0.37
Nov	5.83	0.34	36.00	43.08	0.59	0.75^1	5.71	14.59	30.42	0.36	0.46
Dec	6.73	0.28	45.59	55.91	0.66	0.70	6.70	19.55	41.48	0.41	0.60
Jan	6.48	0.33^1	49.15	55.73	0.69	0.63	6.78	21.46	43.20	0.42	0.59^2
Feb	6.06	0.53	45.89	50.41	0.67	0.91	6.26	19.70	37.85	0.40	0.58
Mar	4.56	0.41	38.25	33.58	0.59	0.93	4.87	15.42	23.78	0.33	0.50
Apr	2.90	0.81	27.52	13.71	0.38	1.14	3.09	9.12	5.31	0.11	0.52
May	2.44	0.46	19.39	5.41	0.18	0.92	2.77	3.74	0.00	0.00	0.37

1 and 2 Interpolated value

Table 13. Estimated monthly and seasonal transpiration (T) and evapotranspiration (ET) for apple trees for the 2000/2001 season. ET_{GR} refers to ET estimated from Class-A pan evaporation and crop factors for deciduous fruit for the Elgin area by Green (1985).

Month	Green-method		Plot and cultivar							
			Molteno Glen		Grabouw Farms				Oak Valley	
	Mid-season cultivar	Late cultivar	Golden Delicious (Young)		Golden Delicious (Full bearing)		Granny Smith (Full bearing)		Golden Delicious (Full bearing & cover crop)	
	ET_{GR} $(m^3 ha^{-1})$	ET_{GR} $(m^3 ha^{-1})$	T $(m^3 ha^{-1})$	ET $(m^3 ha^{-1})$	T $(m^3 ha^{-1})$	ET $(m^3 ha^{-1})$	T $(m^3 ha^{-1})$	ET $(m^3 ha^{-1})$	T $(m^3 ha^{-1})$	ET $(m^3 ha^{-1})$
Sep	240	-	-	-	-	-	-	-	-	-
Oct	400	360	151	250	233	240	-	286	232	382
Nov	550	480	266	396	445	493	-	708	462	661
Dec	860	750	328	611	608	574	-	930	669	916
Jan	1060	950	370	682	726	804	-	1085	760	1092
Feb	990	960	308	573	627	789	-	967	691	1114
Mar	630	720	226	411	529	608	-	929	636	805
Apr	200	200	78	277	276	469	-	687	447	658
May	170	170	13	176	112	207	-	556	328	363
Oct to May	5100[1]	4590	1739	3378	3556	4148	-	6148	4224	5991

[1] September to May

Table 14. Estimated monthly and seasonal evapotranspiration (ET) for pear trees for the 2000/2001 season. ET_{GR} refers to ET estimated from Class-A pan evaporation and crop factors for deciduous fruit for the Elgin area by Green (1985).

Month	Green-method		Plot and cultivar			
			De Rust		Oak Valley	Molteno Glen
	Early cultivar	Mid-season cultivar	Rosemary (Young)	Bon Rouge (Young)	Forelle (Full bearing & cover crop)	Packhams' Truimph (Full bearing)
	ET_{GR} ($m^3 ha^{-1}$)	ET_{GR} ($m^3 ha^{-1}$)	ET ($m^3 ha^{-1}$)			
Aug	210	-	-	-	-	-
Sep	280	240	-	-	-	-
Oct	430	400	349	315	553	556
Nov	690	550	874	635	729	718
Dec	940	860	840	1300	1127	828
Jan	1140	1060	882	1204	1269	992
Feb	970	990	725	906	1180	871
Mar	560	630	806	726	1036	677
Apr	200	200	659	563	717	700
May	170	170	427	652	915	634
Oct to May	5590[1]	5100[2]	5562	6301	7526	5976

[1] August to May

[2] September to May

Table 15. Estimated monthly and seasonal transpiration (T) and evapotranspiration (ET) for peach trees for the 2000/2001 season. ET_{GR} refers to ET estimated from Class-A pan evaporation and crop factors for deciduous fruit for the Robertson area by Green (1985).

Month	Green-method	Plot and cultivar					
		Asthon				Robertson	
	Early cultivar	Keisie (Young)		Neethling (Full bearing)		Neethling (Full bearing)	
	ET_{GR} (m^3 ha^{-1})	T (m^3 ha^{-1})	ET (m^3 ha^{-1})	T (m^3 ha^{-1})	ET (m^3 ha^{-1})	T (m^3 ha^{-1})	ET (m^3 ha^{-1})
Aug	190	-	-	-	327	-	-
Sep	320	-	374	238	853	152	423
Oct	510	-	719	704	1251	407	567
Nov	840	-	588	1034	1311	608	793
Dec	1180	-	580	1387	1464	857	1243
Jan	1420	-	668	1382	1265	893	1237
Feb	1160	-	893	1129	1542	707	1014
Mar	650	-	573	833	1321	491	751
Apr	230	-	705	329	988	106	481
May	150	-	349	134	693	0	318
Sep to May	6650[1]	-	5450	7170	11014[1]	4221	6829

[1] August to May

water per season than that estimated from the Class A-pan crop-factors (Table 14). Evapotranspiration for full bearing peach trees was underestimated according to the Green-method, especially at Ashton where 4300 m^3 ha^{-1} more water was used (Table 15).

4.2.7 SWB Simulations

Input data: Weather data from automatic weather stations listed in Tables 1-3, were imported into SWB. The field data used in simulations are partially summarized in Table 16. The irrigation system was selected as micro, while system efficiency and storage efficiency was entered as 100% at all plots. Soil water content was measured for the first time during the season on the 17th of August for peach plots and 29th September for apple and pear plots. The Forelle pear tree plot (Oak Valley) was selected later and soil water content measurements only started on 13th of October 2000.

The lengths of the development, mid and late growth stages for simulation purposes for the different cultivars were determined from graphs of RFI values expressed as a function of time for apple, pear and peach trees (Figures 26, 27 & 28). The lengths of the growth stages are summarized in Table 17. The first date of soil water content measurement was used as start date for the initial growth stage. According to Snyder, Ferreira and Schakel (2000) the start date for the FAO development stage for deciduous fruit trees corresponds to leaf out (bud break). Bud break had already occurred in some of the plots when SWC measurements started and in order to use these values as initial SWC in the simulation, the number of days for the initial growth stage or development stage was adjusted. The crop data used in simulations are partially summarized in Table 18. Crop list information is summarized in Table 19. Soil data used in simulations for the profile and eleven layers are summarized as runoff curve number for the soil profile and depths per soil layer (Table 20), water content at field capacity (FC) per soil layer (Table 21), initial water content per soil layer (Table 22) and water content at permanent wilting point (PWP) per soil layer (Table 23). The soil bulk density was assumed to be 1.5 Mg m^{-3} and soil matric potential –1500 kPa at PWP for all plots. Soil matric potential at FC was –5 kPa, except for the Golden Delicious plot at Grabouw farms (Field GDGP2001) where a value of –10 kPa was used. A drainage rate of 100 mm d^{-1} and a drainage factor of 1 was used in simulations for all plots, excluding a second simulation for the Keisie plot at Ashton (Field PCHAK2001), when the drainage factor was altered to 0.63 .

Output: The simulations of SWB are presented for apple (Figs. 29-32), pear (Figs. 33-38) and peach plots (Figs. 39-43). Output graphs shown for each simulation performed include 1) Soil water deficit to field capacity 2) Precipitation and irrigation and 3) Drainage. The soil water deficit graph includes simulated (solid line) and measured (symbols) data points. SWB calculates parameters of statistical analysis between measured and simulated data and outputs them in the right corner of each graph. SWB predicted profile soil water deficits to field capacity were visually fitted to measured values. Model prediction reliability parameters recommended by De Jager (1994) were used as guideline to evaluate the statistical fit. The coefficient of determination (r^2) and index of agreement of Willmot (D) should be > 0.8, while the mean absolute error (MAE) should be < 20% for reliable prediction. The SWB model water balance output, namely seasonal rainfall, irrigation, transpiration, evaporation, drainage, canopy interception and runoff, is summarized for all plots in Table 24.

Table 16. Summary of selected Field data used in simulations of SWB.

Field	Crop	PlantDate/ StartDate	WeatherID	Description	Wetted Diameter (m)	Lateral Spacing (m)	Emitter Spacing (m)	Delivery (L h^{-1})	Fraction Root Wet Zone
GDGP2001	APPLES,GDGP2001	29/09/2000	7	APPLES,G.D. GRABOUW FARMS	3.00	4.00	1.5	32	1.00
GDMG2001	APPLES,GDMG2001	29/09/2000	8	APPLES, G.D. MOLTENO GLEN	3.00	3.50	2.0	32	1.00
GDOV2001	APPLES,GDOV2001	02/10/2000	10	APPLES, GDOV2001	4.24	4.25	2.0	50	1.00
GSGP2001	APPLES,GSGP2001	29/09/2000	7	APPLES, GSGP2001	3.00	4.00	1.5	32	1.00
P-BR2001FS	PEARBR2001FS	29/09/2000	9	PEARS, BON ROUGE-DR2001FS	2.80	3.50	1.0	20	1.00
P-F2001FS	PEARF2001FS	13/10/2000	10	PEARS, FORELLE-OV2001FS	2.50	4.00	1.2	30	1.00
P-RM2001FS	PEARRM2001FS	29/09/2000	9	PEARS, ROSEMARY-DR2001FS	2.80	3.50	1.0	20	1.00
PCHAK2001	PEACH(KS), ASHTON	17/08/2000	12	PEACH (KS), ASHTON	3.00	4.50	2.0	32	1.00
PCHAN2001	PEACH(N), ASHTON	17/08/2000	12	PEACHES (N), ASHTON	3.00	5.00	2.5	50	1.00
PCHRN2001	PEACH(N),ROBERTSON	17/08/2000	11	PEACHES (N), ROBERTSON	3.20	5.00	2.5	32	1.00
PEARPT2001	PEARPT2001	29/09/2000	8	PEARS, PT, MOLTENO GLEN	3.00	4.50	1.3	32	0.67
PT2001FS	PEARPT2001 FS	29/09/2000	8	PEARS, PT, MOLTENO GL FS	3.00	4.50	1.3	32	0.67

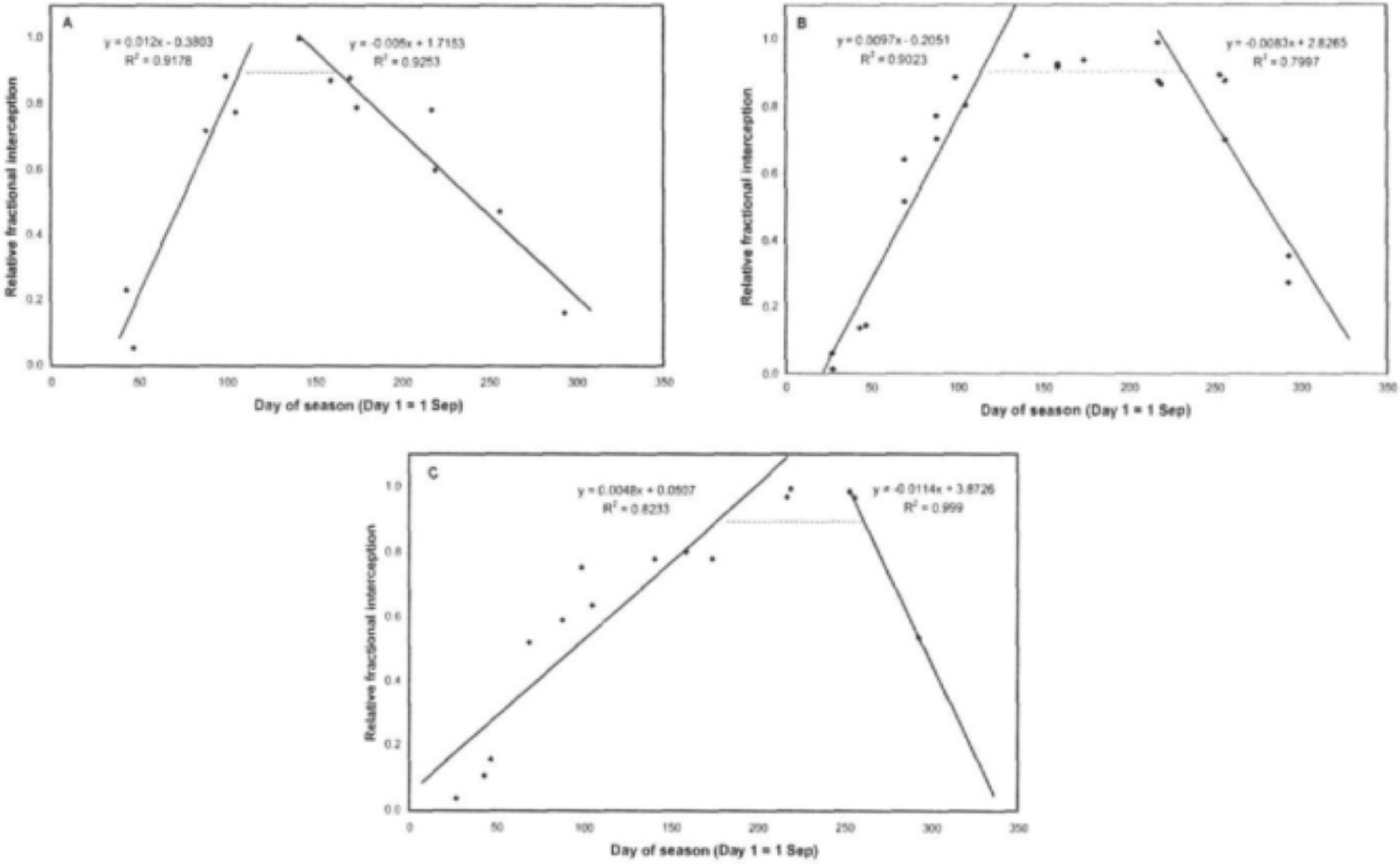


Figure 26. The estimated relative fractional interception of (A) young and (B) full bearing Golden Delicious and (C) full bearing Granny Smith apple trees. The dotted line indicates the relative fractional interception during mid-stage.

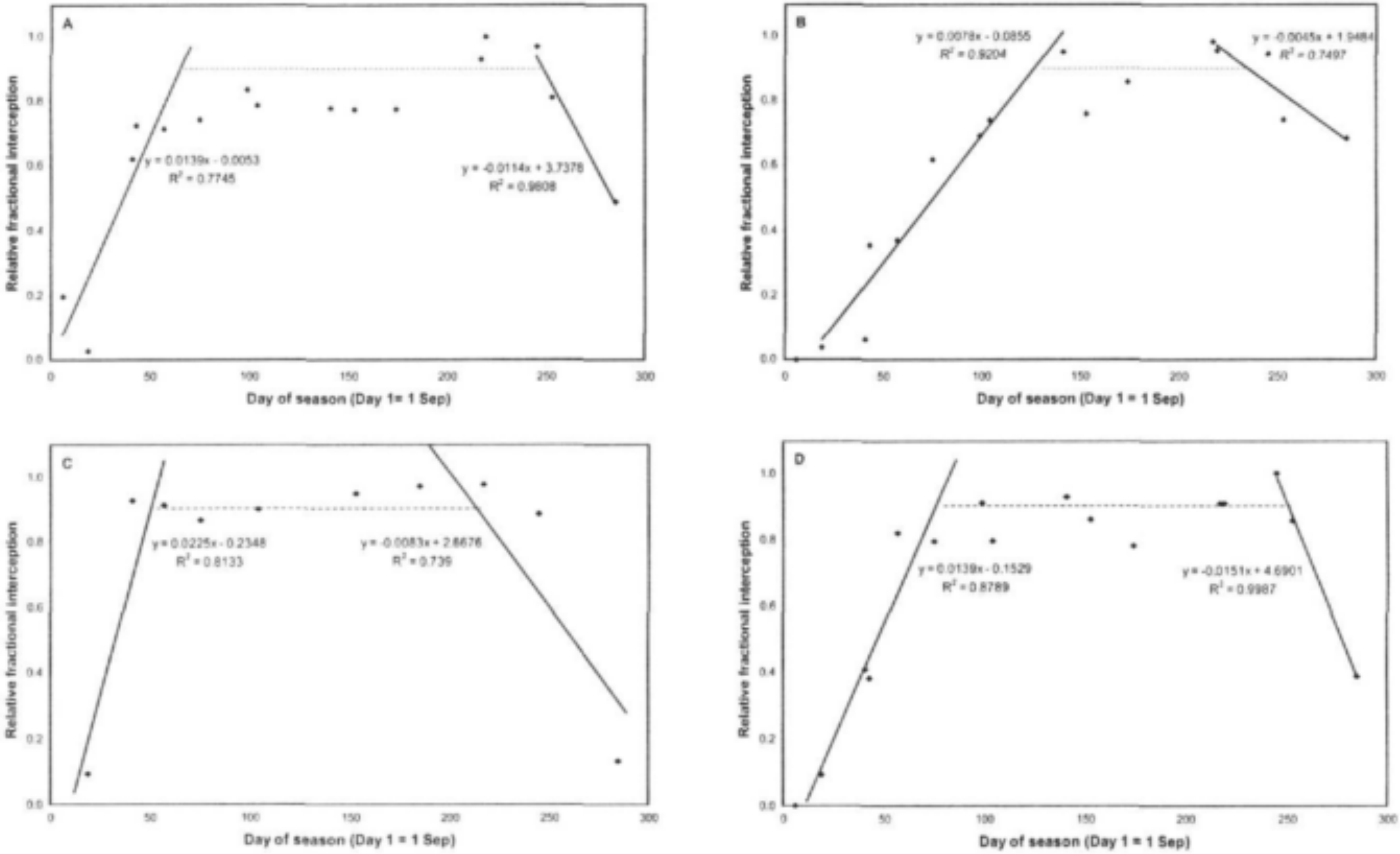


Figure 27. The estimated relative fractional interception of young (A) Rosemary and (B) Bon Rouge and full bearing (C) Forelle and (D) Packhams' Truimph pear trees. The dotted line indicates the relative fractional interception during mid-stage.

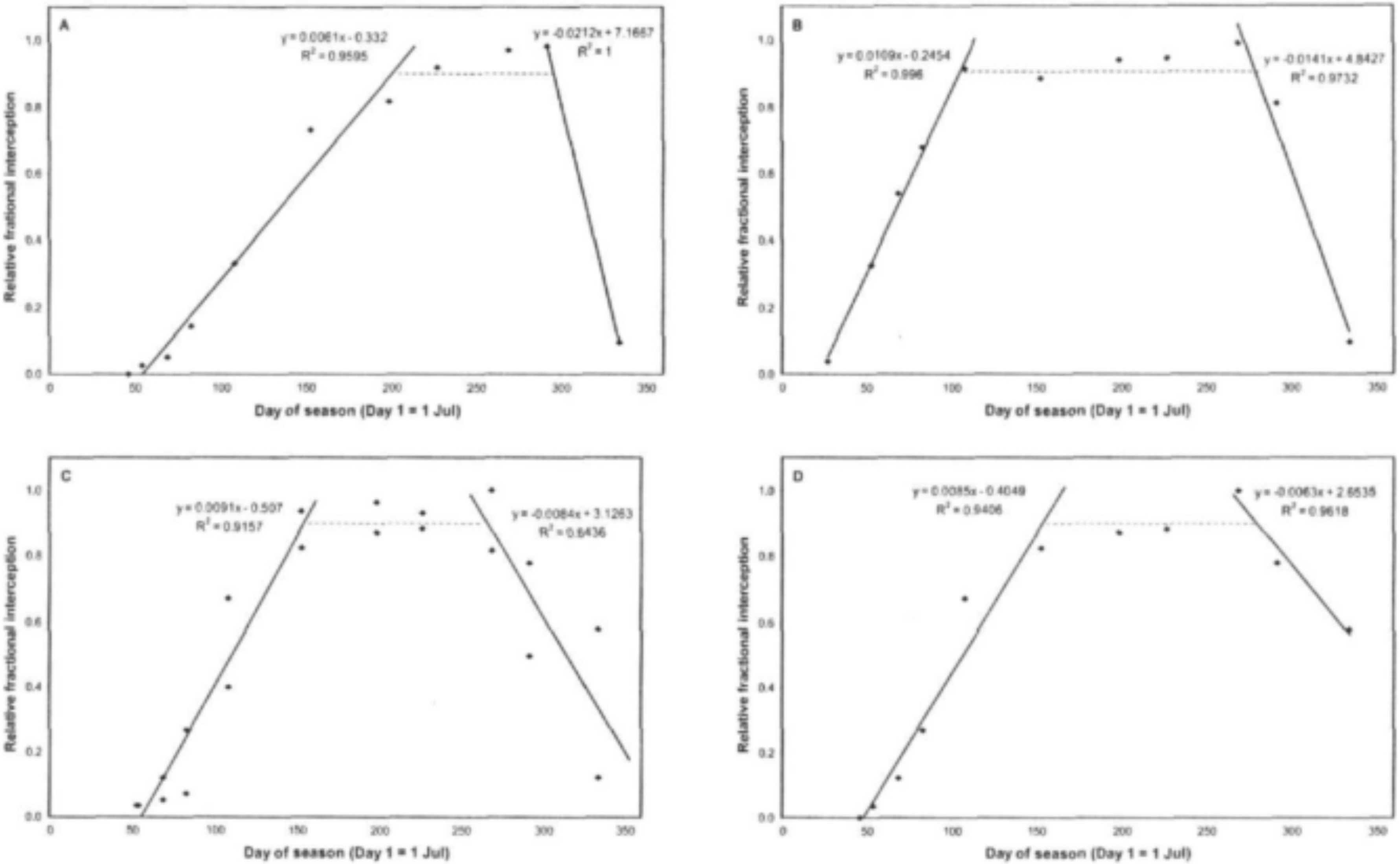


Figure 28. The estimated relative fractional interception of young (A) Keisie and full bearing (B) Zandvliet, (C) Neethling (Ashton and Robertson) and (D) Neethling (Ashton) peach trees. The dotted line indicates the relative fractional interception during mid-stage.

Table 17. Start dates, end dates and lengths of the development, mid and late growth stages for the different apple, pear and peach cultivars as estimated from day of season and relative fractional interception data.

Plot	Cultivar	Stage	Start date	End date	Period (days)
Molteno Glen	G.Delicious (Young)	Development	10-Oct	15-Dec	66
		Mid	16-Dec	10-Feb	56
		Late	08-Mar	30-Jun	114
Grabouw Farms	G.Delicious (Full bearing)	Development	02-Oct	22-Dec	81
		Mid	23-Dec	20-Apr	118
		Late	21-Apr	30-Jun	70
	Granny Smith) (Full bearing)	Development	10-Sep	24-Feb	167
		Mid	25-Feb	19-May	83
		Late	20-May	30-Jun	41
De Rust	Rosemary (Young)	Development	07-Sep	04-Nov	58
		Mid	05-Nov	07-May	183
		Late	08-May	30-Jun	53
	Bon Rouge (Young)	Development	23-Sep	04-Jan	103
		Mid	05-Jan	21-Apr	106
		Late	22-Apr	30-Jun	69
Oak Valley	Forelle) (Full bearing)	Development	15-Sep	19-Oct	34
		Mid	20-Oct	31-Mar	162
		Late	01-Apr	30-Jun	90
Molteno Glen	Packhams' Truimph) (Full bearing)	Development	18-Sep	14-Nov	57
		Mid	15-Nov	10-May	176
		Late	11-May	30-Jun	50
Ashton	Keisie (Young)	Development	08-Sep	17-Jan	131
		Mid	18-Jan	22-Apr	94
		Late	23-Apr	30-Jun	68
	Neethling (Full bearing)	Development	29-Aug	02-Dec	95
		Mid	03-Dec	06-Apr	124
		Late	07-Apr	30-Jun	84
Ashton and Robertson	Neethling (Full bearing)	Development	04-Sep	01-Dec	88
		Mid	02-Dec	22-Mar	110
		Late	23-Mar	30-Jun	99
Robertson	Zandvliet (Full bearing)	Development	02-Aug	13-Oct	72
		Mid	14-Oct	06-Apr	173
		Late	07-Apr	30-Jun	84

Table 18. Summary of selected Crop data used in SWB simulations. Duration, basal crop coefficients (Kcb), root depth (RD) and maximum tree height for the development (Dev) and late and/or initial (Init) and mid growth stages. The abbreviations Tr_{max}, Pot Tr_{max} and Canopy Int refers to maximum transpiration rate, leaf water potential at Tr_{max} and canopy interception respectively.

CropID	**Days Init**	**Days Dev**	**Days Mid**	**Days Late**	**Kcb Init**	**Kcb Mid**	**Kcb Late**	**RD Init (m)**	**RD Mid (m)**	**MaxH Init (m)**	**MaxH Mid (m)**	**Tr_{max} (mm d^{-1})**	**Pot Tr_{max} (kPa)**	**Stress Index**	**Canopy Int (mm)**
APPLES,GDGP2001	3	81	119	70	0.05	0.25	0.12	0.9	0.9	2.14	2.59	9	-1500	0.95	1
APPLES,GDMG2001	11	66	56	139	0.05	0.15	0.05	0.6	0.6	2.24	2.8	9	-1500	0.95	1
APPLES,GDOV2001	3	81	118	70	0.05	0.36	0.05	0.9	0.9	3.71	4.1	9	-1500	0.95	1
APPLES,GSGP2001	1	167	83	41	0.05	0.90	0.30	0.9	0.9	2.5	2.92	9	-1500	0.95	1
PEACH(KS), ASHTON	22	130	94	68	0.05	0.34	0.05	0.9	0.9	2.91	3.62	9	-1500	0.95	1
PEACH(KS), ASHTON*	22	130	94	68	0.05	0.36	0.05	0.9	0.9	2.91	3.62	9	-1500	0.95	1
PEACH(N), ASHTON	12	95	125	85	0.05	1.00	0.05	0.9	0.9	4.4	5.1	9	-1500	0.95	1
PEACH(N),ROBERTSON	18	88	109	99	0.05	0.38	0.05	0.9	0.9	4.1	3.8	9	-1500	0.95	1
PEARBR2001FS	0	97	106	69	0.05	0.31	0.05	0.9	0.9	3.08	3.9	9	-1500	0.95	1
PEARF2001FS	0	7	162	90	0.05	0.15	0.05	0.9	0.9	3.77	4.15	9	-1500	0.95	1
PEARPT2001	0	46	176	50	0.05	0.41	0.05	0.9	0.9	4.04	4.08	9	-1500	0.95	1
PEARPT2001 FS	0	46	176	50	0.05	0.43	0.05	0.9	0.9	4.04	4.08	9	-1500	0.95	1
PEARRM2001FS	0	36	183	53	0.05	0.23	0.05	0.9	0.9	3.39	3.46	9	-1500	0.95	1

* Second simulation with Kcb Mid adjusted.

Table 19. Crop List information used in SWB simulations.

Crop	Description
APPLES,GDGP2001	Golden Delicious, Grabouw Farms, Partially wetted soil surface, Cover crop in alley, Roots limited to clean cultivated wetted area, Root depth 0.9 m, Soil water deficit from clean cultivated area, Season 2000/2001.
APPLES,GDMG2001	Golden Delicious, Molteno Glen, Partially wetted soil surface, Cover crop in alley, Roots limited to clean cultivated wetted area, Root depth 0.6 m, Soil water deficit from clean cultivated area, Season 2000/2001.
APPLES,GDOV2001	Golden Delicious, Oak Valley, Fully wetted soil surface, Cover crop in alley, Roots distributed in total area, Root depth 0.9 m, Soil water deficit from total area, Season 2000/2001.
APPLES,GSGP2001	Granny Smith, Grabouw Farms, Partially wetted soil surface, Cover crop in alley, Roots limited to clean cultivated wetted area, Root depth 0.9 m, Soil water deficit from clean cultivated area, Season 2000/2001.
PEACH(KS), ASHTON	Keisie peaches, Ashton, Partially wetted soil surface, Cover crop in alley, Roots limited to clean cultivated wetted area, Root depth 0.9 m, Soil water deficit from clean cultivated area, Season 2000/2001.
PEACH(N), ASHTON	Neethling peaches, Ashton, Partially wetted soil surface, Cover crop in alley, Roots limited to clean cultivated wetted area, Root depth 0.9 m, Soil water deficit from clean cultivated area, Season 2000/2001.
PEACH(N),ROBERTSON	Neethling peaches, Robertson, Partially wetted soil surface, Cover crop in alley, Roots limited to clean cultivated wetted area, Root depth 0.9 m, Soil water deficit from clean cultivated area, Season 2000/2001.
PEARBR2001FS	Pears, Bon Rouge, De Rust, Partially wetted soil surface, Cover crop in alley, Roots restricted by compaction to clean cultivated area, Root depth 0.9 m, Soil water deficit from clean cultivated area, Season 2000/2001.
PEARF2001FS	Pears, Forelle, Oak Valley, Fully wetted soil surface, Cover crop in alley, Roots restricted by compaction to clean cultivated area. Root depth 0.9 m, Soil water deficit from clean cultivated area, Season 2000/2001.
PEARPT2001	Pears, Packhams' Truimph, Molteno Glen, Partially wetted soil surface, Cover crop in alley, Roots extend beyond clean cultivated wetted area, Root depth 0.9 m, Soil water deficit from clean cultivated area, Season 2000/2001.
PEARPT2001 FS	Pears, Packhams' Truimph, Molteno Glen, Partially wetted soil surface Cover crop in alley, Roots extend beyond clean cultivated wetted area, Root depth = 0.9 m, Soil water deficit from total area, Season 2000/2001.
PEARRM2001FS	Pears, Rosemary, De Rust, Partially wetted soil surface. Cover crop in alley, Roots restricted by compaction to clean cultivated area, Root depth 0.9 m, Soil water deficit from clean cultivated area, Season 2000/2001.

Table 20. Summary of runoff curve number (rop) and depths (m) per soil layer (Z1 to Z11) used in SWB simulations.

Field	rop	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10	Z11
GDGP2001	1000	0.080	0.16	0.25	0.33	0.41	0.49	0.57	0.66	0.74	0.82	0.9
GDMG2001	1000	0.065	0.11	0.17	0.22	0.28	0.33	0.39	0.44	0.5	0.55	0.6
GDOV2001	1000	0.080	0.16	0.24	0.33	0.41	0.49	0.57	0.66	0.74	0.82	0.9
GSGP2001	1000	0.080	0.16	0.25	0.33	0.41	0.49	0.57	0.66	0.74	0.82	0.9
P-BR2001FS	1000	0.080	0.16	0.25	0.33	0.41	0.49	0.57	0.66	0.74	0.82	0.9
P-F2001FS	1000	0.080	0.16	0.25	0.33	0.41	0.49	0.57	0.66	0.74	0.82	0.9
P-RM2001FS	1000	0.080	0.16	0.25	0.33	0.41	0.49	0.57	0.66	0.74	0.82	0.9
PCHAK2001	1000	0.080	0.16	0.25	0.33	0.41	0.49	0.57	0.66	0.74	0.82	0.9
PCHAN2001	1000	0.080	0.16	0.25	0.33	0.41	0.49	0.57	0.66	0.74	0.82	0.9
PCHRN2001	1000	0.080	0.16	0.25	0.33	0.41	0.49	0.57	0.66	0.74	0.82	0.9
PEARPT2001	1000	0.080	0.16	0.25	0.33	0.41	0.48	0.57	0.66	0.74	0.82	0.9
PT2001FS	1000	0.080	0.16	0.25	0.33	0.41	0.49	0.57	0.66	0.74	0.82	0.9

Table 21. Summary of water content (m water per m soil depth) at field capacity per soil layer (fcwc1 to fcwc11) used in SWB simulations.

Field	fcwc1	fcwc2	fcwc3	fcwc4	fcwc5	fcwc6	fcwc7	fcwc8	fcwc9	fcwc10	fcwc11
GDGP2001	0.205	0.205	0.204	0.204	0.205	0.214	0.214	0.214	0.253	0.292	0.292
GDMG2001	0.252	0.252	0.252	0.252	0.252	0.245	0.236	0.236	0.236	0.236	0.236
GDOV2001	0.211	0.211	0.213	0.214	0.218	0.243	0.243	0.243	0.355	0.466	0.466
GSGP2001	0.227	0.227	0.229	0.230	0.235	0.270	0.270	0.270	0.287	0.303	0.303
P-BR2001FS	0.292	0.292	0.292	0.309	0.336	0.336	0.336	0.348	0.354	0.354	0.354
P-F2001FS	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311	0.311
P-RM2001FS	0.308	0.308	0.308	0.341	0.397	0.397	0.397	0.368	0.354	0.354	0.354
PCHAK2001	0.231	0.231	0.231	0.248	0.275	0.275	0.275	0.259	0.251	0.251	0.251
PCHAN2001	0.197	0.197	0.197	0.193	0.186	0.186	0.186	0.249	0.281	0.281	0.281
PCHRN2001	0.221	0.221	0.225	0.229	0.231	0.245	0.245	0.245	0.242	0.239	0.239
PEARPT2001	0.257	0.257	0.257	0.260	0.264	0.264	0.264	0.251	0.244	0.244	0.244
PT2001FS	0.257	0.257	0.257	0.260	0.264	0.264	0.264	0.251	0.244	0.244	0.244

Table 22. Summary of initial water content (m water per m soil depth) per soil layer (wc1 to wc11) used in SWB simulations for the 2000/2001 season.

Field	wc1	wc2	wc3	wc4	wc5	wc6	wc7	wc8	wc9	wc10	wc11
GDGP2001	0.182	0.182	0.187	0.191	0.193	0.208	0.208	0.208	0.238	0.267	0.267
GDMG2001	0.250	0.250	0.250	0.246	0.241	0.241	0.241	0.246	0.247	0.247	0.247
GDOV2001	0.211	0.211	0.213	0.214	0.218	0.243	0.243	0.243	0.355	0.466	0.466
GSGP2001	0.202	0.202	0.207	0.211	0.218	0.270	0.270	0.270	0.291	0.312	0.312
P-BR2001FS	0.282	0.282	0.270	0.261	0.273	0.354	0.354	0.354	0.389	0.423	0.423
P-F2001FS	0.273	0.273	0.284	0.292	0.296	0.324	0.324	0.324	0.318	0.311	0.311
P-RM2001FS	0.279	0.279	0.276	0.273	0.288	0.390	0.390	0.390	0.406	0.422	0.422
PCHAK2001	0.189	0.189	0.199	0.207	0.207	0.205	0.205	0.205	0.187	0.169	0.169
PCHAN2001	0.123	0.123	0.121	0.119	0.115	0.088	0.088	0.088	0.086	0.083	0.083
PCHRN2001	0.190	0.190	0.197	0.203	0.206	0.227	0.227	0.227	0.225	0.222	0.222
PEARPT2001	0.249	0.249	0.251	0.253	0.254	0.259	0.259	0.259	0.278	0.296	0.296
PT2001FS	0.244	0.244	0.247	0.250	0.251	0.254	0.254	0.254	0.274	0.293	0.293

Table 23. Summary of water content (m water per m soil depth) at permanent wilting point per soil layer (pwpwc1 to pwpwc11) used in SWB simulations.

Field	pwpwc1	pwpwc2	pwpwc3	pwpwc4	pwpwc5	pwpwc6	pwpwc7	pwpwc8	pwpwc9	pwpwc10	pwpwc11
GDGP2001	0.055	0.055	0.055	0.057	0.059	0.059	0.059	0.062	0.064	0.064	0.064
GDMG2001	0.138	0.138	0.138	0.138	0.138	0.133	0.129	0.129	0.129	0.129	0.129
GDOV2001	0.072	0.072	0.072	0.073	0.074	0.074	0.074	0.128	0.155	0.155	0.155
GSGP2001	0.056	0.056	0.056	0.068	0.088	0.088	0.088	0.125	0.143	0.143	0.143
P-BR2001FS	0.133	0.133	0.133	0.135	0.139	0.139	0.139	0.230	0.276	0.276	0.276
P-F2001FS	0.136	0.136	0.136	0.142	0.152	0.152	0.152	0.149	0.147	0.147	0.147
P-RM2001FS	0.158	0.158	0.158	0.150	0.136	0.136	0.136	0.211	0.249	0.249	0.249
PCHAK2001	0.152	0.152	0.152	0.154	0.156	0.156	0.156	0.161	0.163	0.163	0.163
PCHAN2001	0.099	0.099	0.099	0.099	0.101	0.104	0.107	0.109	0.110	0.110	0.111
PCHRN2001	0.118	0.118	0.118	0.121	0.126	0.126	0.126	0.124	0.123	0.123	0.123
PEARPT2001	0.130	0.130	0.130	0.132	0.134	0.134	0.134	0.127	0.123	0.123	0.123
PT2001FS	0.130	0.130	0.130	0.132	0.134	0.134	0.134	0.127	0.123	0.123	0.123

Table 24. Summary of SWB model water balance simulated seasonal rainfall (P), irrigation (I), transpiration (T), evaporation (E), drainage (D), canopy interception (INT) and runoff (RO) in mm for all plots for the 2000/2001 season.

Field	P	I	T	E	D	INT	RO
GDGP2001	315	430	191	396	134	12	0
GDMG2001	386	284	115	398	153	7	0
GDOV2001	378	402	312	400	83	11	0
GSGP2001	315	559	510	205	124	30	0
P-BR2001FS	335	450	247	461	93	16	0
P-F2001FS	372	253	149	444	36	5	0
P-F2001FS[1]	372	253	145	444	64	5	0
P-RM2001FS	335	548	213	471	182	15	0
PCHAK2001	136	649	334	342	109	9	0
PCHAK2001[1]	136	649	355	404	37	9	0
PCHAN2001	136	1126	1015	114	100	22	0
PCHRN2001	137	817	415	328	223	9	0
PCHRN2001[1]	137	817	415	334	210	9	0
PEARPT2001	386	405	396	289	99	21	0
PT2001FS	386	405	416	280	86	21	0

[1] Second simulation.

Young Golden Delicious apple trees:

The simulation output for the young Golden Delicious trees (Molteno Glen) is presented in Figure 29. The model overestimated the soil water deficit from October to mid-November and after harvest (01/03/2001). During mid-season measured and estimated values agreed well, except for a period in January where it underestimated. It is possible that evaporation was overestimated by the model due to the initial soil water content entered for the top soil layer being too high. Soil water content measured by the neutron water meter was integrated for the 0-200 mm soil depth and it probably did not reflect the correct water content for the top soil layer (0-0.08 m), except shortly after irrigation. The model probably continued evaporating from the top soil layer under conditions of high ETo. Limited leaf senescence after a hot spell before harvest (12/02/2001) and removal of fruit at harvest could have contributed to the overestimation of the soil water deficit after harvest. The model does not simulate growth and cannot account for leaf senescence during mid-season.

The cascading model evaporates water from the top soil layer until it is air dry before it stops. The model could underestimate evaporation under conditions of high ETo, but not shortly after irrigation. In such a case a model that is able to simulate evaporation also from deeper soil layers would have worked better. Two periods where evaporation was underestimated were from 10/12/2000 to 17/12/2000 and 26/02/2001 to 1/03/2001 (data not shown).

The statistical output parameters indicated a poor fit and that the prediction by the model was outside the reliability criteria. Measured data points from 20 November to end February, however, agreed well visually with the simulated soil water deficit. It is important to take into account that the measured soil water content for the top soil layer was not available. This could have caused discrepancies between measured and simulated values of soil water deficit. The use of only statistical output parameters to evaluate the success of the calibration is therefore questionable.

Full bearing Golden Delicious apple trees:

The simulation output for the full bearing Golden Delicious apple trees is presented for Grabouw Farms and Oak Valley (Figs. 30&31). The model overestimated the deficit for Golden Delicious trees at Grabouw Farms in October and the beginning of November and underestimated it during March before harvest (Fig. 30). The statistical output parameters indicated that the prediction by the model was inside the reliability criteria, but that the MAE was 22%. The simulation for Golden Delicious apple trees at Oak Valley was updated on 22/02/2001 and 01/03 2001 due to problems with the irrigation system (Fig. 31). The model overestimated during October and February and underestimated during November, December, April and May. The D-value indicated good agreement and the MAE was marginally outside the 20% criterium. The coefficient of determination, however, was poor.

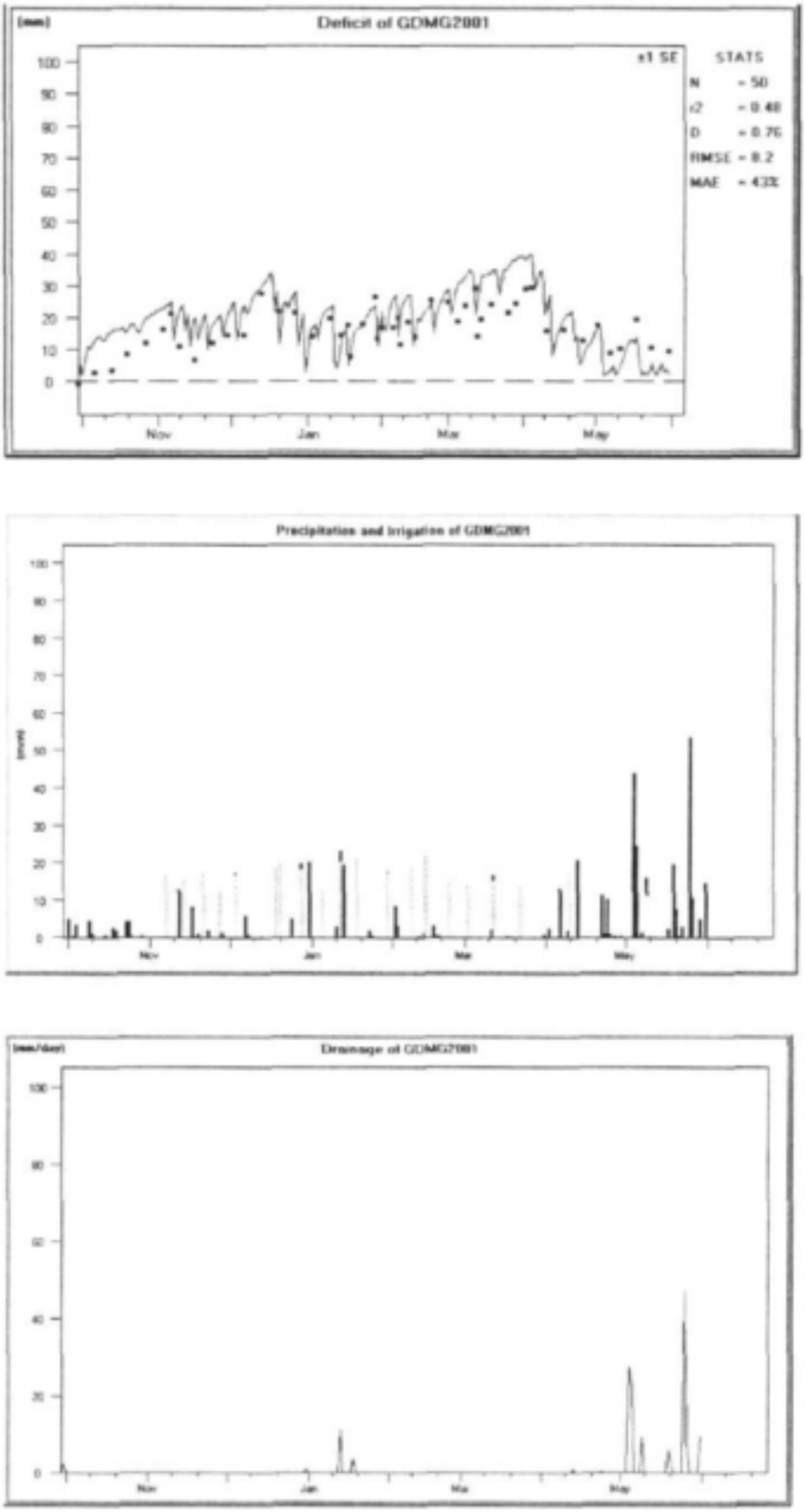


Figure 29. Simulated (solid line) and measured (symbols) soil water deficit, measured precipitation (red columns) and irrigation (cyan columns) as well as simulated drainage for young Golden Delicious apple trees at Molteno Glen.

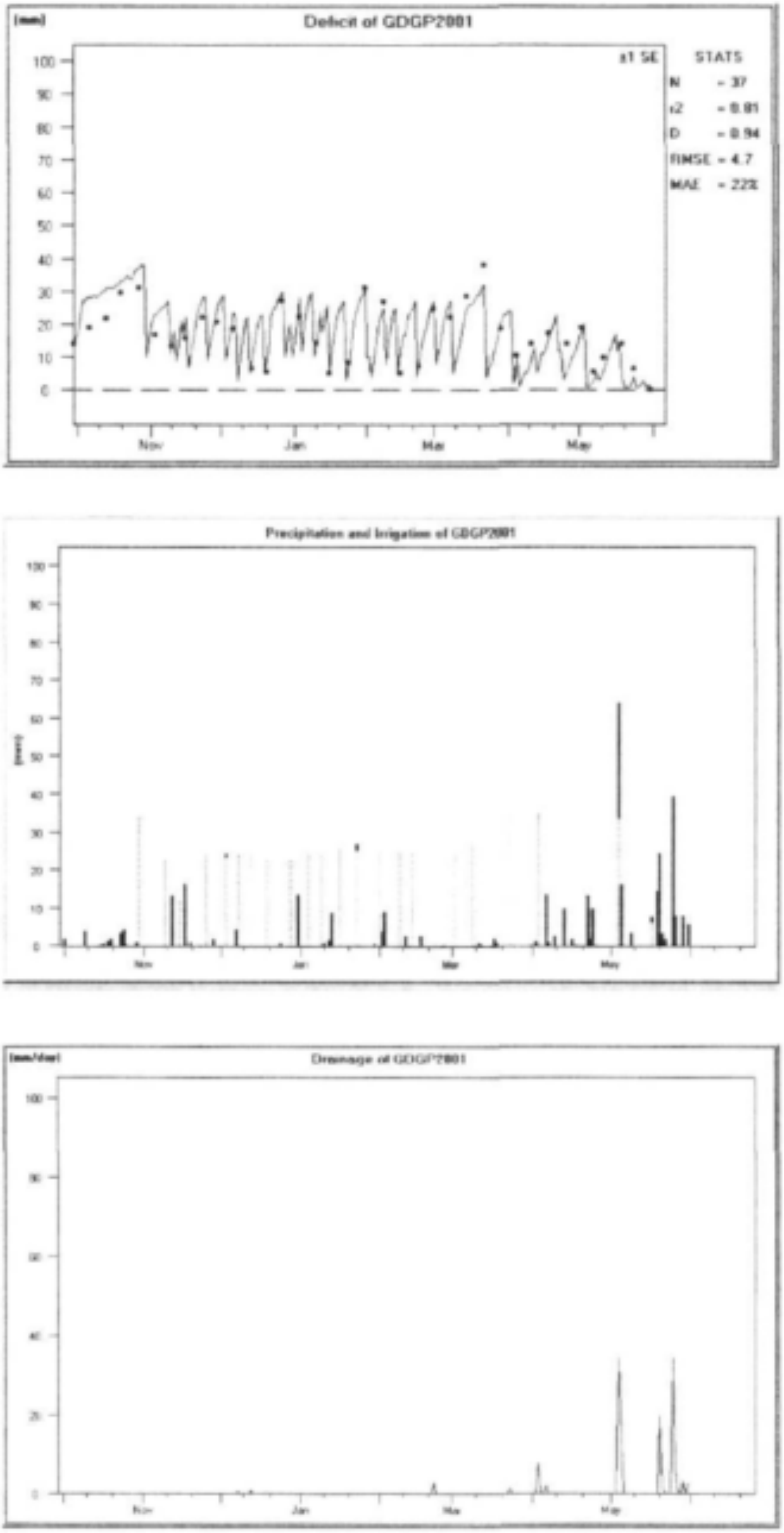


Figure 30. Simulated (solid line) and measured (symbols) soil water deficit, measured precipitation (red columns) and irrigation (cyan columns) as well as simulated drainage for full bearing Golden Delicious apple trees at Grabouw Farms.

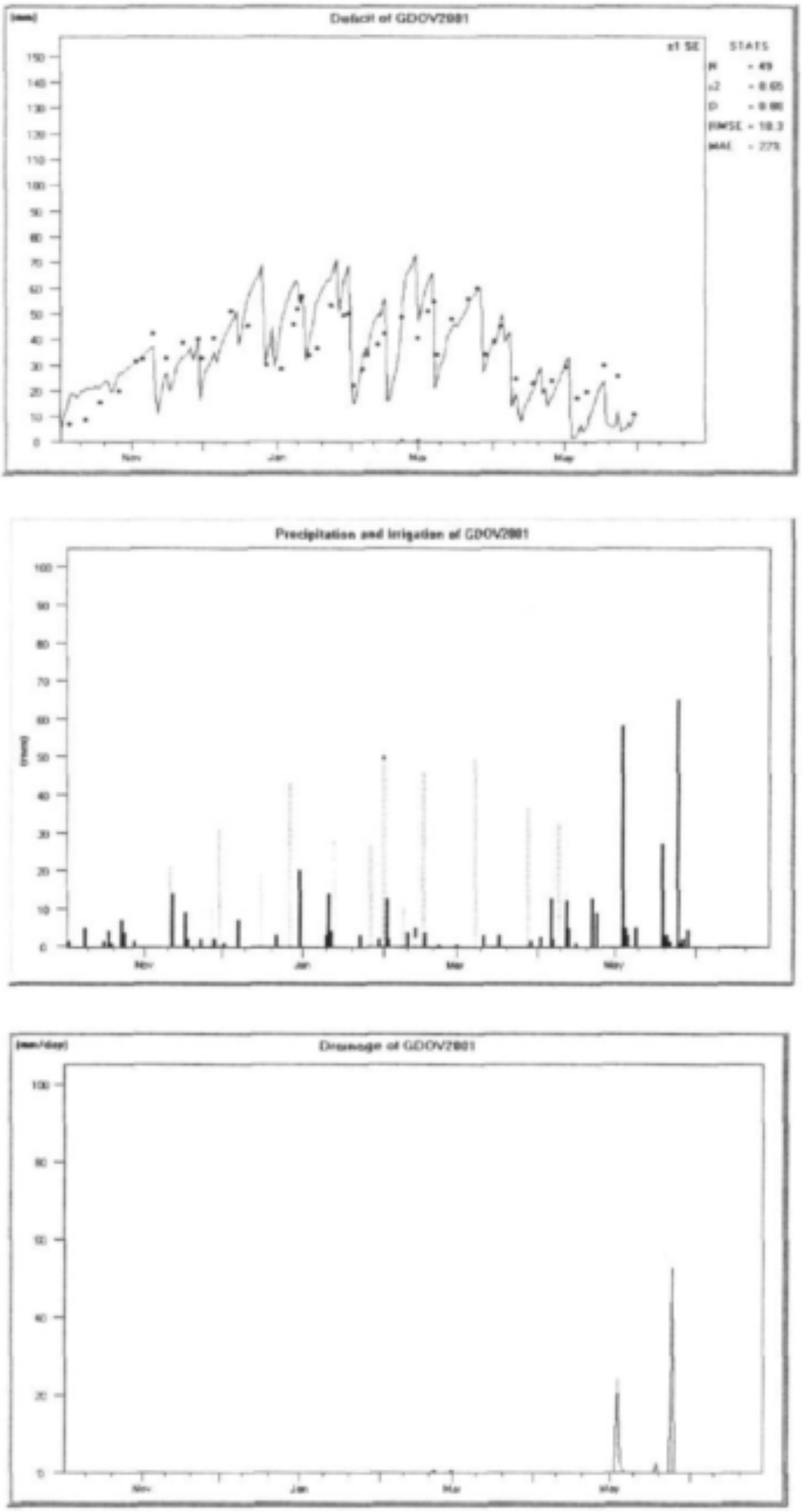


Figure 31. Simulated (solid line) and measured (symbols) soil water deficit, measured precipitation (red columns) and irrigation (cyan columns) as well as simulated drainage for full bearing Golden Delicious apple trees at Oak Valley. Soil water content was updated on 22/02/2001 and 01/03/2001.

The reason for the overestimation at the start of the season at both plots could be that evaporation was overestimated by the model because the initial soil water content entered for the top soil layer was too high (See *Young Golden Delicious apple trees*).

A further source of error could be the linear Kcb approach that the SWB FAO model utilizes. The data points on the relative fractional interception versus time graph indicate that canopy development was not linear (Fig. 26B). A higher Kcb than that could be estimated from the linear approach, is necessary during the development and post harvest stages of the season to increase the predicted soil water deficit. The soil water deficit was underestimated for these periods at the Oak Valley plot (Fig. 31). In addition, the model could not simulate separate water balances for the tree and the cover crop under full surface irrigation. The underestimation of the deficit could therefore partially be ascribed to the contribution of the cover crop to some of the water loss (Fig. 13C). The use of a combined Kcb for the two crops is possible, but not desirable. Growth stages for the two crops differed markedly.

The developers of SWB suggested that cover crop contribution should be simulated as bare soil. The assumption that cover crop ET equals evaporation from a soil surface is a poor assumption. Grass does not behave like a soil if irrigated and frequently mowed. This could cause underestimation of ET by the model. Water consumption of the cover crop remained fairly constant until April after which it started to decrease. Maximum water consumption for the cover crop with a root depth of 200 mm was 0.99 mm per day in December (data not shown).

Full bearing Granny Smith apple trees:

The simulation output for the full bearing Granny Smith apple trees is presented in Figure 32. A good D-value was obtained when the simulation was fitted to measured data points, but the coefficient of determination was marginally outside the reliability criteria and the MAE large. Reasons for the poor fit could be excessive evaporation from the top soil layer (See *Young Golden Delicious apple trees*), the canopy development of trees not conforming to the FAO linear Kcb approach (Fig. 26C) and underestimation of water consumption by the model after crop removal end April.

Rosemary pear trees:

The simulation output for the young Rosemary pear trees is presented in Figure 33. The model displayed poor fit especially at the start (overestimated during October) and end of the season (underestimated during April). The statistical output parameters indicated a poor fit and the prediction with the model was outside the reliability criteria. Sources of error could be excessive evaporation from the top soil layer (See *Young Golden Delicious apple trees*), the canopy development of trees not conforming to the FAO linear Kcb approach (Fig. 27A) and application of canopy management (pruning) during the growing season (Fig. 22A). The predicted to measured soil water deficit, with the exception of the abovementioned periods, visually agreed well for this cultivar.

Bon Rouge pear trees:

The simulation output for the young Bon Rouge pear trees is presented in Figure 34. Predicted soil water content was updated on the third date of soil water content measurement because measured values were

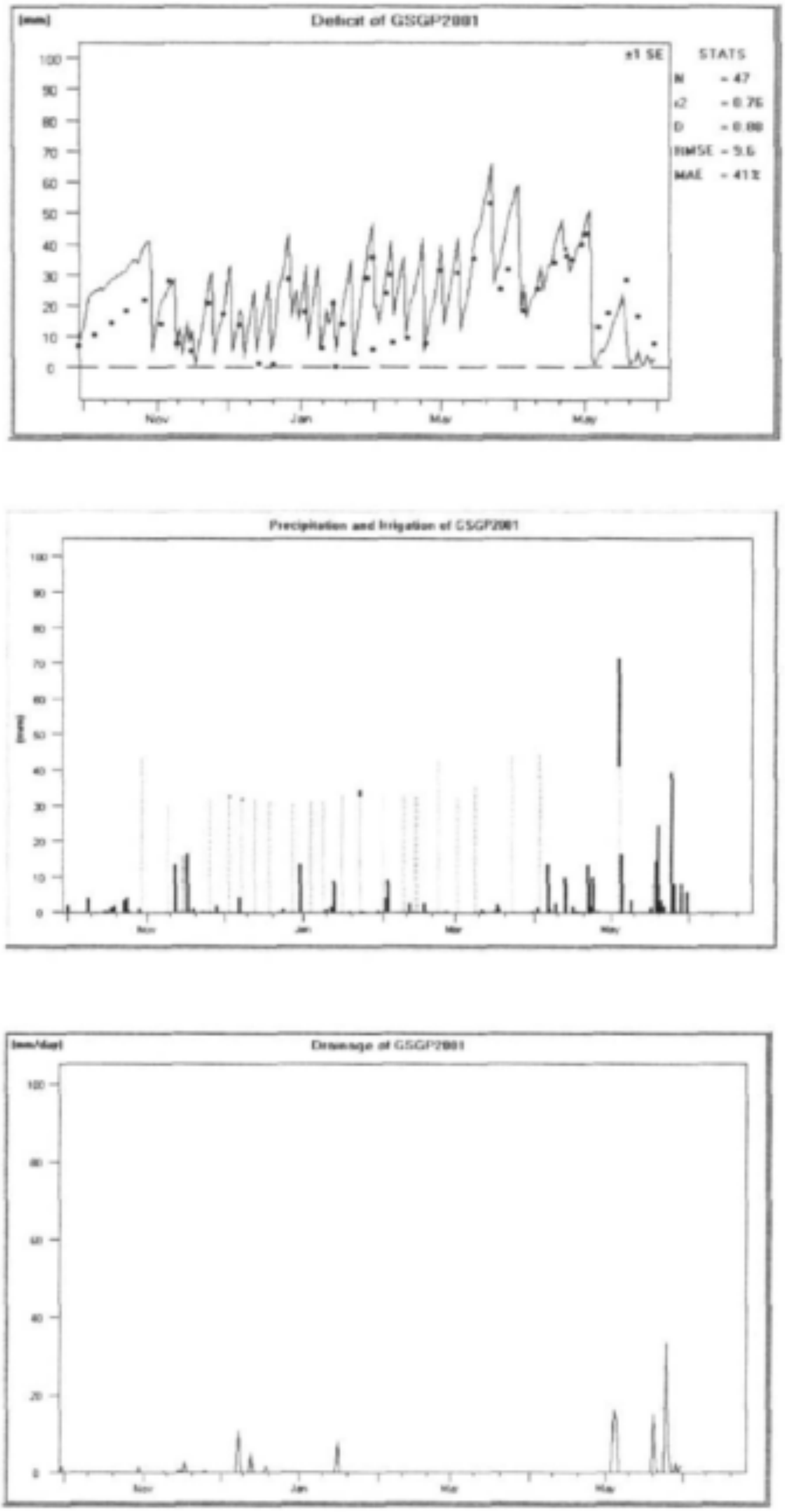


Figure 32. Simulated (solid line) and measured (symbols) soil water deficit, measured precipitation (red columns) and irrigation (cyan columns) as well as simulated drainage for full bearing Granny Smith apple trees at Grabouw Farms.

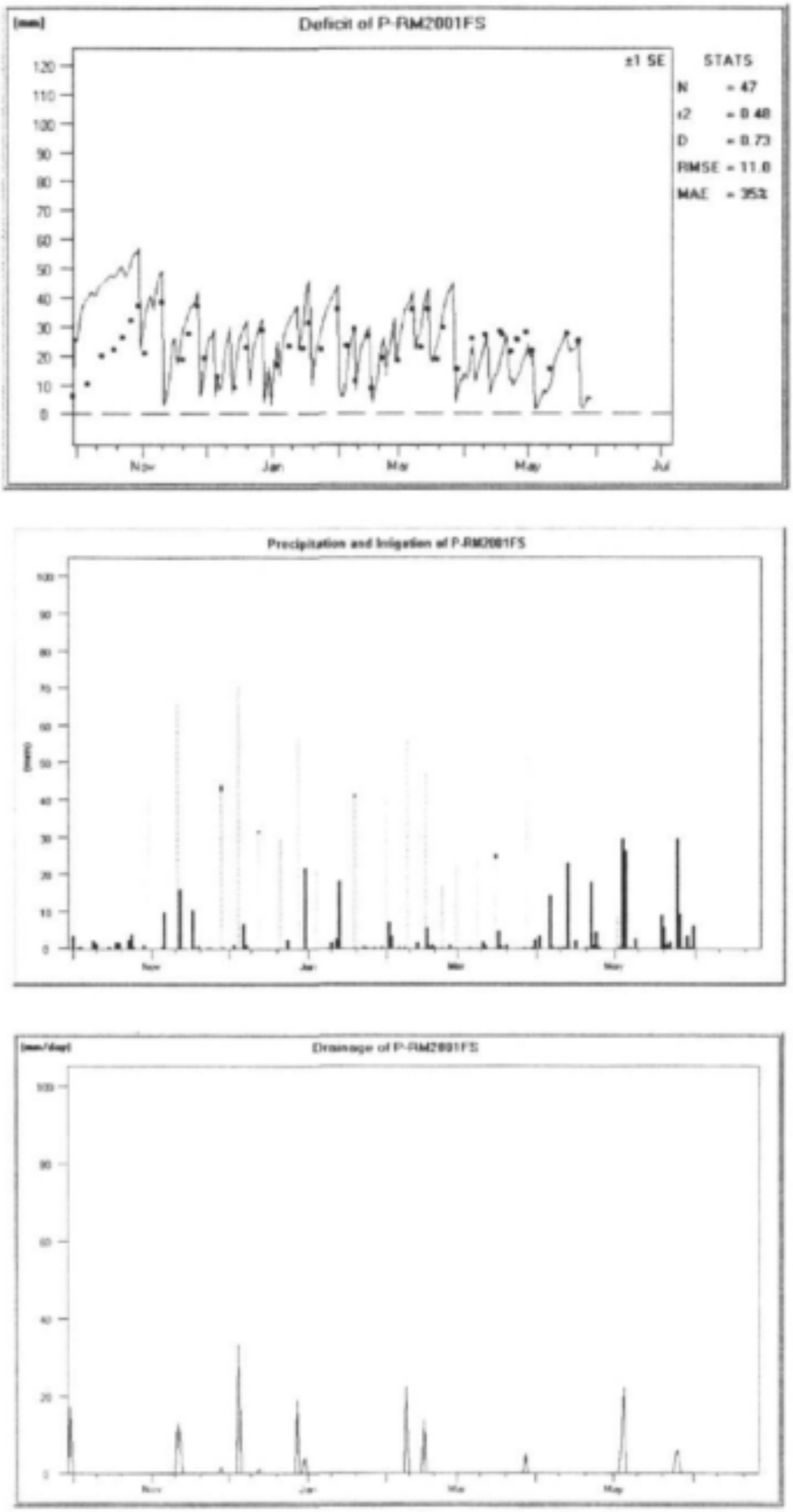


Figure 33. Simulated (solid line) and measured (symbols) soil water deficit, measured precipitation (red columns) and irrigation (cyan columns) as well as simulated drainage for young Rosemary pear trees at De Rust.

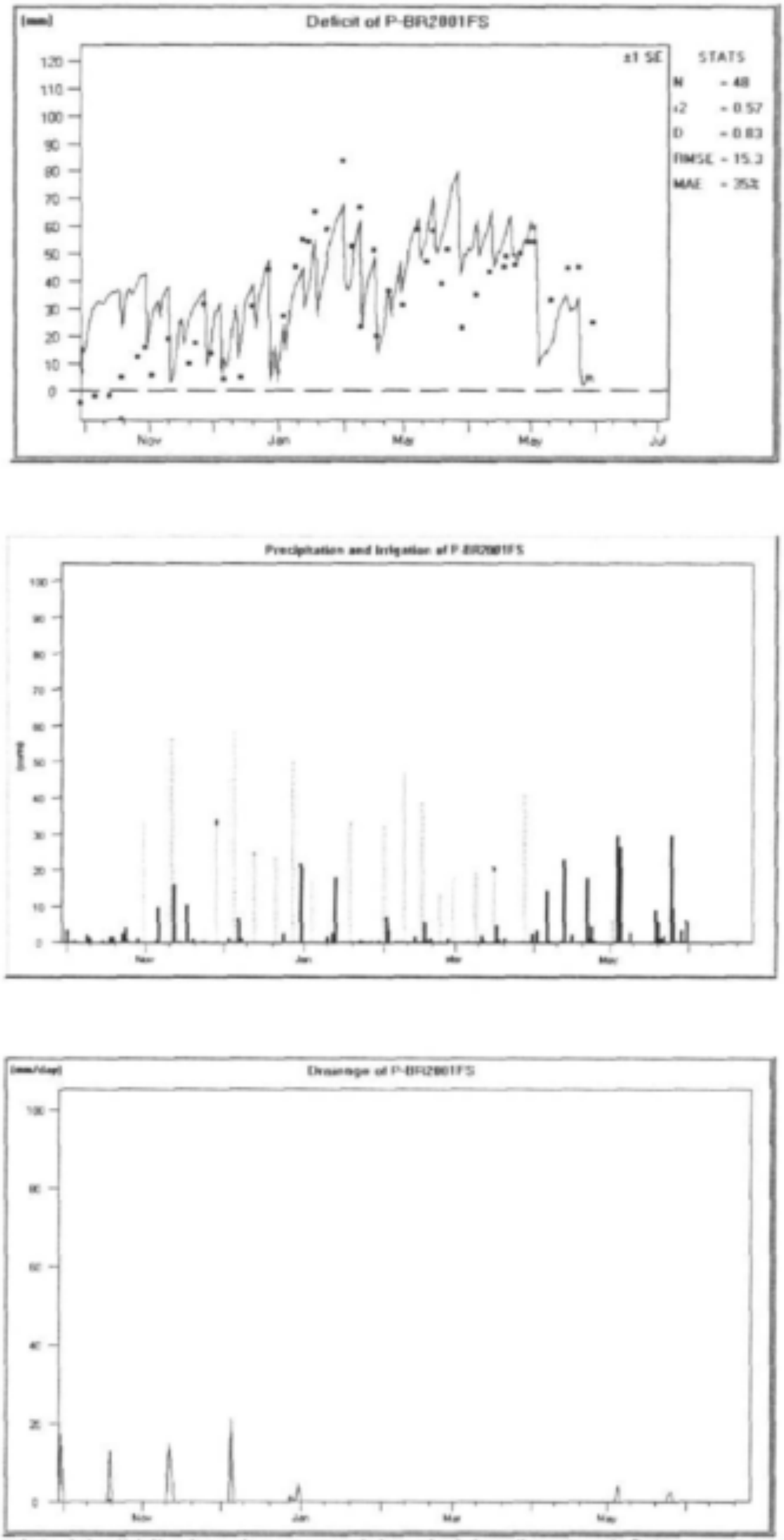


Figure 34. Simulated (solid line) and measured (symbols) soil water deficit, measured precipitation (red columns) and irrigation (cyan columns) as well as simulated drainage for young Bon Rouge pear trees at De Rust.

above field capacity. The model overestimated during October (See *Young Golden Delicious apple trees*), March and April and underestimated during January (before harvest) as well as May.

The D-value indicated good agreement between measured and predicted values, but a poor coefficient of determination and large MAE. One source of error could be the soil water retention curve that was used to predict the field capacity values for the 600 mm to 900 mm soil depth at this plot. Data points in the wet range were limited when the soil water retention curve was fitted. Field measured soil water content values for the 900 mm depth was higher than the estimated field capacity values for this depth for nearly the complete season (data not shown). It was confirmed that there was no water table at the 900 mm depth at the start of the season during installation of neutron water meter access tubes.

The high soil water content values at the 900 mm depth could also be the result of irrigation water or precipitation not draining through the soil profile within a day. The drainage factor (Df) in the SWB model represents the fraction of water above field capacity that cascades from one soil layer to the following layer within one day. A Df can be estimated by determining an *in situ* drainage curve or estimated values may be used. Simulations done with a drainage factor less than one, however, did not improve simulation results for this plot (data not shown).

Full bearing Forelle pear trees:

The simulation output for the full bearing Forelle pear trees is presented in Figure 35. The model overestimated from January to the end of the season. Irrigation amounts applied from start of December were not adequate to replenish the soil to field capacity. Furthermore, irrigation was withheld during the period of harvest (16/02/2001 to 02/03/2003). It is possible that trees experienced water stress. The model does not simulate the effect of water stress on canopy size. If the simulation is done until 18/01/2001 (before the soil matric potential at 900 mm depth reached the –100 kPa point), the statistical output parameters for model performance are marginally within criteria set for reliablility (N=22, r^2 = 0.85, D= 0.91, RMSE = 10.1, MAE = 24%). The other source of error in the simulation could be excessive evaporation from the top soil layer (See *Young Golden Delicious apple trees*). If the simulated soil water deficit is updated shortly after irrigation (01/02/2001 and 12/03/2001) to measured values, the simulation improved (Fig. 36). The statistical output parameters indicated that the prediction by the model was inside the reliability criteria (r^2 = 0.88, D= 0.96, RMSE = 9.3, MAE = 16%). The Kcb determined for the mid-stage was very low if the LA for Forelle is compared to the Kcb and LA of other pear trees (Fig. 22, Table 18).

Full bearing Packhams' Truimph pear trees:

The simulation for the soil water deficit from the wetted strip only (Fig. 37) resulted in poorer statistical fit compared to that from the full surface (Fig. 38). Soil water deficit from the wetted strip was overestimated in the period after harvest (March and April) and underestimated for May (Fig. 37). The statistical output parameters of the simulation for soil water deficit from the full surface indicated a good fit and that the prediction by the model was inside the reliability criteria, but with a MAE of 23% (Fig. 38). Roots beyond the wetted strip probably contributed significantly to the soil water deficit, especially during May when

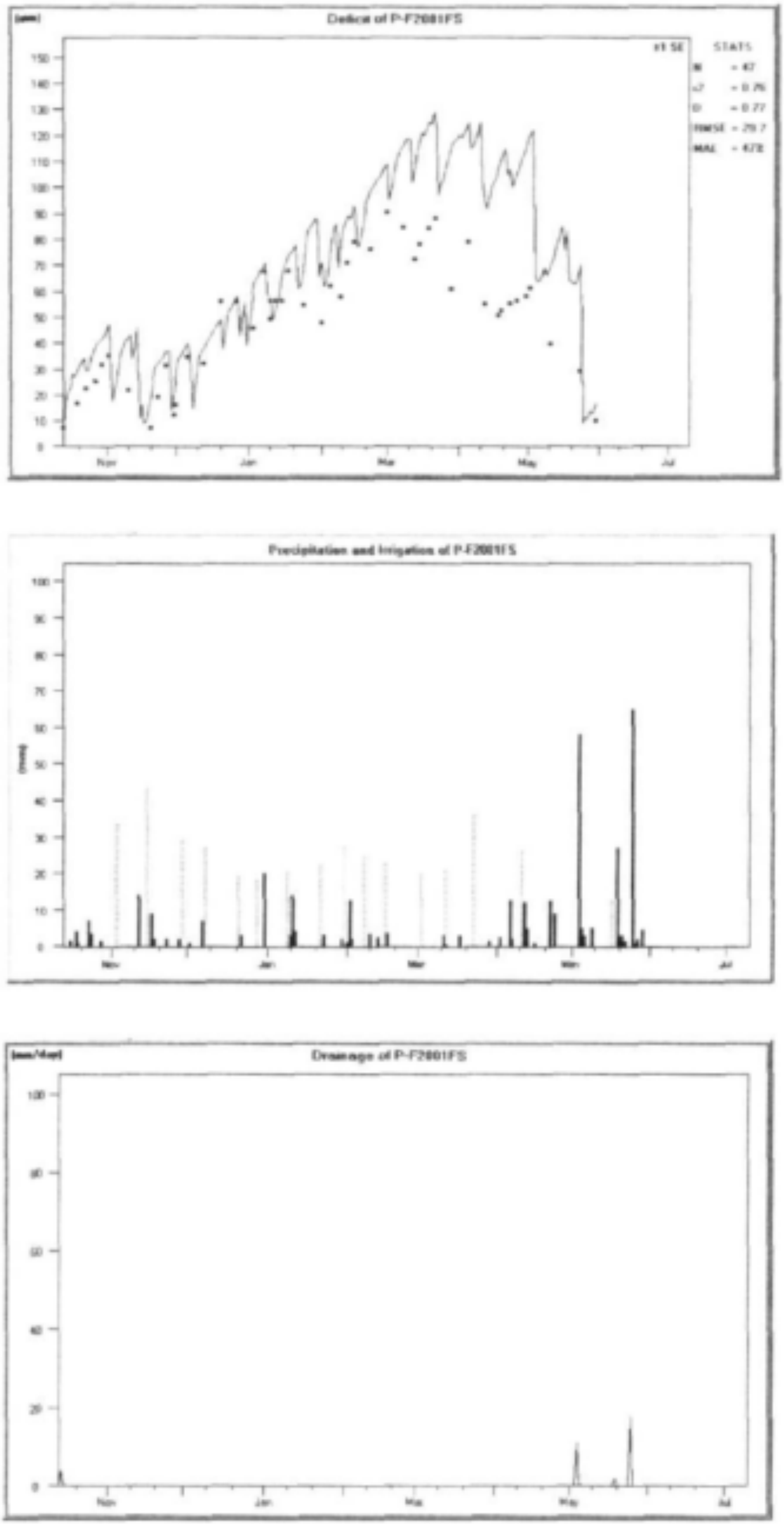


Figure 35. Simulated (solid line) and measured (symbols) soil water deficit, measured precipitation (red columns) and irrigation (cyan columns) as well as simulated drainage for full bearing Forelle pear trees at Oak Valley.

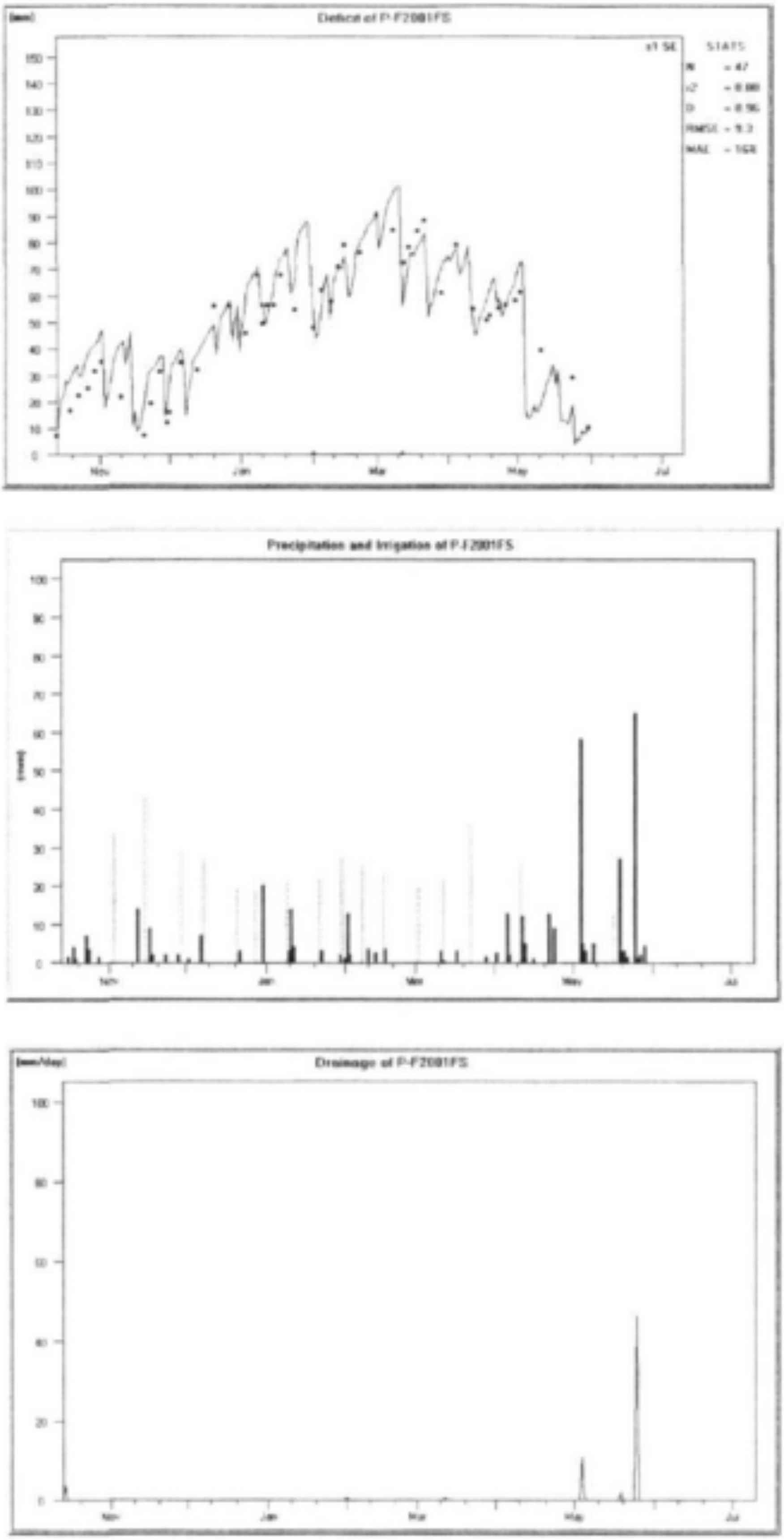


Figure 36. Simulated (solid line) and measured (symbols) soil water deficit, measured precipitation (red columns) and irrigation (cyan columns) as well as simulated drainage for full bearing Forelle pear trees at Oak Valley. Simulated soil water deficit was updated shortly after irrigation (01/02/2001; 12/03/2001).

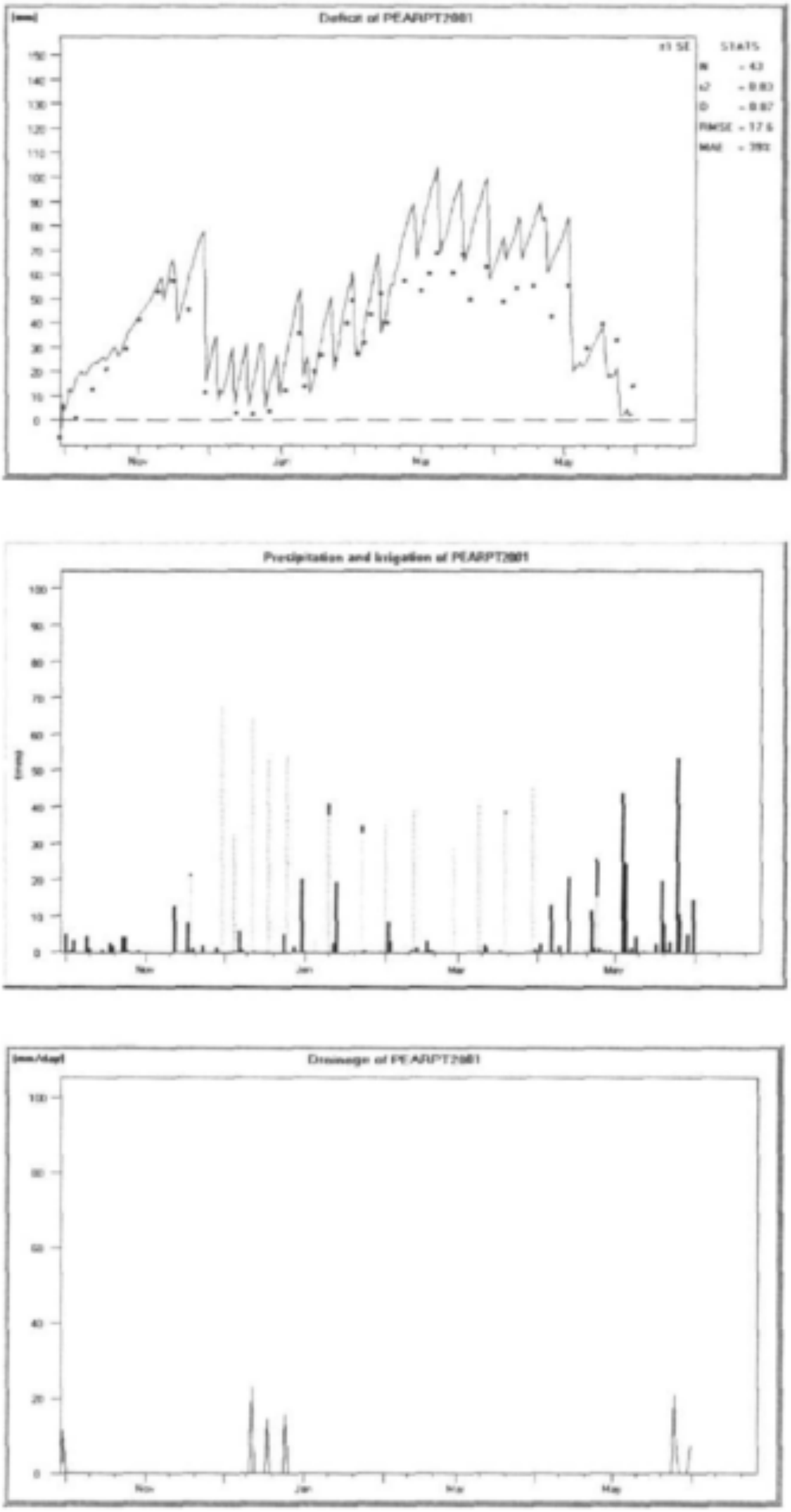


Figure 37. Simulated (solid line) and measured (symbols) soil water deficit, measured precipitation (red columns) and irrigation (cyan columns) as well as simulated drainage for full bearing Packhams' Truimph pear trees at Molteno Glen.

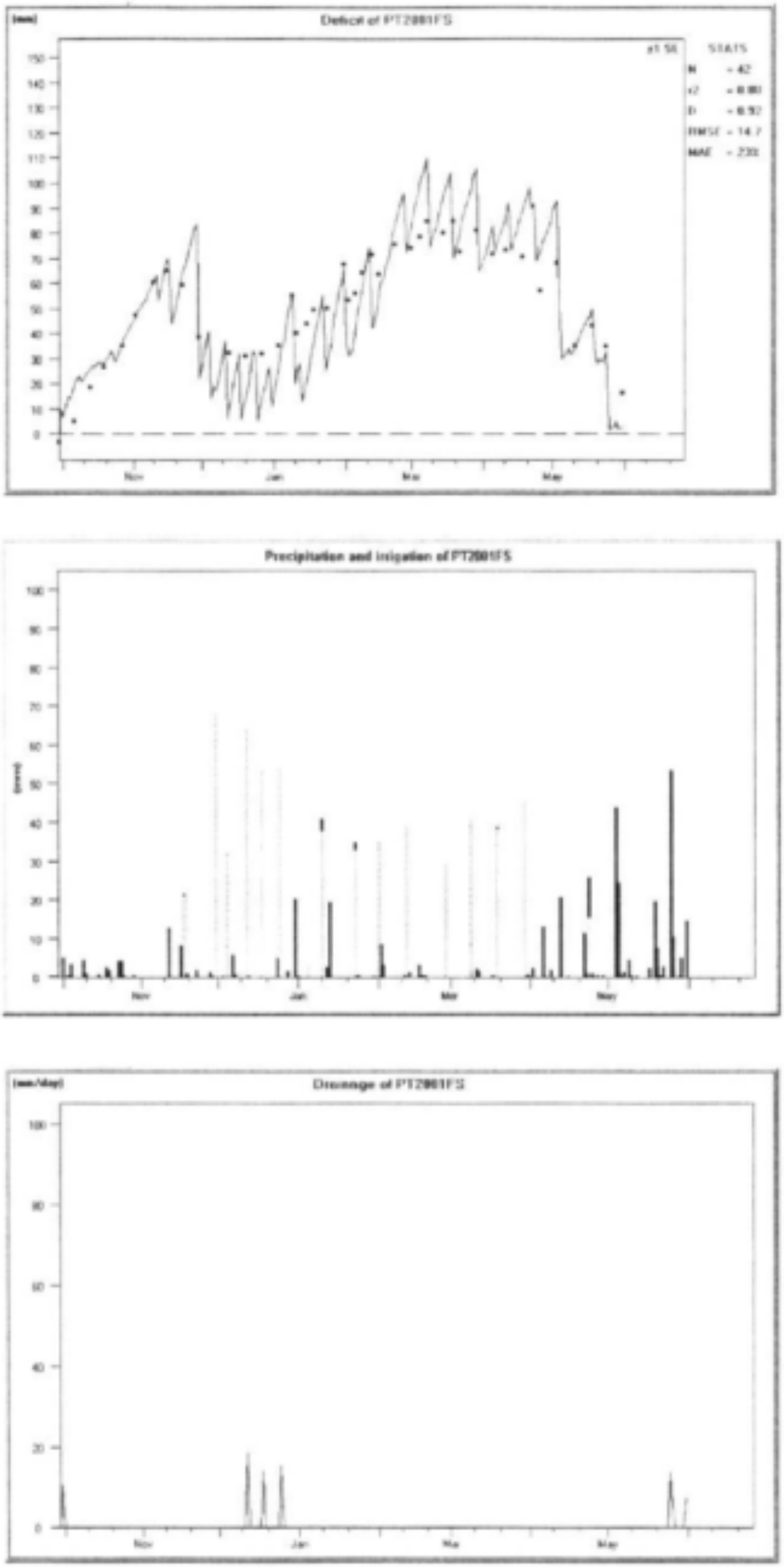


Figure 38. Simulated (solid line) and measured (symbols) soil water deficit, measured precipitation (red columns) and irrigation (cyan columns) as well as simulated drainage for full bearing Packhams' Truimph pear trees at Molteno Glen.

precipitation occurred more frequently (refer Soil Water Balance graph). The water consumption of the cover crop, however, was also included in the soil water deficit from the full surface and the model does not simulate the tree and cover crop water balances separately (See *Full bearing Golden Delicious apples*). The cover crop at this plot was not irrigated and was patchy. The assumption that cover crop ET equals evaporation from a soil surface probably applied better in this case compared to that of the irrigated cover crop.

Young Keisie peach trees

The simulation output for the young Keisie peach trees is presented in Figure 39. The statistical output parameters of the simulation for soil water deficit from the full surface indicated a poor fit and that the prediction with the model was outside the reliability criteria. The soil contained a high percentage of clay and fine sand (Table 6) and water infiltration was impeded. Free water remained on the soil surface after irrigations. A Df value of 0.63 improved the agreement between measured and predicted values and the MAE reduced to 22%, but the coefficient of determination was still outside reliability criteria (Figure 40).

Full bearing Neethling peaches

The simulation output for the full bearing Neethling peach trees at Robertson is presented in Figure 41. The predicted values underestimated after a large irrigation was applied on the 29th of September. A second simulation after predicted soil water deficit was updated on the 5th of October resulted in a good fit and the prediction by the model was inside the reliability criteria (Fig. 42).

The simulation output for the full bearing Neethling peach trees at Ashton is presented in Figure 43. The statistical output parameters of the simulation for soil water deficit from the full surface indicated a poor coefficient of determination, while the D-value was within the range set for reliability. The MAE was marginally outside the range needed for reliable prediction. The predicted values were underestimated especially in May. The statistical output parameters improved if the simulation was done only until the end of the mid growth stage (06/04/2001) with the $r^2 = 0.68$, D = 0.9 , RMSE = 13.8 and MAE = 16%. The visual fit of predicted and measured data points was good despite the low coefficient of determination.

Comparison of transpiration coefficients and basal crop coefficients: Comparison of Kt values to Kcb values estimated by means of the SWB model for selected plots, showed that the two coefficients cannot necessarily be used interchangeably (Fig. 44). Estimation of Kcb from Kt improved if regressions were performed for individual fruit crops compared to that performed for a combination of fruit crops. Basal crop coefficient values for Golden Delicious apple trees at Grabouw Farms was lower, and for Neethling peach trees at Ashton higher, compared to the corresponding Kt values. Transpiration coefficients represent the relationship between transpiration of the trees and reference ET (T/ETo), while Kcb is defined as the ratio of crop ET to the reference ET (ETc/ETo) when the soil surface is dry but transpiration is occuring at the potential rate. It does include a residual diffusive evaporation component supplied by soil water below the dry surface and by soil water from beneath dense vegetation (Allen *et al.*, 1998).

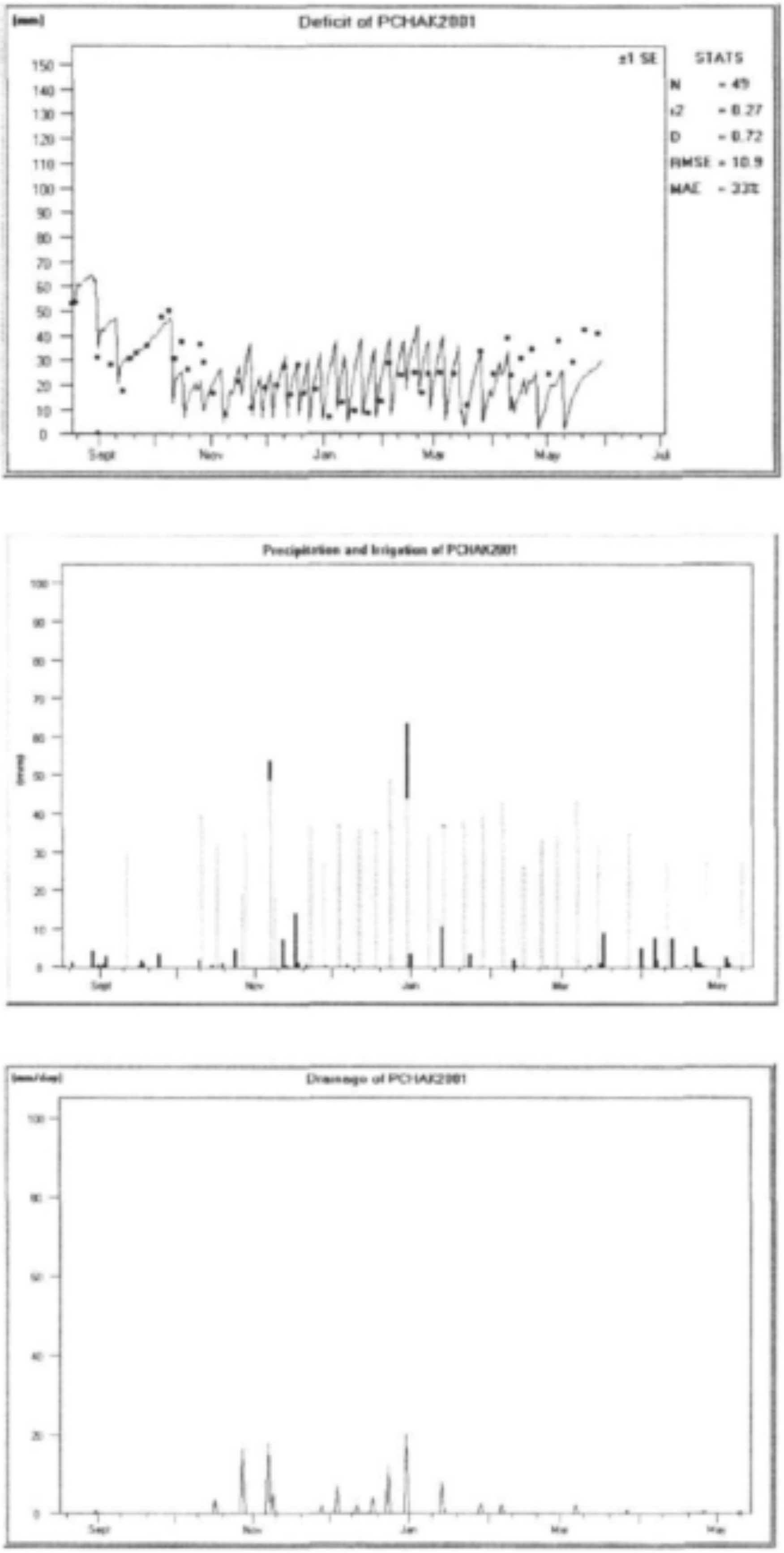


Figure 39. Simulated (solid line) and measured (symbols) soil water deficit, measured precipitation (red columns) and irrigation (cyan columns) as well as simulated drainage for young Keisie peach trees at Ashton.

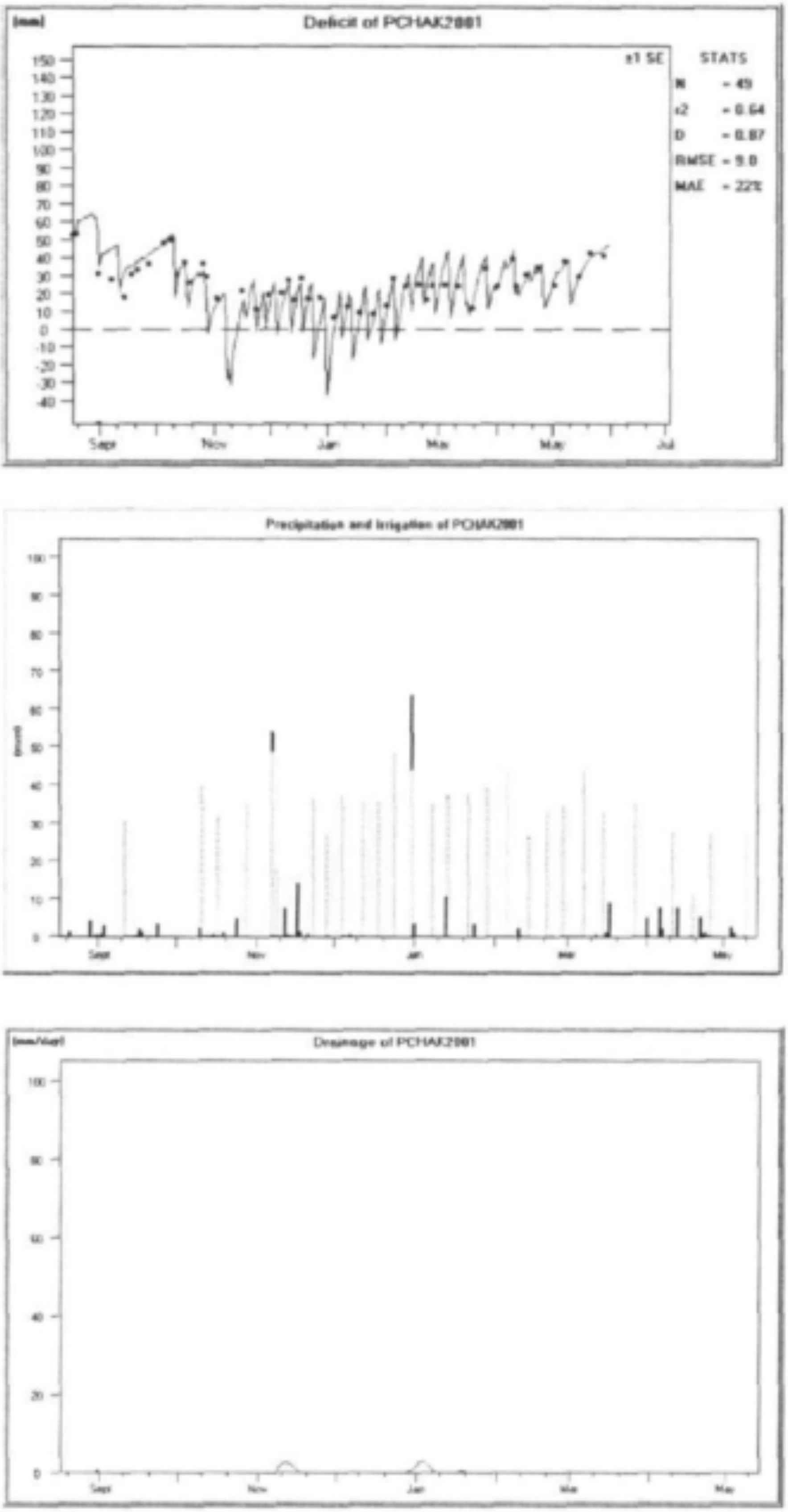


Figure 40. Simulated (solid line) and measured (symbols) soil water deficit, measured precipitation (red columns) and irrigation (cyan columns) as well as simulated drainage for young Keisie peach trees at Ashton. The drainage factor was adjusted to improve agreement between simulated and measured values.

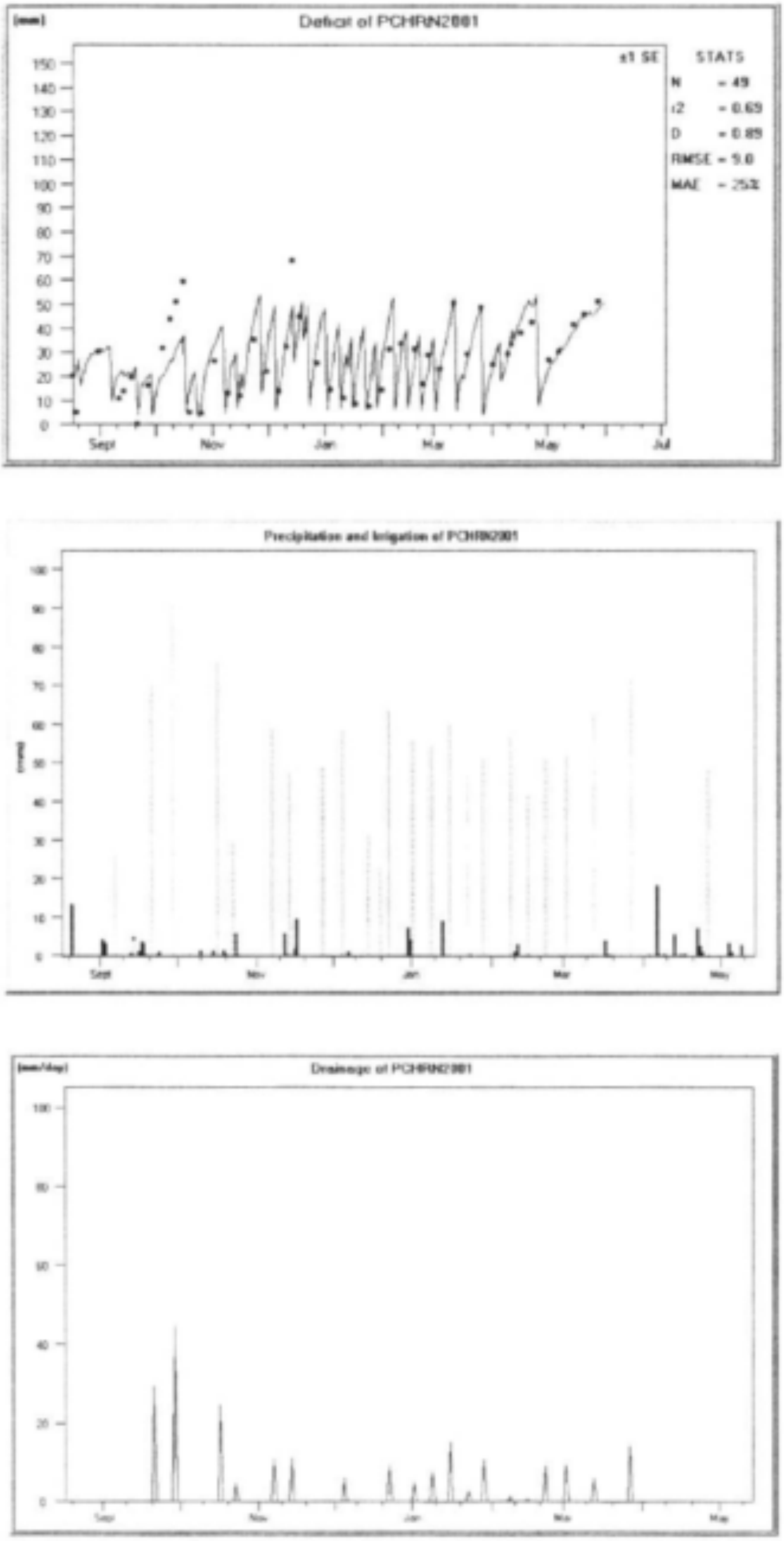


Figure 41. Simulated (solid line) and measured (symbols) soil water deficit, measured precipitation (red columns) and irrigation (cyan columns) as well as simulated drainage for full bearing Neethling peach trees at Robertson.

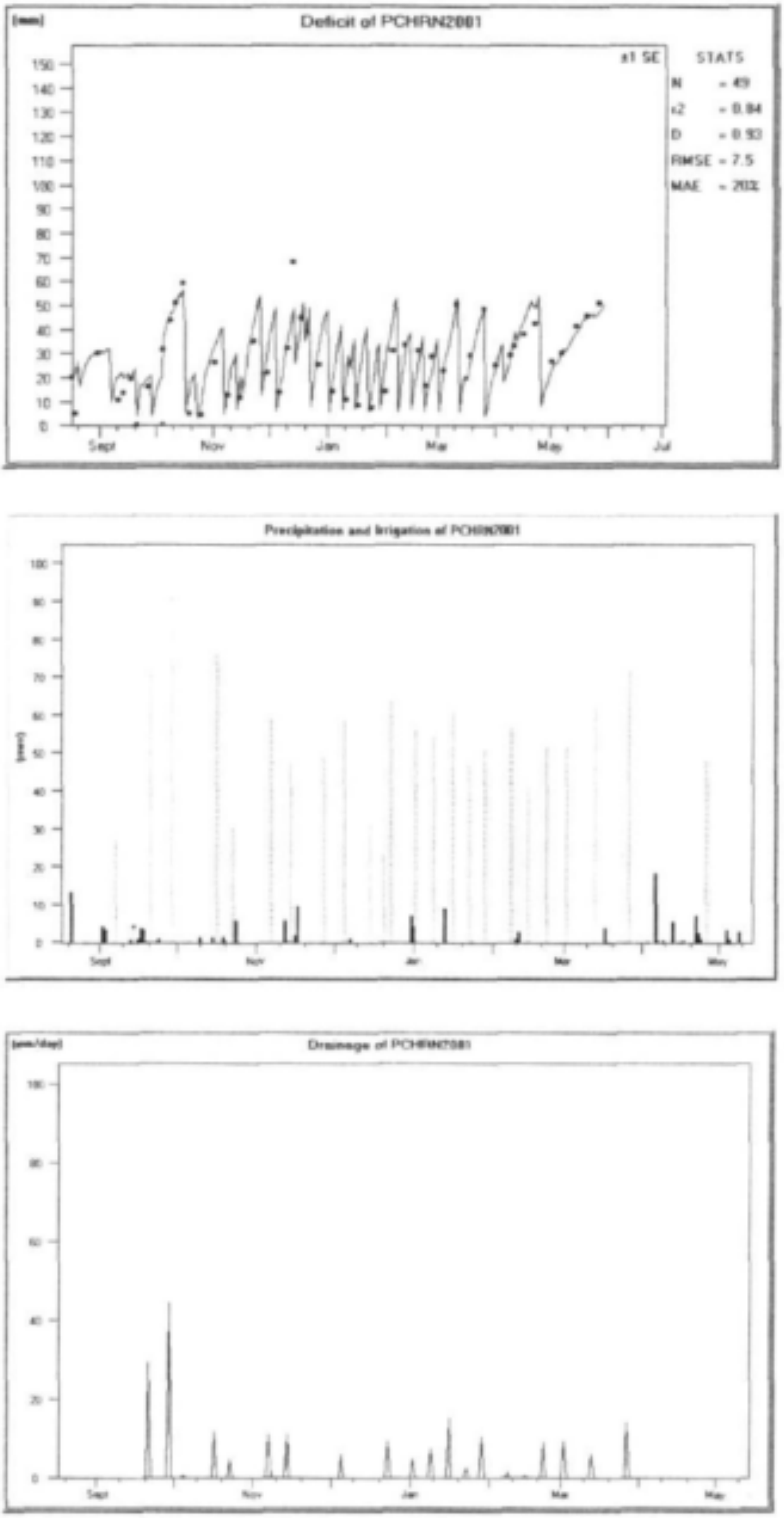


Figure 42. Simulated (solid line) and measured (symbols) soil water deficit, measured precipitation (red columns) and irrigation (cyan columns) as well as simulated drainage for full bearing Neethling peach trees at Robertson. Simulated soil water deficit was updated after irrigation (05/10/2000).

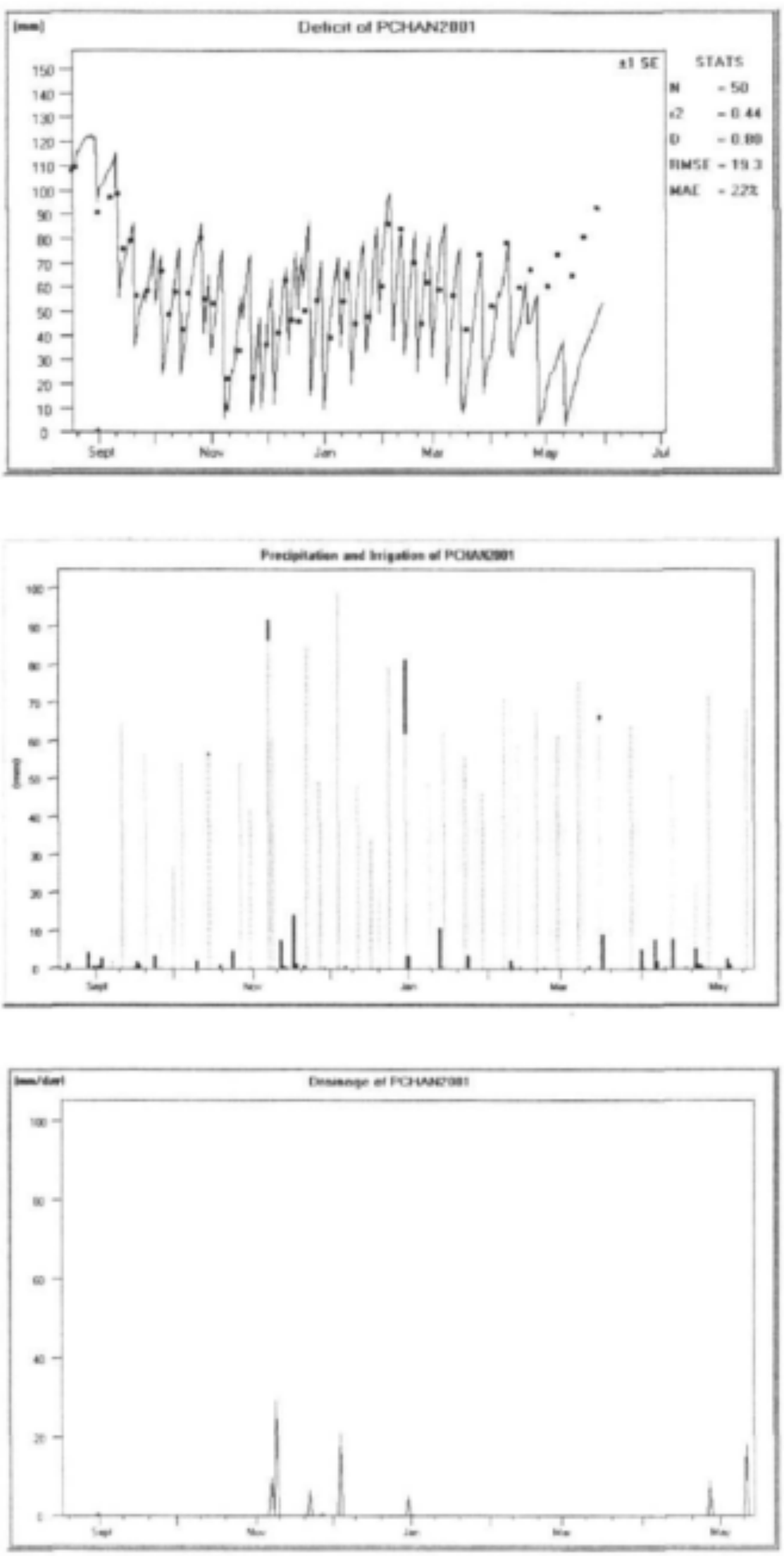


Figure 43. Simulated (solid line) and measured (symbols) soil water deficit, measured precipitation (red columns) and irrigation (cyan columns) as well as simulated drainage for full bearing Neethling peach trees at Ashton.

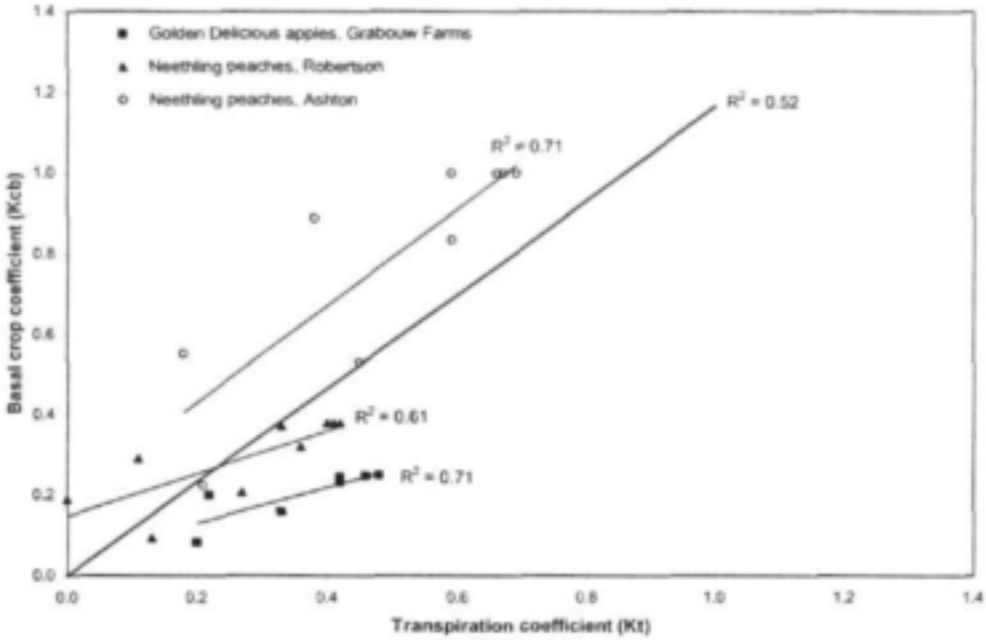


Figure 44. Comparison of transpiration coefficients to basal crop coefficients estimated by means of SWB for selected plots.

The SWB model, however, evaporates only from the top soil layer and therefore does not simulate evaporation from deeper soil layers. The Kcb values determined by using the simulation fitting procedure should therefore theoretically be comparable to the Kt values. It was earlier speculated that evaporation at the start of the season at the Golden Delicious apple plot could be overestimated by the model, because the initial soil water content entered for the top soil layer was too high. Given that the simulation was fitted according to measured soil water deficit values, the Kcb in the model had to be lowered to offset the high evaporation. This could have resulted in the low Kcb values compared to the Kt at this plot.

With regard to the Neethling peach trees at Ashton, evaporating only from the top soil layer could underestimate evaporation if the simulated water content of the top soil layer is air-dry during periods of high reference ET (ET_o). The model could further underestimate evaporation during periods of high ET_o where the canopy cover fraction exceeds the irrigated fraction of the soil surface, such as at this specific plot, especially if the irrigation frequency is high. The underestimation of evaporation would necessitate a higher Kcb to fit the simulated to measured soil water deficit. The fitting procedure in these cases thus did not work well to determine the Kcb values.

SWB-predicted monthly and seasonal transpiration and evapotranspiration: Comparison of SWB-predicted monthly transpiration to transpiration estimated from LA and ETo showed good agreement (Fig. 45A). SWB-predicted monthly ET agreed slightly better to that estimated from crop coefficients determined by means of the measured soil water balance and average monthly ETo (Fig. 45B). Seasonal transpiration was underestimated by SWB for Golden Delicious apple trees, agreed well for Neethling peach trees at Robertson, but was overestimated for peach trees at Ashton (Fig. 46A). This indicated that the fitted Kcb Mid value for the apple plot could be too low, and for the peach tree plot at Ashton, too high.

The predicted seasonal ET for peach trees agreed well with measured values (Fig. 46B). The transpiration, however, made up the main component of the ET for the Neethling trees at Ashton (Fig. 46A). This indicated that the model severely underestimated evaporation for this plot. The model simulates evaporation only from the non-irrigated portion of the ground if the canopy cover fraction is larger than the irrigated surface fraction. FI for the Neethling trees at Ashton exceeded the irrigated surface fraction of 0.6 for day of season 108 to 292 and reached values above 0.8. The leaves of Neethling trees at Robertson were less dense, and the maximum FI for the season of 0.54 never exceeded the irrigated surface fraction. As discussed earlier, a model that is able to simulate evaporation also from deeper soil layers, would work better under conditions of high ET_o (See *Young Golden Delicious apple trees*). Ashton and Robertson are high ETo areas compared to Elgin (Figs. 4D&6D). Seasonal ET for the Golden Delicious apple trees was overestimated (Fig. 46B). Lack of measured soil water content values for the top soil layer at the start of the season could be the cause of excessive evaporation from the top soil layer (See *Young Golden Delicious apple trees*).

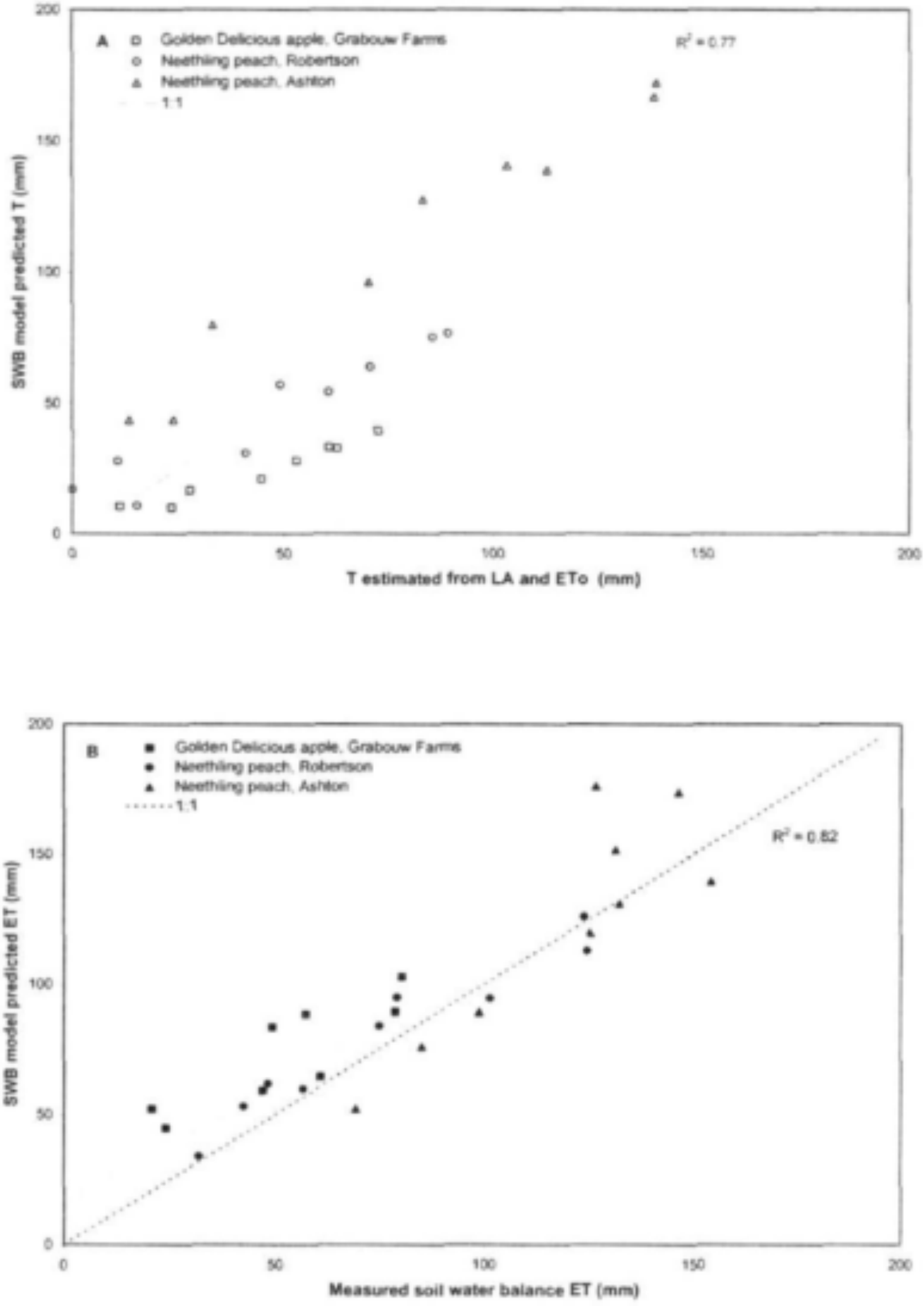
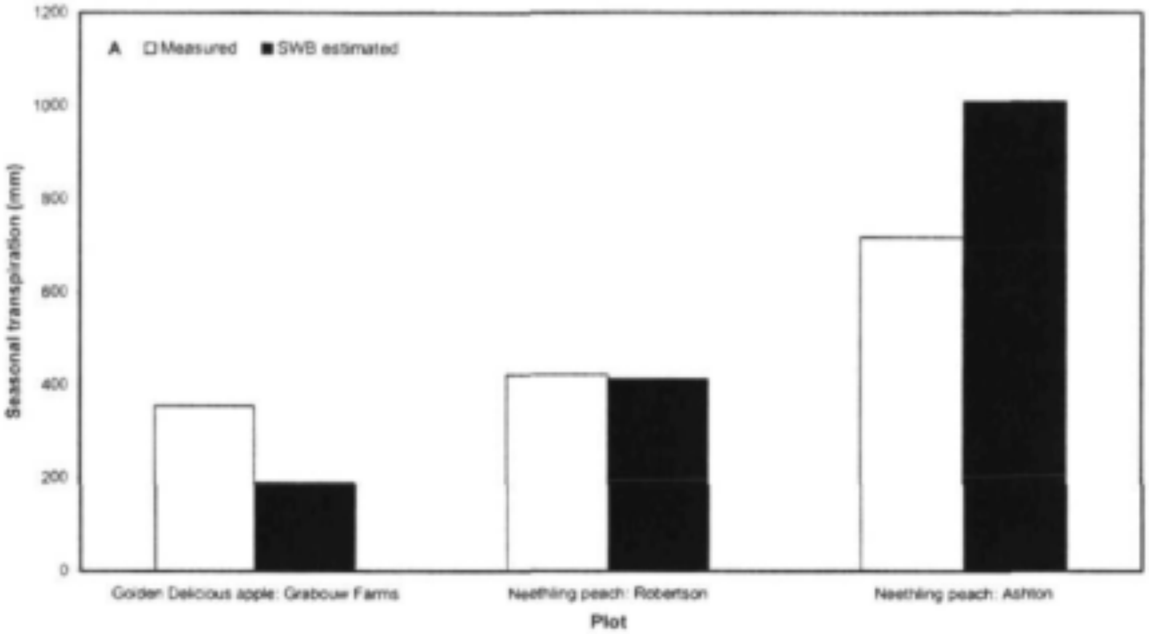


Figure 45. Comparison of (A) monthly transpiration (T) predicted by SWB and T estimated from leaf area and Penman-Monteith reference evapotranspiration (ET_o) and (B) evapotranspiration (ET) predicted by SWB and ET estimated from crop coefficients derived from a measured soil water balance and ET_o.



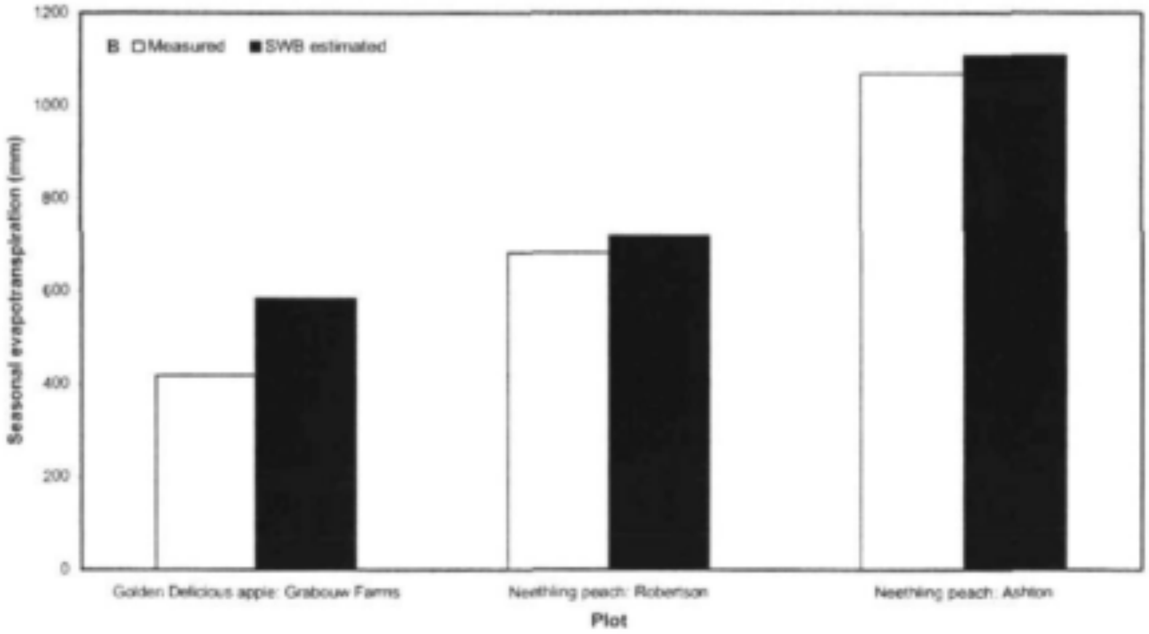


Figure 46. Comparison of seasonal (A) transpiration and (B) evapotranspiration for Golden Delicious apples (Grabouw Farms) and Neethling peaches (Robertson and Ashton). The months of season was from October to May for apples and September to May for peaches.

CHAPTER 5

ESTIMATION OF BASAL CROP COEFFICIENTS FOR OTHER ORCHARDS

The SWB model needs Kcb values as input to simulate transpiration for crops. To enable farmers to use the model effectively for irrigation scheduling purposes, such information should be readily available. Although the FAO has published such coefficients for non-stressed, well-managed, deciduous fruit crops in subhumid climates for use in the dual crop coefficient approach (Allen et al., 1998), it is expected that values will vary especially where management practices are different from conditions under which the FAO factors have been determined. A means to estimate Kcb from easily measurable orchard parameters is therefore considered necessary if the model is to be used for practical irrigation scheduling on farms.

5.1 Material and methods

The relationships between Kcb and several variables were determined in order to establish if it is possible to estimate Kcb from easily measurable orchard parameters. Canopy width of the tree was used to calculate fractional cover (fc) as the fraction of soil surface that is covered by the tree as seen from directly overhead (Tree width/Lateral spacing). Tree volume, LA, FI and LAD were derived as described previously (refer to 4.1). Orchard leaf area index (OLAI) was calculated as LA/Plant spacing. Basal crop coefficients were obtained from SWB from simulation results for the dates corresponding to that of LAI measurements.

5.2 Results and discussion

First and second order polynomial functions were fitted to establish the best relationship between Kcb and fc, LA, OLAI, LAD and FI for the different cultivars. Second order polynomial functions improved the relationship between Kcb and the other variables compared to the linear approach. The coefficient of determination, root mean square error and significance level are summarized for fc, LA, LAD, and FI in Table 25. Regression coefficients are summarized in Table 26 & 27. Results for OLAI was good, but it was omitted from tables because it is related to LA.

The high coefficient of determination and significance level for the function of Kcb over fc for pear cultivars and Keisie peaches were misleading (Table 25). The function estimated the same Kcb values for high as well as low fc values. LA gave the best relationship of all the variables with the Kcb if all cultivars are taken into account. The functions for Kcb over LAD were, depending on cultivar, better or worse compared to those for Kcb over LA. The relationship between Kcb and FI was better or the same as that determined between Kcb and LA for all cultivars except for Forelle and Packhams' Truimph pear trees. The function was not significant for Forelle pear trees. Two of the FI data points remained high while the corresponding Kcb values for the end of the season were decreasing. This could be the result of the linear fit applied to the RFI data for estimation of the late stage start date at the end of the season (Fig. 27C). The Rosemary data included one outlier which was omitted from the analysis. The LA and therefore FI was lower on day of season 88 after pruning was applied to the trees (Fig. 22A). The SWB model, however, was not updated for the change in FI and the corresponding Kcb mid was too high. It is not recommended that the LA-related functions for Keisie (Table 26 & 27) be used for Kcb estimation purposes, due to the uncertainty that exists regarding the PCA calibration for this cultivar.

Results indicated that it was not possible to get a reliable estimate of Kcb from easily measurable parameters in the orchard. Producers will have to make use of expertise and specialised equipment to determine LA, LAD or FI before Kcb can be estimated.

Table 25. Coefficient of determination (R^2), root mean square error (RMSE) and level of significance (Pr > F) for 2nd order polynomial functions of Kcb on fractional canopy cover (fc), leaf area (LA), leaf area density (LAD) and fractional interception (FI).

Fruit	Cultivar	fc			LA			LAD			FI		
		R^2	RMSE	Pr>F	R^2	RMSE	Pr>F	R^2	RMSE	Pr>F	R^2	RMSE	Pr>F
Apple	GD	0.52	0.067	0.0014	0.88	0.034	<.0001	0.68	0.055	<.0001	0.93	0.025	<.0001
	GS	0.57	0.250	0.1852	0.86	0.142	0.0193	0.71	0.206	0.0865	0.99	0.045	0.0002
Pear	RM	0.86	0.019	0.0201	1.00	0.004	<.0001	0.96	0.010	0.0018	0.96	0.010	0.0017
	BR	0.60	0.070	0.1614	0.81	0.048	0.0351	0.69	0.061	0.0957	0.85	0.043	0.0238
	FOR	0.63	0.010	0.0116	0.96	0.004	0.0082	0.97	0.002	0.0016	0.03	0.020	0.9600
	PT	0.75	0.068	0.0615	0.79	0.063	0.0442	0.83	0.057	0.0306	0.76	0.067	0.0587
Peach	Keisie	0.85	0.060	0.0014	0.87	0.056	0.0008	0.86	0.057	0.0010	0.92	0.045	0.0002
	Neeth	0.47	0.266	0.0044	0.96	0.069	<.0001	0.93	0.098	<.0001	0.96	0.076	<.0001

Table 26. Regression coefficients for 2nd order polynomial functions ($y = a + bx + cx^2$) of Kcb on fractional canopy cover (fc) and leaf area (LA).

Fruit	**Cultivar**	**fc**			**LA**		
		a	**b**	**c**	**a**	**b**	**c**
Apple	GD	0.16627	-0.73561	1.56561	0.08163	0.01437	-0.00018253
	GS	6.94795	-28.28389	29.92464	0.11271	0.00184	0.00105000
Pear	RM	-2.16652	13.70868	-19.55046	-0.50452	0.41426	-0.05818000
	BR	-27.95693	108.14600	-103.54124	0.06293	0.02628	-0.00067929
	FOR	-2.47575	-11.57762	-12.75015	-0.99441	0.23071	-0.01162000
	PT	-14.37531	51.63831	-45.02524	0.14653	-0.00318	0.00048231
Peach	Keisie	-5.46454	19.55437	-16.39285	0.07301	0.01394	-0.00017977
	Neeth	11.35544	-34.23029	26.36492	0.05493	0.02707	-0.00016551

Table 27. Regression coefficients for 2nd order polynomial functions ($y = a + bx + cx^2$) of Kcb on leaf area density (LAD) and fractional interception (FI).

Fruit	Cultivar	LAD			FI		
		a	b	c	a	b	c
Apple	GD	0.03858	0.07123	-0.00573	0.03858	0.07123	-0.00573
	GS	0.16937	-0.06259	0.01149	0.16937	-0.06259	0.01149
Pear	RM	-0.15462	0.19046	-0.02339	-1.52015	10.53819	-15.68913
	BR	0.05184	0.05895	-0.00411	0.05184	0.05895	-0.00411
	FOR	-0.15705	0.11065	-0.00995	-0.54736	3.19759	-3.69459
	PT	0.10953	0.02901	0.00775	0.10953	0.02901	0.00775
Peach	Keisie	0.05161	0.08402	-0.00604	0.05161	0.08402	-0.00604
	Neeth	0.04057	0.26132	-0.00758	0.04057	0.26132	-0.00758

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

A soil water balance model (SWB) that utilises crop, soil, meteorological and irrigation management data and employs separate estimation of transpiration and evaporation for crops, was selected to estimate water use of deciduous fruit orchards.

The calibration of the SWB FAO-based crop factor model was approached in two ways. Firstly, to determine if sap flow derived Kt values could be used instead of Kcb values in combination with measured soil water deficit to calibrate the model. Secondly, to perform SWB simulations and fit SWB predicted soil water deficit to measured soil water deficit from orchards, until the best statistical fit was obtained.

Transpiration coefficients were only determined for Golden Delicious apples and Neethling peaches. Comparison of Kt to SWB derived Kcb values indicated that the former cannot necessarily be used interchangebly with the latter for the SWB model. Pear Kt values were too high and the sap flow calibration should be verified for intact potted pear trees.

Statistical output parameters and/or visual fit indicated reasonable agreement of SWB predicted to measured soil water deficit for six of the eleven plots where the fitting procedure was used. These included the full bearing Golden Delicious apple trees at Grabouw Farms, Rosemary and Packhams' Truimph pear as well as Keisie and Neethling peach trees. Reasonable agreement was obtained between monthly SWB predicted transpiration and transpiration (sap flow) estimated from LA and ETo. SWB predicted ET also agreed reasonably well with ET estimated from Kc and ETo. Comparison of seasonal transpiration and ET, however, indicated that the transpiration was undererestimated for Golden Delicious apples at Grabouw Farms and overestimated for Neethling peach trees at Ashton. It follows that the Kcb values determined by the fitting procedure for the two cultivars was too low and too high, respectively. Evaporation was severely underestimated for the Neethling peach tree plot at Ashton. It is important to note that the model could underestimate evaporation grossly for warmer areas where the canopy cover fraction exceeds the irrigated fraction of the soil.

Since measured soil water deficit values for the top soil layer were not available, the fitting procedure to obtain Kcb values did not work well. This, as well as discrepancies between measured and SWB model simulated soil water deficit values complicated interpretation of statistical output parameters used to evaluate the reliability of the model prediction. Several reasons for poor fit of simulated to measured data were identified. Evaporation could be severely overestimated by the SWB model if the measured soil water content of the top soil layer is not used as initial soil water content input. Although this is considered a once-off error, overestimation could re-occur if soil water content is updated according to measured data. Evaporation is limited to the top soil layer and the model could underestimate evaporation if the simulated water content of the top soil layer is air-dry during periods of high reference

ET (ET_o). The model could underestimate evaporation during periods of high ET_o where the canopy cover fraction exceeds the irrigated fraction of the soil surface, especially if the irrigation frequency is high. Since the effect of crop removal or limited leaf senescence after harvest cannot be accurately simulated, the model over- or underestimated the soil water deficit at several plots after harvest. Use of the linear Kcb approach of the Food and Agriculture Organisation (FAO) of the United Nations could cause over- or underestimation of soil water deficit because the leaf area (LA) development and therefore fractional interception (FI), is not linear, especially during the development stage. The model does not simulate separate water balances for trees and cover crop under full surface irrigation. The recommended assumption that the cover crop contribution would be similar to that of bare soil proved to be invalid where the cover crop was irrigated and frequently mowed. However, it did apply where tree roots extended beyond the wetted area and the non-irrigated cover crop was patchy and dry. The Kcb values will have to be adjusted if canopy management practices like pruning change the FI. This can be done by updating simulated FI of the model to measured FI.

Alternative ways to obtain Kcb values for other orchards were investigated. It was not possible to obtain a reliable Kcb estimate from easily measurable tree parameters. It was, however, possible to estimate it from measured LA, LAD or FI. It follows that producers will have to make use of expertise and specialised equipment to determine these variables for estimating Kcb.

A comparison of seasonal ET predicted by means of crop factors and Class-A pan evaporation (Green, 1985) to ET obtained from soil water balance measurements, indicated that crop water requirement was underestimated by the former method for full bearing trees of early and mid-season cultivars. Hence, producers should consider the higher seasonal irrigation requirement of these trees when managing irrigation water.

Future research

The use of an irrigation scheduling model such as SWB, that utilizes the dual crop coefficient approach, has the potential to address some of the variability present in irrigation of orchards and to improve water management. Development of separate water balances for trees and cover crop under full surface irrigation in the SWB model could enable more realistic simulations for such orchards. Furthermore, the availability of Kcb values apart from those published by the FAO, is problematic and a simple and practical approach to determine Kcb is still a challenge. In this regard, estimation of Kcb from radiation interception determined through the recently developed two dimensional energy interception model for hedgerow tree crops, as well as indirect methods in the orchard could be further investigated. Although models are available to estimate radiation interception with acceptable reliability, LA is generally needed as input. Future research could therefore provide much needed information for modelers and enhance the use of models for management purposes if it eliminates the use of LA as an input variable or finds a practical, less laborious way to determine it. The dual crop coefficient approach of the FAO and adjustment procedures for local conditions could be evaluated in parallel to such a study.

Our research has shown that Kt cannot necessarily be used interchangebly with Kcb. However, it was also demonstrated that sap flow could provide accurate information regarding water flow and therefore transpiration of trees. The dual crop coefficient approach states that it models transpiration and evaporation separately. It should therefore be ideal if transpiration, estimated from Kt values, is combined with a reliable soil water evaporation submodel. In this regard the detailed two-dimensional finite difference soil water balance model for hedgerow tree crops or other suitable evaporation models could be considered to be used either directly, or to determine evaporation coefficients for simpler models. It will be very valuable if an evaporation model is calibrated and validated for the main soil types in deciduous fruit producing areas, including gravelly soils.

Practical application

With regard to practical use of the SWB model for real time irrigation scheduling on farms, trained professionals to collect input data and assist farmers in using the model, are perhaps needed. Fractional interception can be used to estimate basal crop coefficients for apple and peach, or leaf area for pear orchards for which those coefficients are not available.

Lateral water movement into orchards on slopes and soil variability may limit the use of models for real time irrigation scheduling. In such cases direct measurement of soil water content, which is also prone to the soil variability problem, may become more important. However, where lateral water flow into orchards is not a concern, real time irrigation scheduling models, that are verified through measurements, could aid in improved water management and saving of limited water resources. Integration of such an irrigation scheduling model with other models in a GIS based, integrated, farm management system that communicate with fruit producers through a computer network could be valuable to promote environmentally friendly farming and possibly facilitate a real time irrigation scheduling service in the Western Cape.

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APPENDIX A

Soil Water Balance model

The improvements made to facilitate prediction of water requirements of hedgerow tree crops in the mechanistic Soil Water Balance (SWB) model are summerised below. The section on yield predictions with the model of the Food and Agriculture Organisation (FAO) of the United Nations (Annandale *et al.*, 2002) was omitted.

FAO-type crop factor modification

SWB calculates the grass reference evapotranspiration (ETo) using the revised FAO Penman-Monteith methodology (Smith *et al.*, 1996). The basal crop coefficient (Kcb) is the ratio of crop evapotranspiration (ETc) to the reference evapotranspiration (ETc/ETo) when the soil surface is dry, but transpiration is occuring at the potential rate (Allen *et al.*, 1998). The crop coefficient (Kc) is the sum of the basal crop coefficient and the time-averaged effects of evaporation from the soil surface layer (Allen *et al.*, 1996).

Potential evapotranspiration is calculated as follows:

$$PET = ETo\ Kc_{max} \qquad (1)$$

Kc_{max} represents the maximum value for Kc following rain or irrigation. It is selected as the maximum of the following two expressions (Allen *et al.*, 1996):

$$Kc_{max} = 1.2 + [0.04\ (U2 - 2) - 0.004\ (RHmin - 45)]\ (Hc/3)^{0.3} \qquad (2)$$

$$Kc_{max} = Kcb + 0.05 \qquad (3)$$

where

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

The upper limit of Kc_{max} is set at 1.45.

FI_{transp} is the amount of radiation intercepted by the canopy and used for photosynthesis and transpiration (Annandale *et al.*, 1999). SWB partitions PET into potential crop transpiration (PT) and potential evaporation (PE) and estimates FI_{transp} using the following equations:

$$PT = Kcb\ ETo \qquad (4)$$

(Allen *et al.*, 1996)

$$FI_{transp} = PT/PET \qquad (5)$$

$$PE = (1 - FI_{transp})\ PET \qquad (6)$$

SWB assumes Kcb, Hc and root depth (RD) are equal to the initial values during the initial stage. During the crop development stage, they increase linearly from the end of the initial stage until the beginning of the mid-stage, when they reach maximum values. They remain constant at this maximum during the mid-stage. During the late stage, Kcb decreases linearly until harvest when it reaches the value for the late stage, whilst RD and Hc remain constant at their maximum value. The crop input parameters that need to be known are Kcb for the initial, mid- and late stages, crop growth periods in days for initial, development, mid- and late stages, initial and maximum RD, as well as initial Hc and Hc_{max}.

The following input parameters are required to run the FAO-type crop factor model: planting date, latitude, altitude, as well as maximum and minimum daily air temperatures. In the absence of measured data, SWB estimates solar radiation, vapour pressure and wind speed according to the FAO recommendations (Smith, 1992; Smith *et al.*, 1996). It is, however, recommended that these be measured.

Caution should be exercised against blind acceptance of the FAO parameters taken from literature, as local conditions, management and cultivars could influence crop growth periods and Kcb's. A simple methodology used to generate a database of Kcb values from limited available data, has therefore been developed. Daily Kcb can be calculated from FI_{transp}, Hc and weather data using the following equation:

$$Kcb = FI_{transp}\ PET/ETo \qquad (7)$$

ETo is calculated from weather data. Weather data and Hc are used to calculate crop PET, whilst FI_{transp} can be measured in the field. The procedure can be applied to determine FAO-type crop factors for any species. Validation of the model with independent data sets is always recommended.

Soil water balance with localised irrigation

An option for the calculation of the soil water balance under localised irrigation (drip or micro-irrigation) was included in SWB. When this option is selected, the model uses a simplified procedure for the calculation of non-uniform wetting of the soil surface, evaporation and transpiration. In this quasi two-dimensional procedure, a cascading water balance is calculated for both the wetted and non-wetted portion of the profile. Daily soil water content per soil layer are calculated for both the wetted and non-wetted volumes of the soil. The output of soil water deficit is based on the soil water content in the wetted volume of soil only, as this is the part of the profile managed by the irrigator.

Water redistribution

Interception of water by the crop canopy is calculated only when rainfall occurs, because the canopy is not wetted by micro-sprinklers or drippers. Micro- or drip irrigation, commonly used in orchards, only wets a limited area under the canopy of the trees. Runoff, infiltration and drainage are calculated like in the one-dimensional cascading model (Annandale *et al.*, 1999), but for both the irrigated and non-irrigated portions of the soil. Runoff and drainage for the irrigated and non-irrigated portions of the soil are weighted by the fraction of the surface irrigated (FI_{irrig}). Total runoff and drainage are calculated as the sum of the components from the irrigated and non-irrigated portions.

Evaporation

Evaporation from the soil surface is also not uniform under micro- or drip irrigation. Two possible cases are simulated when drip/micro irrigations are performed:

i) If the canopy cover fraction is larger than the irrigated surface fraction ($FI_{transp} \geq FI_{irrig}$), evaporation is simulated only from the non-irrigated portion of the ground.

ii) If ($FI_{transp} < FI_{irrig}$), evaporation from the non-irrigated surface fraction ($1-FI_{irrig}$) and from the non-shaded area ($FI_{irrig} - FI_{transp}$) are calculated separately and added to calculate total evaporation.

The procedure used to calculate water loss by evaporation in the cascading model was described in Annandale *et al.* (1999).

Transpiration

No root water uptake is calculated for the uppermost soil layer. SWB assumes layer water uptake is weighted by root density when soil water potential is uniform (Campbell & Diaz, 1988). Water loss by crop transpiration is calculated as a function of maximum transpiration rate (T_{max}) and leaf water potential at T_{max} (Ψ_{lm}) (Campbell, 1985; Annandale *et al.*, 2000). It represents the lesser of root water uptake or maximum loss rate. T_{max} and Ψ_{lm} are input parameters that can be estimated from researcher's experience. Ψ_{lm} is the minimum leaf water potential occurring generally in the early afternoon under no water constraints, when the transpiration rate is at its peak. The mechanistic supply and demand limited water uptake calculation, was in this manner, linked to the FAO crop factor approach with a minimal addition of crop input parameters required.

The user can enter the fraction of roots in the wetted volume of soil as model input. Daily transpiration is then calculated as the sum of water loss from the wetted and non-wetted volumes of soil, weighted for root fraction and matric potential.

The input data required to run the two-dimensional cascading model are rainfall and irrigation amounts, volumetric soil water content at field capacity and permanent wilting point, initial volumetric soil water content as well as bulk density for each soil layer. Row spacing, wetted diameter, distance between micro-sprinklers or drippers, and the fraction of roots in the wetted volume of soil are also required.

APPENDIX B

MORECS

The following section summarises the documentation available on the MORECS model. It includes information on evaporation, precipitation and dew deposition, runoff and water budget calculations. Unfortunately no further information with regard to the source code was obtained. This information dates back to March 1997 and it should be kept in mind that the model could have changed since then.

Evaporation:

Evaporation is estimated with the Penman-Monteith equation and includes soil and plant surfaces.

$$\lambda E = \frac{\Delta(R_n - G) + \rho c_p (e_s - e_a)/r_a}{\Delta + \gamma (1 + r_s/r_a)} \qquad (1)$$

E = rate of water loss ($kg\ m^{-2}s^{-1}$)
Δ = rate of change of e_s with temperature ($mb\ °C^{-1}$)
R_n = net radiation ($W\ m^{-2}$)
G = soil heat flux ($W\ m^{-2}$)
ρ = Air density ($Kg\ m^{-3}$)
c_p = specific heat of air at constant pressure ($1005\ JKg^{-1}$)
e_s = saturation vapour pressure (mb)
e_a = actual vapour pressure (mb)
λ = latent heat of vaporization ($2.465 \times 10^6\ JKg^{-1}$)
γ = psychromatic constant ($0.66\ mb\ °C^{-1}$)
r_s = surface resistance (sm^{-1})
r_a = aerodynamic resistance (sm^{-1})

Soil heat flux density

Soil heat flux density during daytime (G_d) is calculated as:

$$G_d = (0.3 - 0.3L)R_{Nd} \qquad (2)$$

Where
L = Leaf area index
R_{Nd} = Daytime net radiation

For grass, L varies from 2.0 during winter to 5.0 during summer, but is assumed to equal 3.33 when calculating G_d. Leaf area index used to calculate G_d for deciduous trees varies linearly from 0.1 during dormancy to 6.0 at full leaf. A similar linear decrease is assumed during senescence. For bare soil L=0.0.

Soil heat flux density during night-time (G_n) is calculated as:

$$G_n = (D(G_d)-P)/(24-D) \qquad (3)$$

Where

D = Number of daylight hours

P = Average daily heat storage in soil (Whr m^{-2})

When estimating Pan evaporation G is set equal to 0.0.

Aerodynamic resistance (r_a)

Using the logarithmic wind profile and assuming neutral stability r_a is given as:

$$r_a = (6.25/u)\ln(10.0/z_o)\ln(6.0/ z_o) \qquad (4)$$

Where

u = wind speed (ms^{-1}) at a height of 10 m above the ground

z_o = roughness length (m)

Fixed roughness lengths of 1.5×10^{-2} m, 5.0×10^{-3} m and 5.0×10^{-4} m are assigned to grass, bare soil and water respectively. For deciduous trees roughness length varies between 0.2 at leaf emergence to 1.0 for full leaf. During autumn, roughness length is decreased from the full leaf value to a defoliated value of 1.5×10^{-2} m. Similarly, roughness length is linearly increased during the period of bud break in spring.

Surface resistance (r_s)

In MORECS water may be extracted from both the soil and the crop. The surface resistance term incorporates resistance due to both the crop and the soil. Daytime values of crop resistance are prescribed for each surface type. These values reflect a crop that is freely supplied with water and thus present a minimum resistance associated with each crop type. For deciduous trees the minimum resistance is set to 80 sm^{-1}, while it varies for grass from 50 during winter to 40 during summer months. A relatively high crop resistance value of 600 sm^{-1} is used for evaporation from bare soil to ensure that transpiration is negligible.

Note:

Orchards are assumed to be largely grass covered, so that the values of r_s calculated for grassland are used when trees are not in leaf. A grass cover with leaf area index of 2.5 is maintained while tree leaves develop and also during the period of tree leaf maturity when the leaf area index of trees is set to 2.5. Thus the calculation of r_s outside the leafless season has to consider resistance of soil, grass and tree. Calculating the combined resistance of tree and grass from leaf area index and separate r_s values is done first. This resistance is then combined with soil surface resistance. Orchard values of r_s at night use calculations with leaf area set equal to the sum of grass and tree leaf areas.

Soil moisture reservoir:

MORECS assumes two soil moisture reservoirs. Water in the top reservoir (x) is freely available for ET, while water in the second reservoir (y) becomes increasingly more difficult to extract as soil moisture decreases. The contents of each reservoir can be subdivided into water available for evaporation (x_{SOIL} or y_{SOIL}) and water available for transpiration (x_{CROP} or y_{CROP}). In the case of bare soil, water can only be evaporated from x_{SOIL} or y_{SOIL}. Provided water exists in x, the crop resistance remains at the minimum value. Soil resistance is set to 100 sm^{-1} until x_{SOIL} has been depleted. After this soil resistance increases according to the formula:

$$r_{SOIL} = 100Cx_{max}/(x_{SOIL} + x_{CROP} + 0.01Cx_{max}) \quad (5)$$

Where

r_{SOIL} is the soil resistance

x_{SOIL} and x_{CROP} is the amount of water contained in each reservoir

Cx_{max} is the maximum amount of water that can be held in x_{CROP}

For potential transpiration, r_{SOIL} remains at 100 sm^{-1} and crop resistance is set at the minimum value for grass.

Once the water in the x reservoir has been exhausted, r_{SOIL} is set to 10^4 sm^{-1} and the crop resistance (r_{CROP}) is increased proportionally to the water deficit of the y reservoir using the formula:

$$r_{CROP} = (r_{CROP})_{min}((2.5y_{max}/(y_{SOIL} + y_{CROP}))-1.5) \quad (6)$$

Where

y_{SOIL} and y_{CROP} is the amount of water contained in each reservoir

y_{max} is the maximum amount that can be held in the y reservoir

$(r_{CROP})_{min}$ is the minimum crop resistance value.

Daytime surface resistance, r_s, is related to r_{CROP} and r_{SOIL} by the expression:

$$r_s = (r_{CROP}\, r_{SOIL})/((r_{SOIL}\, (1-A))+(r_{CROP}\, A)) \quad (7)$$

Where

$A = 0.7^L$

At night when stomata are closed r_s is given by:

$$r_s = 2500(r_{SOIL})/(r_{SOIL}(L)+2500) \quad (8)$$

However, when the surface is bare soil and all water in x_{SOIL} has been depleted, regardless of the time of day, r_s is specified as:

$$r_s = 100(3.5(1-(y_{SOIL}/Sy_{max})) + \exp(0.2(Sy_{max}/(y_{SOIL}-1)))) \quad (9)$$

Where:

Sy_{max} is the maximum amount of water that can be held in y_{SOIL}

For an open water surface, r_s equals 0.0.

Precipitation:

Each of the reservoirs can be replenished by rainfall and, theoretically by dew deposition. In cases where the soil is covered by vegetation, a certain amount of rainfall is intercepted by the plant canopy and is thus unavailable to the soil. The proportion of rainfall that can be intercepted by grass (P) is:

$$P = (1.0\text{-}0.5^{L}) \qquad (10)$$

The amount of interception (I) is simply the product of P and the daily rainfall. However, I cannot exceed 20% of the leaf area index, L (i.e. $I \leq 0.2L$). Particularly during summer, several individual showers may contribute to the daily rainfall total. In such cases, the interception that is associated with the first shower may evaporate prior to any subsequent rainfall. Thus Thompson *et al.* (1981) suggested that the calculated value of I be multiplied by an adjustment factor during different months of season. During all months, however, I is limited to the daily rainfall total.

Interception by deciduous trees is treated differently. Helvey and Patric (1965) present a regression-based approach for estimating interception of rainfall in eastern hardwood forests. During dormancy (trees are in a defoliated state), interception is given as:

$$I = 0.086R + 0.015 \qquad (11)$$

Interception by trees in full leaf is calculated using:

$$I = 0.099R + 0.031 \qquad (12)$$

Where:

R is the daily rainfall and the date of full leaf is obtained using phenological data. During leaf emergence, I is linearly increased from its dormancy value. Conversely, during senescence, I is linearly decreased from its full leaf value.

When interception is present, evaporation of the intercepted moisture occurs prior to any evapotranspiration from the soil. After setting r_s to 0.0, the open water value, evaporation is calculated hourly until the foliage is completely dry (no interception). Subsequent hourly estimates are calculated using r_s given by Equations 7 and/or 8. If intercepted water still exists after 24 hours, the unevaporated interception is assumed to fall to the soil.

Dew Deposition:

The formation of dew is assumed when night-time evaporation is negative. In these instances, dew is treated as open water and night-time evaporation is recalculated after setting r_s to zero. If this calculation again yields positive evaporation, the deposition of dew is assumed with the amount of dew equal to the absolute value of evaporation. Ensuing calculations treat dew deposition in the same manner as rainfall. If recalculation yields positive evaporation, night-time evaporation is set to zero. In such cases it is assumed that only dew has evaporated.

Runoff:

For surface types other than deciduous trees, runoff is assumed to be equal to zero unless both the x and y reservoirs are at capacity. In the case of trees, runoff is also assumed to occur if the daily rainfall exceeds 1.0 inch or regardless of the daily rainfall total, when x_{SOIL} is greater than zero. These criteria are based on the curve number method. Using a simplification of this method, the runoff from a tree covered surface is:

$$RO_{tree} = (R-0.2D)^2/(R=0.8D) \quad (13)$$

R is the daily rainfall (cm), and D is given by:

$$D = (x_{max} + y_{max}) - (x_{SOIL} + x_{CROP} + y_{SOIL} + y_{CROP}) \quad (14)$$

Where x_{max} and y_{max} are the capacities of the x and y soil water reservoirs

Water Budget Calculations:

The total amount of water available for ET from a specific crop (AW) is assumed to fill two soil moisture reservoirs. Water in the x reservoir, 40% of AW, is freely available for ET, while the remaining 60% of the AW, which fills the y reservoir, becomes increasingly difficult to transpire or evaporate as the contents of y decrease. The amount of water in each reservoir is further subdivided into water available for evaporation from bare soil (x_{SOIL} or y_{SOIL}) and water available for ET from a crop covered surface (x_{CROP} or y_{CROP}). For soil with typical soil water holding capacity, AW is assigned a value of 20 mm for bare soil, 125 mm for grass and 175 mm for trees. Thus, regardless of crop type, x_{SOIL} and y_{SOIL} cannot exceed 8 and 12 mm, respectively, for a soil with average water holding capacity.

Through the process of ET, water is withdrawn from x_{SOIL} until the entire x reservoir is empty. Subsequent ET draws water from x_{CROP} until the entire x reservoir is exhausted. At this point ET draws water from the y reservoir, depleting y_{SOIL} before tapping the reserve stored in y_{CROP}. Soil moisture is replenished in a similar manner. Rainfall must fill the x_{SOIL} sub-reservoir to capacity before replenishing any moisture deficit in x_{CROP}. Once the x reservoir is at capacity, additional rainfall fills y_{SOIL} and finally y_{CROP}. This sequence of ET and recharge quantitatively represents the decreasing availability of soil moisture for evaporation and/or transpiration. Such an assumption simplifies the process of specifying crop and soil resistance as soil moisture becomes increasingly depleted or recharged.

APPENDIX C

SOIL PROFILE CLASSIFICATION AND DESCRIPTIONS

Locality:	Elgin	**Soil form**:	Tukulu
Farm name:	Molteno Brothers	**Soil family**:	Tu 2120
Fruit type:	Golden Delicious	**Topsoil texture**:	Fine sandy loam

General description: Tukulu form with a bleached A horizon, non-red and luvic B1 horizon, with a fine sandy loam topsoil texture.

Horizon	Depth (mm)	Description	Diagnostic horizon
A	150	Moist; moist 10YR 3/4 dark yellowish brown; dry 10YR 5/3 brown; fine sandy loam (18%); weak fine subangular blocky to granular; hard to very hard; firm; few ferruginous fine gravel; clear transition.	Orthic
B1	500	Moist; moist 10YR 3/6 dark yellowish brown; fine sandy clay loam (30%); weak fine subangular blocky; hard to very hard; firm; many ferruginous and other fine and coarse gravel; clear transition.	Neocutanic
B2	800	Moist; moist 10YR 4/4 dark yellowish brown; fine sandy clay loam (30%); weak fine to medium subangular blocky; hard to very hard; firm; many ferruginous and other fine and coarse gravel; clear transition.	Neocutanic
C	NR	Moist; moist 10YR 7/6 yellow; common fine to medium faint to distinct grey and red mottles; silty clay loam (30%); weak to moderate coarse angular blocky; hard; slightly firm.	Unspecified with signs of wetness; soft saprolite

General remarks:

- No evidence of deep soil cultivation.
- Virtually no roots in interrow area.
- Few thick roots at B2-B3 contact.

Locality: Elgin
Farm name: Grabouw Farms
Fruit type: Golden Delicious & Granny Smith

Soil form: Tukulu
Soil family: Tu 2110
Topsoil texture: Loamy fine sand

General description: Tukulu form with a bleached A horizon, non-red and non-luvic B1 horizon, with a loamy fine sand topsoil texture.

Horizon	Depth (mm)	Description	Diagnostic horizon
A	200	Moist; moist 10YR 3/2 very dark greyish brown; dry 10YR4/3 brown; loamy fine sand (8%*); weak fine subangular blocky to granular; slightly hard; friable; very few ferruginous fine gravel; clear transition.	Orthic
B1	700	Moist; moist 10YR 5/4 yellowish brown; dry 10YR 5/2 greyish brown; fine/coarse sandy loam (12%); weak fine subangular blocky; slightly hard; friable; common ferruginous fine and coarse gravel; gradual transition.	Neocutanic
B2	800-900	Moist; 10YR 5/3 brown; dry 10YR 7/3 very pale brown; fine/coarse sandy loam (12%); weak fine subangular blocky; slightly hard; friable; common ferruginous and sandstone fine and coarse gravel; clear transition.	Unconsolidated material with signs of wetness
C	NR**	Moist; moist 10YR; common fine distinct grey, pale brown and olive mottles; fine sandy loam to sandy clay loam (20%); weak medium angular blocky; hard; firm.	Soft saprolite with signs of wetness

* Field estimated clay content
** Not-reached

General remarks:

- Based on dry B soil colour the soil tends to Estcourt soil form
- Soil shift delphed to depth of 800 mm.
- Very good root distribution. Common fine and medium roots to depth of 800 mm and in interrow area.

Locality: Elgin
Farm name: Oak Valley (G7)
Fruit type: Golden Delicious

Soil form: Tukulu
Soil family: Tu 2120
Topsoil texture: Fine sandy loam

General description: Tukulu form with a bleached A horizon, non-red and luvic B1 horizon, with a fine sandy loam topsoil texture.

Horizon	Depth (mm)	Description	Diagnostic horizon
A	200	Moist; moist 10YR 3/3 dark brown; dry 10YR 5/2 greyish brown; fine sandy loam to clay loam (20%); weak fine granular; hard to very hard; firm; clear transition.	Orthic
B1	500	Moist; moist 10YR 3/4 dark yellowish brown; dry 10YR 4/2 dark greyish brown; fine sandy clay loam (25%); weak fine subangular blocky; hard to very hard; firm; common ferruginous and other fine gravel; few clay cutans; clear transition.	Neocutanic
B2	700-800	Moist; moist 10YR 5/3 brown; fine sandy clay loam (30%); few fine faint red mottles; moderate fine subangular blocky; hard to very hard; slightly firm to firm; many ferruginous and other fine and coarse gravel; common clay cutans; clear transition.	Neocutanic/ Unspecified with signs of wetness
C	NR	Moist; moist 10YR 5/8 yellowish brown; few to common medium distinct red, grey and white mottles; clay (40%); moderate to strong medium to coarse angular blocky; very hard; very firm.	Unspecified with signs of wetness; pedocutanic

General remarks:

- Well shift delph ploughed to 800 mm.
- Common fine and medium roots to 800 mm and in interrow area.

Locality: Elgin
Farm name: De Rust
Fruit type: Bon Rouge & Rosemary

Soil form: Sterkspruit
Soil family: Ss 2100
Topsoil texture: Fine sandy loam

General description: Sterkspruit form with a bleached A horizon, non-red B1 horizon, with a fine sandy loam topsoil texture.

Horizon	Depth (mm)	Description	Diagnostic horizon
A	300	Moist; moist 10YR 4/3 brown; dry 10YR6/3 pale brown; fine sandy loam (15%); weak fine subangular to granular; very hard; slightly firm; few fine and coarse gravel; clear transition.	Orthic
B1	650	Moist; moist 10YR 5/6 yellowish brown; few medium grey and yellow mottles; sandy clay (40%); strong coarse prismatic; common brown clay cutans; very hard; very firm; gradual transition.	Prismacutanic
C	NR	Moist; colour highly variable; abundant coarse distinct yellow, pale brown and grey mottles; silty clay loam (30%); weak coarse subangular blocky; hard; firm.	Soft saprolite with signs of wetness

General remarks:

- Very poorly delphed to depth of 600 mm.
- Very poor root distribution.

Locality:	Elgin	**Soil form**:	Bloemdal
Farm name:	Molteno Brothers	**Soil family**:	Bd 2100
Fruit type:	Packham's Triumph	**Topsoil texture**:	Loamy fine sand

General description: Bloemdal form with a moderately leached and non-luvic B1 horizon, with a loamy fine sand topsoil texture.

Horizon	Depth (mm)	Description	Diagnostic horizon
A	200	Moist; moist 7.5YR 3/3 dark brown; dry 7.5YR5/3 brown; loamy fine sand (10%); apedal to weak fine subangular to granular; friable; clear transition.	Orthic
B1	600	Moist; moist 5YR 4.5/6 yellowish red; fine/medium sandy loam (12%); apedal massive to weak fine subangular blocky; friable; gradual to clear transition.	Red apedal
B2	800	Moist; 7.5YR 5/6 strong brown; fine/medium sandy loam (12%); apedal massive to weak fine subangular blocky; slightly hard; friable; clear transition.	Yellow-brown apedal/Unspecified material with signs of wetness
B3/C	NR	Moist; colour highly variable; abundant coarse distinct red, yellow, pale brown and grey mottles; fine/medium sandy loam (15%); weak medium to coarse angular blocky; slightly firm.	Unspecified material with signs of wetness; soft saprolite

General remarks:

- The B1 horizon has weak neocutanic features and the soil is transitional to Tukulu 2210.
- Soil poorly shift delphed to depth of 400-450 mm.
- Poor root distribution in B1 and B2. Rare thick roots. Common fine and medium roots in A.

Locality:	Elgin	**Soil form**:	Swartland
Farm name:	Oak Valley	**Soil family**:	Sw 211/21
Fruit type:	Forelle	**Topsoil texture**:	Fine sandy loam

General description: Swartland form with a bleached A horizon, non-red B1 with a subangular to angular blocky structure, with a fine sandy loam topsoil texture.

Horizon	Depth (mm)	Description	Diagnostic horizon
A	200	Moist; moist 10YR 4/4 dark yellowish brown; dry 10YR 5/3 brown; fine sandy loam to clay loam (20%); apedal to weak fine granular to subangular blocky; hard; slightly firm; very few fine and coarse gravel; clear transition.	Orthic
B	500	Moist; moist 10YR 5/6 yellowish brown; few fine red and grey mottles; sandy clay loam to sandy clay (30%); moderate medium angular blocky; hard to very hard; slightly firm to firm; few to common clay cutans; gradual transition.	Pedocutanic
C	NR	Moist; moist 10YR 6/6 brownish yellow; common to many medium to coarse red, grey and white mottles; silty clay loam (30%); weak medium angular blocky; slightly hard to hard; firm; few clay cutans.	Saprolite with signs of wetness

General remarks:

- Well shift delph ploughed to 600 mm.
- Common fine and medium roots to 700 mm and in interrow area.

Locality:	Robertson	**Soil form**:	Addo
Farm name:	ARC Experimental farm	**Soil family**:	1221
Fruit type:	Neethling	**Topsoil texture**:	Fine sandy loam

General description: Addo form with a non-bleached A horizon, red and luvic B1 horizon, no signs of wetness in carbonate horizon, with a fine sandy loam topsoil texture.

Horizon	Depth (mm)	Description	Diagnostic horizon
A	250	Moist; moist 7.5YR 5/4 brown; dry 7.5YR 6/4 light brown; few medium faint grey and yellow mottles; fine sandy loam (10%); apedal massive to weak fine granular; slightly firm; clear transition.	Orthic
B1	650	Moist; moist 2.5YR 4/4 reddish brown; few medium faint grey and white mottles; fine sandy clay loam (30%); very few to few coarse gravel (lime nodules and dorbank fragments); weak medium subangular blocky; slightly firm; moderate effervecence with 10% HCl; gradual transition.	Neocarbonate
B2	1200	Moist; moist 5YR 5/6 yellowish red; common medium distinct grey and yellow mottles; fine sandy clay loam (30%); few coarse gravel (lime nodules and dorbank fragments); weak medium subangular blocky; slightly firm; strong effervescence with 10% HCl.	Soft carbonate horizon
C	NR	On side of pit is a moderately hard dorbank layer	Dorbank

General remarks:

- Well shift delphed to a depth of 800 mm
- Very good root distribution with depth and in interrow area.

Locality:	Robertson	**Soil form**:	Oakleaf
Farm name:	ARC Experimental farm	**Soil family**:	2210
Fruit type:	Zandvliet	**Topsoil texture**:	Loamy fine to medium sand

General description: Oakleaf form with a bleached A horizon, red and non-luvic B1 horizon, with a loamy fine to medium sand topsoil texture.

Horizon	Depth (mm)	Description	Diagnostic horizon
A	200	Moist; moist 7.5YR 4/4 brown; loamy fine to medium sandy (8%); apedal massive to weak fine granular; slightly firm; clear transition.	Orthic
B1	600	Moist; moist 5YR 4/6 yellowish red; fine to medium sandy loam (12%); weak fine subangular blocky to apedal massive; slightly firm to firm; clear transition.	Neocutanic
B/C	800	Stoneline with common coarse gravel and stones consisting of quartzite and phyllite fragments; clear transition.	Stoneline
C	NR	Moist; moist 5YR 4/6 yellowish red; few fine red and white mottles; fine sandy loam (12%); weak fine subangular blocky to apedal massive; slightly firm; very weak effervescence with 10% HCl along macropores.	Unspecified material without signs of wetness

General remarks:

- Poorly cultivated to a depth of 600 mm
- Moderate to poor root distribution with depth and in interrow area.

Locality: Ashton
Farm name: Ashton Canning
Fruit type: Keisie

Soil form: Tukulu
Soil family: 1220
Topsoil texture: Fine sandy clay loam

General description: Tukulu form with a non-bleached A horizon, red and luvic B1 horizon, with a fine sandy clay loam topsoil texture.

Horizon	Depth (mm)	Description	Diagnostic horizon
A	200	Moist; moist 5YR 4/6 yellowish red; fine sandy clay loam (25%); weak medium granular; slightly firm to firm; clear transition.	Orthic
B	600-850	Moist; moist 5YR 4/4 reddish brown; few fine reddish brown mottles; sandy clay loam to sandy clay (35%); weak to moderate medium to coarse subangular to angular blocky; firm; slight effervescence with 10% HCl; gradual uneven transition.	Neocutanic
C	NR	Moist; moist 7.5YR 4/6 strong brown; common fine to medium red, yellow and brown mottles; sandy clay loam (30%); weak medium subangular blocky; slightly firm; moderate effervescense with 10% HCl.	Soft carbonate horizon

General remarks:

- Because of deep soil cultivation the B horizon is disturbed. Could have qualified as pedocutanic and soil classified as Sepane 11/220.
- The soil has been delph ploughed to an uneven depth of 600-850 mm. Mixing is poor.
- Poor root distribution with depth with few roots in interrow area.

Locality: Ashton
Farm name: Ashton Canning
Fruit type: Neethling

Soil form: Etosha/Augrabies
Soil family: 2110
Topsoil texture: Loamy fine to medium sand

General description: Etosha (transitional to Augrabies) form with a bleached A horizon, non-red and non-luvic B1 horizon, with a loamy fine to medium sand topsoil texture.

Horizon	Depth (mm)	Description	Diagnostic horizon
A	250	Moist; moist 7.5YR 4/4 brown; loamy fine to medium sand (10%); apedal to weak fine granular; slightly firm; gradual to clear transition.	Orthic
B1	900	Moist; moist 10YR 3/3 dark brown; loamy fine to medium sand(8%); apedal to weak massive to subangular blocky; friable; very slight effervescence with 10% HCl; gradual transition.	Neocutanic/ Neocarbonate
B2	NR	Moist; moist 10YR 3/3 dark brown; few fine white lime mottles; loamy fine to medium sand(8%); apedal to weak massive to subangular blocky; friable; moderate effervescence with 10% HCl.	Soft carbonate horizon/ Neocarbonate

General remarks:

- The B1 has a weak tendency to a Neocarbonate.
- The B2 is marginally a soft carbonate horizon
- Very good root distribution with depth and in interrow area.

APPENDIX D

NEUTRON PROBE ACCESS TUBE POSITIONING AND WEIGHTING

Table I. Coordinates of access tubes used in the double-ellipsoid configuration for estimation of total profile volumetric soil water content by means of the neutron probe. Coordinates of the inner ellipse refers to positions of access tubes 1 to 4, while X- and Y-coordinates of the outer ellipse refer to access tubes 5 and 7 and 6 and 8 respectively (Figure 2).

Plot	Block	Fruit kind	Cultivar	Plant spacing	Inner ellipse			Outer ellipse	
				m x m	X[1]	Y[2]	r[3]	X	Y
Molteno Glen	53	Apple	G.Delicious	3.5 x 2.0	0.354	0.619	0.710	1.000	1.750
Grabouw Farms	124		G.Delicious	4.0 x 1.5	0.247	0.707	0.749	0.750	2.000
			G.Smith	4.0 x 1.5	0.247	0.707	0.749	0.750	2.000
Oak Valley	G17		G.Delicious	4.25 x 2.0	0.354	0.751	0.830	1.000	2.125
De Rust	6E2	Pear	Bon Rouge	3.5 x 1.0	0.177	0.619	0.643	0.500	1.750
	6E2		Rosemary	3.5 x 1.0	0.177	0.619	0.643	0.500	1.750
Molteno Glen	23(B)		Packhams' Truimph	4.5 x 2.5	0.442	0.795	0.910	1.250	2.250
Oak Valley	A22		Forelle	4.0 x 1.2	0.210	0.707	0.740	0.600	2.00
Robertson Experiment Farm	B2	Peach	Neethling	5.0 x 3.0	0.530	0.880	1.030	1.500	2.500
	Z(M)		Zandvliet	5.0 x 2.5	0.442	0.884	0.988	1.250	2.500
Ashton Canning Experiment Farm	357		Keisie	4.5 x 2.0	0.354	0.796	0.871	1.000	2.250
	352		Neethling	5.0 x 2.5	0.442	0.883	0.988	1.250	2.500

[1] Distance in row direction relative to the tree.
[2] Distance perpendicular to row direction.
[3] Distance from tree to position of neutron probe access tube.

Table II. Weights assigned to neutron water meter access tubes (T1 to T8) for calculation of weighted volumetric soil water content for the different plots.

Partially wetted soil surface

Plot	Cultivar	Irrigated area		Total area		
		T1-4	T5,7	T1-4	T5-7	T6,8
MOL	GD	0.794	0.206	0.680	0.177	0.143
GP	GD	0.763	0.237	0.573	0.177	0.250
GP	GS	0.763	0.237	0.573	0.177	0.250
ROB	NEETH	0.725	0.275	0.464	0.176	0.360
ROB	ZAND	0.686	0.314	0.384	0.176	0.440
DR	RM	0.719	0.281	0.452	0.177	0.371
DR	BR	0.719	0.281	0.452	0.177	0.371
MOL	PT	0.735	0.265	0.490	0.177	0.333
ASH	KEISIE	0.735	0.265	0.490	0.177	0.333
ASH	NEETH	0.706	0.294	0.423	0.177	0.400
ROB	NEETH	0.725	0.275	0.464	0.176	0.360
ROB	ZAND	0.686	0.314	0.384	0.176	0.440

Fully wetted soil surface

Plot	**Cultivar**	**Clean cultivated area**		**Total area**		
		T1-4	**T5,7**	**T1-4**	**T5-7**	**T6,8**
OV	GD	0.700	0.300	0.412	0.177	0.411
OV	FOR	0.717	0.283	0.448	0.177	0.375

APPENDIX E

After careful consideration it was decided not to include long lists and tables with data in the report, but to archive raw data at ARC Infruitec-Nietvoorbij in hard copy and CD-ROM format in the project file in the project office. Data for research purposes can be obtained via the WRC from ARC Infruitec-Nietvoorbij.

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Two dimensional energy interception and water balance model for hedgegrow tree crops

Annandale JG • Jovanovic NZ • Mpandeli NS • Lobit P • du Sautoy N

Two types of model, both predicting crop water requirements on a daily time step, were developed for hedgerow tree crops. These models were incorporated into the Soil Water Balance (SWB) model. The models are:

- A mechanistic two-dimensional energy interception and finite difference, Richards' equation based soil water balance model; and
- An FAO-based crop factor model, with a quasi 2-D cascading soil water balance model.

The two-dimensional model for hedgerow crops calculates the two-dimensional energy interception, based on solar and row orientation, tree size and shape as well as leaf area density. Inputs required to run the two-dimensional canopy interception model are: day of year, latitude, standard median, longitude, daily solar radiation, row width and orientation, canopy height and width, skirting height and width, extinction coefficient, absorptivity and leaf area density. For the two-dimensional soil water balance model, the input required included starting and planting dates, altitude, rainfall and irrigation water amounts, as well as maximum and minimum daily temperature. To run the FAO-type crop factor model, the required input included planting date, latitude, altitude, maximum and minimum daily air temperatures, FAO crop factors and duration of crop stages. The two-dimensional SWB model evaluation consisted of checking internal consistency and units used, comparison of model output with independent data sets of real life observations and sensitivity analysis. Inspection of the qualitative behaviour of the model and its implementation was done by checking whether the response of the model output to changing values of a parameter conforms to theoretical insights. There was good agreement between predicted and measured daily soil water deficit for water-stressed and non-stressed treatments. Field measurements indicated that in hedgerow plantations the whole area across the row must be borne in mind when assessing soil water content. The reason for this is the effect of irrigation distribution and rain interception by the canopy, the variation in radiation interception by the canopy across the row, the irradiance reaching the soil surface as the season progresses, the presence of a grass sod or bare soil in the inter-row region and the root density across the row. It was found that there are significant amounts of roots in the inter-row region and thus this portion of the rooting volume must not be ignored when assessing the water balance.

The contribution to crop water uptake from the inter-row volume of soil can be high, particularly under high atmospheric evaporative demand, and thus needs to be accounted for in irrigation management in order to maximise rainfall use efficiency.

Report Number: 945/1/02 **ISBN: 1 86845 869 5**

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