QUANTIFYING WATER USE AND WATER PRODUCTIVITY OF HIGH PERFORMING APPLE ORCHARDS OF DIFFERENT CANOPY SIZES IN WINTER RAINFALL AREAS OF SOUTH AFRICA

Sebinasi Dzikiti, Theresa Volschenk, Stephanie Midgley, Mark Gush, Nicolette Taylor, Elmi Lötze, Solomon Zirebwa, Zanele Ntshidi, Nompumelelo Mobe, Michael Schmeisser, Qamani Doko

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QUANTIFYING WATER USE AND WATER PRODUCTIVITY OF HIGH PERFORMING APPLE ORCHARDS OF DIFFERENT CANOPY SIZES

Report to the

WATER RESEARCH COMMISSION & HORTGRO SCIENCE

by

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EXECUTIVE SUMMARY

Motivation

The Deciduous Fruit Industry is a multi-billion Rand industry in South Africa with apples (*Malus domestica* Borkh.) accounting for about 30% of the area planted (Hortgro, 2016). High yielding apple orchards (> 100 t ha^{-1}) have become common in recent years as a result of improved plant material and orchard management practices. International literature has shown that high crop loads are associated with high water demands. However, no information currently exists on the water requirements of high yielding apple orchards in South Africa. There is a need to understand the water use of these orchards from planting until full-bearing age to improve irrigation scheduling and water allocation decision-making. Information is also needed on how the high crop loads affect fruit quality which influences the fruit selling price.

Most apples produced in South Africa are grown in the Western Cape Province - mainly in the Koue Bokkeveld (KBV) and the Elgin/ Grabouw/ Vyeboom/ Villiersdorp (EGVV) regions. There are smaller growing regions in the Eastern Cape, parts of the Free State, and Mpumalanga Provinces. During the 2015/16 growing season, the apple industry employed 27 526 workers who in turn supported 110 106 dependents (Hortgro, 2016). The industry is therefore an important source of employment despite not receiving government subsidies. The availability of adequate water is critical for the sustainability and growth of the country's fruit industry as all apples commercially produced in South Africa are grown under irrigation. It is also important to maintain the global competitiveness of the country since more than 40% of the fruit is exported, mainly to the United Kingdom (UK), Far East, Asia, and to the rest of the African continent.

Water supply in key apple producing regions is experiencing significant strain and the situation is expected to get worse in future as demand outstrips supply. Major drivers of increased water demand include increasing competition as a result of population growth, and climate change. For example, the population of the Cape Town Metro has been growing at a rate close to 1% per year in recent years. Consequently, the demand for water for household and industrial use has also been rising. According to the Western Cape Department of Environmental Affairs and Development Planning, expected future climate change projections for the region include: 1) higher average annual air temperatures, 2) higher maximum air temperatures, 3) more hot days and heat waves, 4) higher minimum temperatures, 5) fewer cold days and frost days, 6) reduced rainfall in the western parts of the Western Cape, and; 7) an increase in the frequency and severity of extreme events including droughts. The increased atmospheric evaporative demand will inevitably increase the water requirements of crops while the warm winters will render some areas unsuitable for apple production.

Accurate quantitative information on the water use of unstressed high performing apple orchards from planting to full-bearing is essential: 1) to improve irrigation scheduling, 2) for water allocation decision-making, 3) for water licensing, and; 4) for developing water saving strategies to cope with water shortages induced by droughts such as the one currently experienced in the Cape provinces.

Aims and objectives

General aim:
To determine the water use, yield and quality of selected high performing apple cultivars from planting to full-bearing in selected climatic zones and specific soils.

Specific objectives:

To measure unstressed apple orchard water use according to seasonal growth stages from planting to full-bearing.
To model the water balance of apple orchards according to seasonal growth stages from planting to full-bearing for future extrapolation to other apple cultivars and climatic zones.
To determine the water productivity in full-bearing orchards in terms of crop yield in relation to quality.

Methodology

The study was conducted in the KBV and EGVV production regions in the Western Cape. Both regions have a Mediterranean-type climate although their microclimates differ. KBV experiences cold winters with the long-term average minimum daily air temperatures for the coldest month (July) being 3 to 4 °C and occasional snowfalls. Summers are generally hot and dry with a mean maximum air temperature for the hottest month (February) reaching 28 to 29 °C. In contrast, EGVV experiences milder winters and summers as the weather is moderated by proximity to the Atlantic Ocean to the south west. Mean minimum daily temperatures in winter are between 8 and 9 °C while average maximum summer temperatures are between 25 and 26 °C.

Cultivars studied were Golden Delicious, which is most widely planted in South Africa occupying approx. 24% of the area under apples, and the blushed cultivar Cripps' Pink and its close relatives Cripps' Red and Rosy Glow. Both the Golden Delicious and the blushed cultivars are high yielding. The blushed cultivars were selected as these are high value late season cultivars with the highest growth potential. We hypothesized that the blushed cultivars used the greatest amount of water given that they maintain a high leaf area for longer compared to the other cultivars. The specific blushed cultivar variant used depended on the availability of suitable orchards in a particular growing region. However, as the blushed cultivar variants are all close relatives, no differences in eco-physiological responses and water use patterns were expected.

Data were collected over three growing seasons namely 2014/15, 2015/16 and 2016/17 (Table I). In 2014/15, data were collected from October to June in two full-bearing and two non-bearing orchards in KBV. The mature full-bearing orchards had a high effective canopy cover varying from 45 to 52% while the young non-bearing orchards had a low canopy cover between 14 and 26%. In the 2015/16 season, data were collected also in four orchards, comprising two full-bearing and two non-bearing orchards, but in the EGVV region. In the 2016/17 season measurements were taken in two orchards in each production region with medium canopy cover ranging from 30 to 44%. Soil types were predominantly sandy to sandy loam except for the full-bearing 'Cripps' Pink' at Radyn, non-bearing 'Golden Delicious' at Vyeboom and the 'Cripps' Pink' at Dennebos, all in EGVV. These orchards had dark red clayey loam soils with a high stone content.

All orchards were irrigated using the micro-sprinkler system. There was one micro-sprinkler per tree delivering between 30 and 35 litres of water per hour. Irrigation frequency ranged from two to three times per week with each event lasting for one to two hours early in the season. The irrigation frequency increased to daily or several times a day during the hot summer months in some orchards.

Three methods were used to quantify the orchard evapotranspiration (ET) to reduce uncertainties in the water use estimates. These included the open path eddy covariance method, which was deployed at selected window periods during the growing season due to equipment limitations. The second technique was the soil water balance approach which was used in two orchards each season, also due to equipment limitations. Thirdly, additional ET data were derived from the remote sensing "FruitLook" product. Interpolation of the eddy covariance ET to seasonal water use was done using a dual source ET model. We adopted and propose improvements to the Shuttleworth and Wallace model applied to apple orchards with varying canopy cover.

Table I. Summary of the study sites used in the KBV and EGVV production regions from 2014-2017. High, medium and low canopy cover denotes >45%, 30-44% and <30% vegetation cover, respectively.

Year	Region	Cultivar	Rootstock	Age (yr.)	Canopy cover	Area (ha)	Plant density (trees ha^{-1})	Farm name
2014/15	KBV	Golden Delicious	M793	22	High	11.1	1 667	Kromfontein
	KBV	Cripps' Pink	M793	9	High	6.0	1 667	Kromfontein
	KBV	Golden Delicious Reinders	M793	3	Low	3.2	1 667	Lindeshof
	KBV	Rosy Glow	MM109	4	Low	6.0	2 285	Paardekloof
2015/16	EGVV	Golden Delicious	M793	29	High	5.5	1 250	Southfield
	EGVV	Cripps' Pink	M793	12	High	5.2	1 667	Radyn
	EGVV	Golden Delicious	MM109	3	Low	6.0	1 250	Vyeboom
	EGVV	Cripps' Red	MM109	3	Low	5.0	1 250	Vyeboom
2016/17	KBV	Golden Delicious Reinders	M793	5	Medium	2.5	1 667	Lindeshof
	KBV	Cripps' Pink	M793	7	Medium	4.2	1 111	Esperanto
	EGVV	Golden Delicious Reinders	M7	5	Medium	5.5	1 250	Vyeboom
	EGVV	Cripps' Pink	MM109	6	Medium	2.8	1 250	Dennebos

Additional data collected include the orchard leaf area index (LAI – m^2 of leaf area per m^2 of ground area), volumetric soil water content at various depths and wet/dry spots in some orchards, soil properties, orchard floor evaporation, tree water status, leaf stomatal conductance and gas exchange rates, yield and fruit quality.

Using the data collected on all eight productive orchards (medium and high canopy cover, both cultivars and both regions) for seasonal water use and yield, we calculated the water use efficiency, defined as kg fruit per m^3 of water used. This was done based on both measured tree transpiration and modelled orchard evapotranspiration. The gross orchard value from packout and price data (thus integrating all quality parameters) were calculated and combined with seasonal water use to estimate the water productivity of all the orchards. This represents the commercial value of the harvest (in Rand) per m^3 of water used.

Results and discussion

In the 2014/15 season, the Koue Bokkeveld sites received ~ 240 mm of rainfall between 1 October 2014 and 30 June 2015. The total short grass reference evapotranspiration (ET_o) over the same period was ~ 1 260 mm which was more than five times higher than the rainfall. The maximum air temperature for the season reached ~ 37 °C on 3 March 2015 while the daily ET_o peaked at ~ 8.8 mm. Climatic conditions in EGVV during the 2015/16 season were somewhat milder than those measured the previous year in KBV. Maximum air temperature in EGVV was 39.7 °C measured on 30 December 2015 with the maximum daily ET_o of 7.3 mm. The seasonal total rainfall (247 mm) was similar to that received in KBV the preceding year although the ET_o was significantly lower at 1 065 mm. Weather conditions during the 2016/17 season followed similar trends to the previous years although the rainfall was significantly lower due to the prevailing drought.

The solar radiation and water vapour pressure deficit of the air (VPD) were the main climatic factors driving water use of both the Golden Delicious and the blushed cultivars. There was a strong linear relationship (R^2>0.70) between the daily solar radiation and the daily total transpiration of the unstressed trees. However, the relationship between the transpiration and VPD was non-linear with peak transpiration reached at VPDs between 2.0 and 3.0 kPa. Seasonal total transpiration of the trees was better related to canopy cover than to crop load as shown in Table II. Orchards with high yields e.g. the full-bearing 'Cripps' Pink' in KBV and EGVV did not necessarily have the highest transpiration rates. Variations in tree transpiration rates in full-bearing orchards were a result of differences in canopy size. 'Cripps' Pink' orchards, for example, had relatively small and open canopies due to pruning and use of shoot growth retardants such as Regalis® (a formulation of Prohexadione-Ca). Open canopies expose the fruit to solar radiation for anthocyanin synthesis to occur and to promote the development of the red fruit colour. On the other hand, full-bearing 'Golden Delicious' orchards had larger canopies since these are managed to provide more shade to fruit which are susceptible to sunburn.

The maximum unstressed seasonal transpiration of mature high yielding 'Cripps' Pink' and 'Golden Delicious' orchards was in the range 6 000 to 8 000 m^3 ha^{-1} depending on canopy cover. The maximum orchard ET varied from 9 000 to just over 10 000 m^3 ha^{-1} $season^{-1}$. In young orchards seasonal total transpiration ranged from 1 330 m^3 ha^{-1} in the low-density plantings in EGVV to 2 710 m^3 ha^{-1} in the high-density orchards in KBV. Seasonal ET was very high (> 5 000 m^3 ha^{-1}) in all the young orchards. This was due to the large exposed orchard floor area which increased the soil and cover crop evaporation fluxes.

The long growing season of 'Cripps' Pink' did not translate to higher seasonal water use compared to the shorter growing season of 'Golden Delicious'. This was because the winter (May and June) transpiration contributed less than 12% of the seasonal total transpiration in these orchards. Tree transpiration contributed between 65 and 82% to the total orchard ET in full-bearing orchards - depending on canopy cover. In young orchards, orchard floor evaporation accounted for more than 60% of ET, which was clearly excessive.

Leaf level measurements of stomatal conductance and gas exchange (photosynthesis and transpiration rates), together with measurements of stem water potential, corroborated the results obtained using sap flow techniques and measurements of soil water content. In some cases, periods of water stress were identified, but in general the data confirmed that the orchards were not water stressed. All orchards (except for some periods in EGVV where afternoon cloud develops) showed the characteristic decline in stomatal conductance from morning to afternoon in response to increasing atmospheric demand (vapour pressure deficit between the air and leaf tissues, VPD_{leaf}), increasing water loss and reductions in stem water potential. This generally stabilised transpiration or reduced further increases in transpiration beyond a VPD_{leaf} of around 3 kPa.

Leaf level photosynthetic water use efficiency is not always optimised in apple trees. Under well-watered and atmospherically milder conditions, carbon assimilation is prioritised to meet the high demand for assimilates in bearing trees. There were indications in EGVV that 'Cripps' Pink' maintained higher gas exchange rates later in the season than 'Golden Delicious' in response to the high assimilate (sink) demands of the fruit crop which is only harvested in April. Across all orchards, stomatal conductance and transpiration rates remained higher in high canopy cover (full-bearing) trees with increasing VPD_{leaf} compared to medium and low canopy cover trees, suggesting that higher water use in these orchards is not only due to the high total leaf area, but also due to the high sink demand of the large fruit crop. Furthermore, analysis of stomatal conductance and stem water potential revealed a likelihood that high canopy cover trees with many fruit have an internal water buffer which is used for the higher rate of transpiration during the day, allowing for higher conductances and thus higher photosynthetic rates. Low canopy cover non-bearing trees with a much lower demand for assimilates and a limited water buffer kept conductances lower even under mild evaporative conditions, to reduce transpired water losses and prevent stronger reductions in stem water potential. Lastly, it was found that under the more stressful prevailing atmospheric conditions (higher evaporative demand) in KBV compared to EGVV, similar stem water potentials were maintained, suggesting some form of acclimation of xylem hydraulic characteristics to prevent damage to the xylem.

There were no clear effects of the high crop load on most fruit quality attributes. Only the full-bearing 'Golden Delicious' orchards in both production regions had smaller fruit size which affected packout of export quality fruit. The water use efficiency varied with production region and with cultivar given the different microclimates and canopy management practices for the Cripps' Pink and Golden Delicious cultivars. The key driver of the water use efficiency of the trees was the leaf area which determined transpiration.

Table II. Summary of the seasonal (Oct-Jun) water use rates of apple orchards from planting to full-bearing in the KBV and EGVV production regions from the 2014/15 to 2016/17 season. T – represents orchard level transpiration, and ET represents the orchard evapotranspiration. Transpiration data was derived from sap flow measurements while ET was simulated from the Shuttleworth and Wallace model. Water productivity is based on measured transpiration.

Year	Region	Cultivar	T (mm)	ET (mm)	Canopy cover	Peak LAI	Yield (t ha^{-1})	Water Productivity (R m^{-3})	Farm name
2014/15	KBV	Golden Delicious	813	1086	High	3.6	74	46.6	Kromfontein
	KBV	Cripps' Pink	589	974	High	2.6	110	92.7	Kromfontein
	KBV	Golden Delicious Reinders	199	481	Low	1.0	-		Lindeshof
	KBV	Rosy Glow	271	562	Low	1.3	-		Paardekloof
2015/16	EGVV	Golden Delicious	757	1110	High	3.3	100	49.4	Southfield
	EGVV	Cripps' Pink	631	902	High	2.8	109	73.4	Radyn
	EGVV	Golden Delicious	155	501	Low	0.7	-		Vyeboom
	EGVV	Cripps' Red	133	500	Low	0.8	-		Vyeboom
2016/17	KBV	Golden Delicious Reinders	420	596	Medium	1.5	18	20.7	Lindeshof
	KBV	Cripps' Pink	547	871	Medium	2.0	61	53.5	Esperanto
	EGVV	Golden Delicious Reinders	249	534	Medium	1.3	35	48.7	Vyeboom
	EGVV	Cripps' Pink	471	872	Medium	1.8	58	66.2	Dennebos

Lower transpiration from smaller canopies of 'Cripps' Pink' was compensated for by higher evaporation from the orchard floor, compared to these values in 'Golden Delicious', so that water use efficiency based on modelled ET was similar between the cultivars. The length of the growing season was not important since the canopies continued to be highly active until the autumn in both cultivars. Water use efficiency was greater under higher yields.

Lastly, the water productivity (Rand of gross income per cubic metre of water consumed) was higher for ‘Cripps’ Pink’ than for ‘Golden Delicious’ (Table II). The primary reason for this is that export-quality ‘Cripps’ Pink’ (Pink Lady®) fetches a higher price than export-quality ‘Golden Delicious’ and this has a significant influence on orchard gross value. A secondary reason was that the two full-bearing ‘Golden Delicious’ orchards produced a high proportion of small fruit of lower value. The medium canopy cover ‘Golden Delicious Reinders’ orchard in KBV had a lower water productivity than expected due to losses ascribed to sunburn and bruising. Generally, water productivity was found to be higher under higher yields, but in ‘Golden Delicious’ it is likely that a maximum water productivity is reached between 75 and 100 t ha^{-1}, where after further increases are constrained by fruit size issues.

Conclusions

This study showed that high apple yields can be produced sustainably without using excessive amounts of water provided the canopy is managed optimally. Current ‘Cripps’ Pink’ canopy management practices promote the development of the red colour on the fruit and also have water saving benefits. High crop loads in this study did not necessarily have a negative effect on most fruit quality attributes in the high yielding orchards. In the high yielding ‘Golden Delicious’ orchards only fruit size was affected, and management of crop load is essential in this cultivar to produce export quality fruit and maximise water productivity. Length of the growing season of different cultivars appeared not to influence the seasonal total water use. Thus, our hypothesis relating to water use and season length must be rejected.

Recommendations

Based on the results of this study, the following recommendations can be made:

- Exceptionally high yielding apple orchards can be sustainably farmed in the Western Cape, but effective canopy management is essential to avoid excessive water use;
- Crop load should be carefully managed in the Golden Delicious cultivar as high fruit numbers reduce fruit size and hence the packout of export quality fruit;

- Water use efficiency and water productivity increase as orchards mature and achieve higher yields. However, in “Golden Delicious’ there appears to be a ceiling to water productivity relating to small fruit size at very high yield;
- Orchard floor evaporative losses in young micro-sprinkler irrigated orchards is currently very high. It is therefore important to implement water saving techniques e.g. accurate irrigation scheduling, mulching, drip irrigation and shade-nets to reduce water wastage.
- Cover crop species with conservative water use characteristics yet providing other desired benefits should be identified and prioritized although further research is needed;
- The dual source Shuttleworth and Wallace model has the potential to accurately estimate the water use of apple orchards with varying canopy cover. However, further validation and improvement of the model are still necessary. While the model accurately predicts the transpiration component, uncertainties are fairly high for the orchard floor fluxes. Expanding the model to a three-source model wherein the cover crop transpiration and soil evaporation components are modelled separately may reduce the uncertainties, and;
- Apple growers with limited or unreliable access to water resources should consider focusing on high value cultivars for new plantings, and gradually remove lower value cultivars. This would gradually increase the farm level water productivity and so maximise profitability for every unit of water that is available for irrigation.
- The use of shade netting over trees on more dwarfing rootstocks which are managed for smaller canopy size, could provide further opportunities for water savings and should be investigated.

Extent to which contract objectives have been met

The contract objectives have, to a large extent, been met and in some instances exceeded. Comprehensive data were collected on the water use of the Golden Delicious and selected blushed apple cultivars in the two prime apple growing regions namely KBV and EGVV. Data were collected in orchards with low, medium and high canopy cover in the two growing regions. The study generated useful information on how orchard water use varies from planting until full-bearing. Valuable data were also collected in bearing orchards on the impact of the crop load on fruit quality and the water productivity. The analysis specifically distinguishes between the water use efficiency and the water productivity which is essential to understand how the water use is related to the economic returns.

However, challenges were faced in identifying suitable ‘Cripps’ Pink’ orchards as stipulated in the project terms of reference. As a result, we used alternative blushed cultivars i.e. Cripps’ Red and Rosy Glow. These also have a long growing season and this decision was taken in consultation with the WRC and Hortgro Science. A suitable model for estimating apple orchard water use was adopted, improved and applied in this study. The model can be used to extrapolate the results of this study to other apple growing regions. Other outputs from the study include:

- One scientific article under review by the Agricultural Water Management journal.
- Three other papers are at various stages of completion, mostly by the PhD students;
- Four popular articles in the SA Fruit journal;
- Three conference proceedings articles, and;
- At least nine presentations at local and international conferences and symposia.

The project had an ambitious capacity building program comprising three PhD and two MSc students. One MSc has been completed and the other studies are still ongoing. Additional funding has been secured to ensure that the candidates complete their studies from: 1) Hortgro Science, 2) DST-NRF Professional Development Program, 3) NRF Thuthuka, and; 4) the CSIR’s Young Researcher Establishment Fund.

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Roman Symbols

A	net photosynthesis (μmol m^{-2} s^{-1})
A_e	available energy (W m^{-2})
A_s	available energy at the orchard surface (W m^{-2})
B	Bowen ratio (-)
C_p	specific heat capacity of air at constant pressure (J kg^{-1} K^{-1})
C_c	a dimensionless canopy resistance coefficient
C_s	a dimensionless soil surface resistance coefficient
D	vapour pressure deficit of the air at the reference height (kPa)
E	leaf level transpiration (mmol m^{-2} s^{-1})
E_s	soil evaporation (mm d^{-1})
ET	actual evapotranspiration (mm d^{-1})
$ET_{\_ec}$	evapotranspiration from the eddy covariance method (mm d^{-1})
$ET_{\_FL}$	evapotranspiration from the FruitLook product (mm d^{-1})
ET_o	short grass reference evapotranspiration (mm d^{-1})
E_{dz}	evaporation from the dry zone (mm d^{-1})
E_w	saturation vapour pressure at soil surface temperature (kPa)
E_{wz}	evaporation from the wet zone (mm d^{-1})
G	soil heat flux (W m^{-2})
g_{sT}	stomatal conductance (m s^{-1})
g_c	canopy conductance (m s^{-1})
g_{smax}	maximum stomatal conductance (m s^{-1})
H	sensible heat flux (W m^{-2})
k	extinction coefficient for radiation (-)
K_c	crop coefficient (-)
K_{cb}	basal crop coefficient (-)
K_e	soil evaporation coefficient (-)
K_r	transpiration reduction coefficient (-)
k_r	parameter for the solar radiation stress factor (-)
K_s	evaporation reduction coefficient (-)
k_{vpd}	parameter for the vapour pressure deficit stress factor (-)
P_b	soil bulk density (kg m^{-3})
R	solar irradiance (W m^{-2})
r^a_a	aerodynamic resistance between canopy and reference level (s m^{-1})

r_a^c	boundary layer resistance of canopy (s m^{-1})
r_a^s	aerodynamic resistance between the soil and the canopy (s m^{-1})
r_b	leaf boundary layer resistance (s m^{-1})
RH_{max}	maximum relative humidity (%)
RH_{min}	minimum relative humidity (%)
r_s^c	canopy resistance (s m^{-1})
r_s^s	soil surface resistance (s m^{-1})
r_{ST}	stomatal resistance (s m^{-1})
r_{STmin}	minimum stomatal resistance (s m^{-1})
R_n	net radiation (W m^{-2})
R_{ns}	net radiation at soil surface (W m^{-2})
S_d	downward solar irradiance (W m^{-2})
T	orchard level transpiration (mm d^{-1})
T_a	air temperature (°C)
T_{avg}	average air temperature (°C)
TAW	Total Available Water (m^3 m^{-3})
T_c	cover crop transpiration (mm d^{-1})
T_{leaf}	leaf surface temperature (°C)
T_{min}	minimum air temperature (°C)
T_{max}	maximum air temperature (°C)
T_{opt}	optimum air temperature for the growth of apple trees (°C)
T_x	air temperature at reference height within the canopy (°C)
VPD	vapour pressure deficit of the air at screen height (kPa)
VPD_{leaf}	leaf to air vapour pressure deficit (kPa)
U	sap flux density (cm^3 cm^{-2} d^{-1})
Y_a	crop yield (kg)

Greek Symbols

Δ	slope of the saturation vapour pressure-temperature curve (kPa K^{-1})
λ	latent heat of vaporization (J kg^{-1})
α	surface albedo (-)
θ	volumetric soil water content (m^3 m^{-3})
ρ	density of air (kg m^{-3})
γ	psychrometric constant (kPa K^{-1})
δ	Stefan-Boltmann constant (W m^{-2} K^{-4})
ε_a	emissivity of the air (-)

ε_s	emissivity of the surface (-)

Abbreviations

ARC	Agricultural Research Council
AWS	Automatic weather station
CSIR	Council for Scientific and Industrial Research
CWR	Crop Water Requirement
CWSI	Crop Water Stress Index
DG	Daily Growth
DM	Dry Mass
EGVV	Elgin/Grabouw/Villiersdorp/Vyeboom
FAO56	Food and Agriculture Organization, paper no 56
FBGD	Full-bearing ‘Golden Delicious’
FBCP	Full-bearing ‘Cripps’ Pink’
FC	Volumetric water content at field capacity
HPV	Heat Pulse Velocity
HRM	Heat Ratio Method
IRGA	Infrared Gas Analyser
LAI	Leaf Area Index
MDS	Maximum Daily Shrinkage (stem/fruit)
IBGR	Intermediate Bearing ‘Golden Delicious/Reinders’
IBCP	Intermediate Bearing ‘Cripps’ Pink’
KBV	Koue Bokkeveld
NBGD	Non-Bearing ‘Golden Delicious’
NBCR	Non-Bearing ‘Cripps’ Red’
NBRG	Non-Bearing ‘Rosy Glow’
PAR	Photosynthetically Active Radiation
RESP	Respiration
Peff	Effective precipitation
PWP	Permanent Wilting Point
SAI	Sapwood Area Index
SW	Shuttleworth and Wallace
SWB	Soil Water Balance
WUEi	Leaf Water Use Efficiency
WUE	Orchard Water Use Efficiency (kg of fruit per m^3 of water)
WP	Water Productivity

CHAPTER 1

INTRODUCTION

1.1 Background

South Africa is ranked as the seventh largest exporter of fresh apples (*Malus domestica* Borkh.) globally. It is second only to Chile in the Southern hemisphere. The Deciduous Fruit Industry in South Africa is a multi-billion Rand industry with apples accounting for about 30% of the area planted (Hortgro, 2016). Orchards that produce more than 100 t ha^{-1} of apples have now become the norm in recent years. This is a result of improved plant material and orchard management practices. International literature has shown that high crop loads are associated with high water demands (Naor et al., 1997, Naschitz and Naor, 2005, Naor, 2006). However, no information currently exists on the water requirements of high yielding apple orchards in South Africa. There is a need to understand the water use patterns of these orchards from planting until they reach full-bearing age given that South Africa is a water scarce country. Information is also needed on how the high crop loads affect fruit quality which influences the fruit selling price.

Most apples produced in South Africa are grown in the Western Cape Province mainly in the Koue Bokkeveld (KBV) and the Elgin/ Grabouw/ Vyeboom/ Villiersdorp (EGVV) regions. There are smaller growing regions in the Eastern Cape, parts of the Free State, and Mpumalanga Provinces. During the 2015/16 growing season, the apple industry employed about 27 526 workers who in turn supported 110 106 dependents (Hortgro, 2016). The industry is thus an important source of employment. All apples commercially produced in South Africa are grown under irrigation. The availability of adequate water is therefore critical for the sustainability and growth of the country's fruit industry. It is also important to maintain the global competitiveness of the country since more than 40% of the fruit is exported, mainly to the UK, Far East, Asia, and to the rest of the African continent.

Water supply in key apple producing regions is experiencing significant strain and the situation is expected to get worse in future as demand outstrips supply. Major drivers of increased water demand include increasing competition as a result of population growth, and climate change. For example, the population of the Cape Town Metro has been growing at a rate close to 1% per year in recent years. Consequently, the demand for water for household and industrial use has also been rising. According to the Western Cape Department of Environmental Affairs, expected future climate change projections for the region include: 1) higher average annual temperatures, 2) higher maximum temperatures, 3) more hot days and heat waves, 4) higher minimum temperatures, 5) fewer cold days and frost days, 6) reduced rainfall in the western parts of the Western Cape, and; 7) an increase in the frequency and severity of extreme events including droughts. The increased atmospheric evaporative demand will inevitably raise the water requirements of crops while the warm winters will render some areas not suitable for apple production (Midgley and Lötze, 2011).

Research questions for this study are:

- What is the maximum unstressed water use of high yielding apple orchards in South Africa?
- How does orchard water use vary from planting until the trees reach full-bearing age?
- How is the water use partitioned into tree transpiration and orchard floor evaporation for trees with different canopy cover?
- How do the high crop loads affect fruit quality, water use efficiency and water productivity?
- What are the key drivers of water use and productivity in the high yielding orchards?
- Can water use by these orchards be accurately modelled in order to scale up the study results to other apple growing regions?

Accurate quantitative information on the water use of unstressed apple orchards from planting to full-bearing is essential: 1) to improve irrigation scheduling, 2) water allocation decision-making, 3) for water licensing, and; 4) for developing water saving strategies to cope with water shortages induced by droughts such as the one currently gripping the Cape Provinces.

1.2 Rationale

Improved plant material and orchard management practices have led to an increase in the average yield of apple orchards in recent years. Many orchards now consistently produce in excess of 100 t ha^{-1} while a few others exceed 150 t ha^{-1} in some years. High yields of good quality fruit are essential for the survival of the fruit industry given the rising cost of inputs, fuel, electricity, labour and water. However, published literature shows that large crop loads are associated with high photosynthesis rates because of the increased demand for carbohydrates. This means that the average canopy conductance has to increase likely raising the transpiration levels. In a water scarce country like South Africa, clearly there is a need for accurate quantitative information on the maximum unstressed water use of the exceptionally high yielding apple orchards in relation to water availability. Within the deciduous fruit industry there is also limited knowledge on water use of young apple orchards up to full-bearing age. This leads to inaccurate irrigation decisions resulting in the wastage of water.

This four-year study, which was initiated and funded by the Water Research Commission and the South African Apples and Pears Producers Association, seeks to close these important information gaps. Given the increasing competition for water between different sectors of the country's economy, a growing population, and the frequent droughts related to climate change, growers will have to produce more fruit with less water in future. Thus, improving on-farm water management is essential for the sustainability and growth of the fruit industry in South Africa. Focus of this study was on the Golden Delicious and the Cripps' Pink cultivars mostly on the M793 rootstock which is the industry standard. Golden Delicious is the major mid-season cultivar accounting for about 24% of the planted area. Cripps' Pink, on the other hand, is a late season highest value cultivar that is experiencing growth potential. However, alternative cultivars and rootstocks with similar attributes were considered in situations where appropriate orchards could not be found. The study was conducted in two prime apple growing regions namely the Koue Bokkeveld (KBV) and the Elgin/Grabouw/Vyeboom/Villiersdorp (EGVV) regions. Although both regions have the Mediterranean-type climate, they have different microclimates. Soil types also vary considerably within the regions and the selection of study orchards took this into account. Outputs from this research will inform strategic decisions by the deciduous fruit industry and relevant government departments.

1.3 Aims and objectives

The general aim of this research was to determine the water use, yield and quality of selected apple cultivars from planting to full-bearing in selected South African climatic zones and specific soils.

Specific objectives are:

- To measure unstressed apple orchard water use according to seasonal growth stages from planting to full-bearing.
- To model the water balance of apple orchards according to seasonal growth stages from planting to full-bearing for future extrapolation to other apple cultivars and climatic zones.
- To determine the water productivity in full-bearing orchards in terms of crop yield in relation to quality.

1.4 Approach

This project was executed by a multi-disciplinary team of researchers with expertise in agricultural meteorology, soil and irrigation science, ecophysiology, horticultural science, and forest hydrology. According to the project terms of reference, the first step in the execution of the project was a detailed knowledge review. The aim of the review was to gather information on the current state of knowledge and to highlight knowledge gaps on the water use, yield dynamics, and water productivity of apple orchards. The review covered both local and international literature. The project terms of reference also specified: 1) that the study was to be done in the KBV and EGVV production regions in the Western Cape, and; 2) that the Golden Delicious and Cripps' Pink apple cultivars be studied. The next step was to develop a detailed plan to produce the envisaged outcomes.

To generate information on the water use and productivity of orchards with low, medium and high canopy cover, the data collection phase was divided into three seasons. The first season (2014/15) investigated two full-bearing and two non-bearing orchards in KBV with high and low canopy cover, respectively. The second season (2015/16) studied similar orchards, but in EGVV. Research in the final season (2016/17) was done on trees with medium canopy cover, but on two orchards in each production region. Next the research team developed an objective criterion to identify suitable study sites. The criteria took into account attributes such as cultivar, rootstock, yield history (for mature orchards), size of the orchard (for micrometeorological measurements), canopy cover (or orchard age group), soils, security of equipment, and cooperation from the farmer. Weights were assigned to each attribute and a score was produced and the highest scoring orchards were selected.

Tree transpiration was measured using sap flow gauges and the Granier probes were calibrated using weighing lysimeters using potted trees in a greenhouse. The heat ratio method could not be calibrated due to lack of potted trees with a suitable stem size. However, other studies e.g. Steppe et al. (2010) provide information on the accuracy of this method. Tree transpiration data was collected at hourly intervals throughout the growing seasons. Orchard evapotranspiration (ET) was quantified using the open path eddy covariance, soil water balance and using the remote sensing based FruitLook product. Uncertainties in the water use measurements with these methods were discussed in detail by, among others, Allen et al. (2011). However, the eddy covariance measurements were only taken during specific window periods due to equipment limitations. Similarly, the soil water balance method could not be implemented on all the orchards for the same reason. Consequently, we adopted and improved the dual-source Shuttleworth and Wallace (1985) model to scale up the ET data to seasonal water use. Calibration of the model was done using data from selected orchards in KBV and validated using data from orchards in EGVV.

To investigate the key drivers of water use and productivity in the various orchards, additional data was collected. This included site weather conditions, measured using automatic weather stations. These measured the basic weather elements at hourly and daily intervals throughout each season. Soil water content in the root zone was also measured at hourly intervals using calibrated soil moisture sensors. The measurement details varied between orchards due to equipment limitations and also depending on soil type. Growth measurements included the orchard leaf area index, fruit and root growth rates. Eco-physiological data such as gas exchange (CO_2/H_2O) and tree water status was measured at selected intervals to gain insights on how environmental factors affected tree response. Yield quality and quantity was determined at the end of each season while fruit price data was collected from the growers and various pack houses. The water use, yield quality and quantity and fruit price data were combined to derive the water productivity of the high yielding orchards.

CHAPTER 2

KNOWLEDGE REVIEW

2.1 Climate, soils and geographical distribution of apple production

Generally, apple cultivation requires climates with warm days, cold nights and high radiation levels. These conditions are met to various extents in the key apple producing regions of South Africa. Sufficient chill units (cumulative number of hours below a specific temperature threshold) during the winter rest period, typically ~ 1 000-1 600 °C day, are crucial for the enzymatic changes needed to stimulate bud break. The exact number of chill units depends on cultivar and various models exist for calculating the chill units (Lötze and Bergh, 2012). Besides the KBV region where winter chill units are theoretically sufficient (~ 1 300 °C day), inadequate chill units (Table 2.1) are a significant problem in the warmer production areas of the country (Cook and Strydom, 2000, Lötze and Bergh, 2012) Consequently growers rely on rest breaking agents such as Dormex, DNOC winter oil, other minerals and combinations thereof to promote the bursting of adequate numbers of buds (Cook and Strydom, 2000).

Table 2.1 Long term averages of accumulated chill units for major apple growing regions of South Africa (Cook and Strydom, 2000)

Region	Accumulated Richardson chill units (°C day)				
	May	June	July	August	Total
Western Cape					
Koue Bokkeveld	202	356	389	364	1311
Elgin	48	183	274	240	745
Langkloof	8	179	226	203	616
Vyeboom	-23	149	238	218	346
Piketberg	-166	69	169	131	203
Eastern Free State					
Bethlehem	115	214	203	130	662

Apple trees can grow in a wide range of soils from medium textured clays to gravelly sands. However, poor soils will produce poor crop. Preferred soil types are fertile sandy and loam soils having a pH in the range 5.5-6.5. Soils should be free from hard substrata and well drained. In most orchards the trees are planted on ridges to facilitate drainage. Poor aeration due to water logging increases the incidence of crown rot (*Phytophtora cactorum*), while too low/ high pH will affect the availability of nutrients to the trees. Soils in the major apple producing areas of South Africa are generally of a poor quality and lack uniformity (Cook and Strydom, 2000).

Table 2.2 Area planted to apple trees in different parts of South Africa (Hortgro, Tree Census, 2016).

District	Number of Trees	Area (ha)
[1]Ceres	10 136 176	7 331
[2]Groenland	8 365 454	6 303
Langkloof East	4 233 469	4 025
[2]Villiersdorp / Vyeboom	4 584 231	3 906
[2]Langkloof West	650 316	546
Free State	839 684	561
Southern Cape	631 171	426
Piketberg	479 092	342
Klein Karoo	255 104	265
Mpumalanga	263 872	187
Somerset West	391 952	179
Worcester	71 877	41
Wolseley / Tulbagh	52 617	39
Northern Province	20 595	21
Eastern Cape	3 739	15
Stellenbosch	20 869	15
Paarl	10 777	9
Franschhoek	3 036	2
North West	528	1
TOTAL	**31 014 923**	**24 212**

[1] KBV
[2] EGVV

Orchard management practices, e.g. tree spacing and vigour management, are therefore adopted to maximise production, with an increasing tendency towards high density plantings. South Africa's main apple producing areas are in KBV near Ceres, in Groenland (EGVV), all in the Western Cape and in the Langkloof Valley of the Eastern Cape. Smaller production areas are found along the Orange River and in the Free State, Mpumalanga and Gauteng (Table 2.2). The Western Cape accounts for more than 75% of all the apples produced in South Africa. The total area planted to apples in 2016 was about 24 212 ha with about 21 565 ha (or 89%) of the planted area found in the Eastern and Western Cape Provinces (Table 2.2). Ceres, Groenland, Langkloof and Villiersdorp/Vyeboom accounted for 30%, 26%, 17% and 16%, respectively, of the planted area. The total planted area in 2016 was about 8% larger than in 2013 representing about 2% annual growth.

2.2 Apple cultivars, rootstocks and production trends

The main apple cultivars planted in South Africa are 'Golden Delicious', 'Granny Smith', 'Royal Gala'/'Gala', 'Topred'/'Starking' and 'Cripps' Pink' (Fig. 1). In 2016 'Golden Delicious' occupied the largest area accounting for 24% of the total planted area, followed by 'Granny Smith' and 'Royal Gala'/ 'Gala' both at 17%, 'Topred' at 12% and 'Cripps' Pink' at 10% (Fig. 2.1). Between 2011 and 2016, the area planted to 'Golden Delicious' increased by about 8% while 'Granny Smith' decreased by about 11% over the same period. The area planted to 'Royal Gala' and 'Cripps' Pink' increased by 22% and 16%, respectively, while Topred decreased by about 3%. Although the area under 'Cripps' Pink' is currently relatively small, this cultivar has, based on the trends shown in the Hortgro tree census (2016), has a huge market potential.

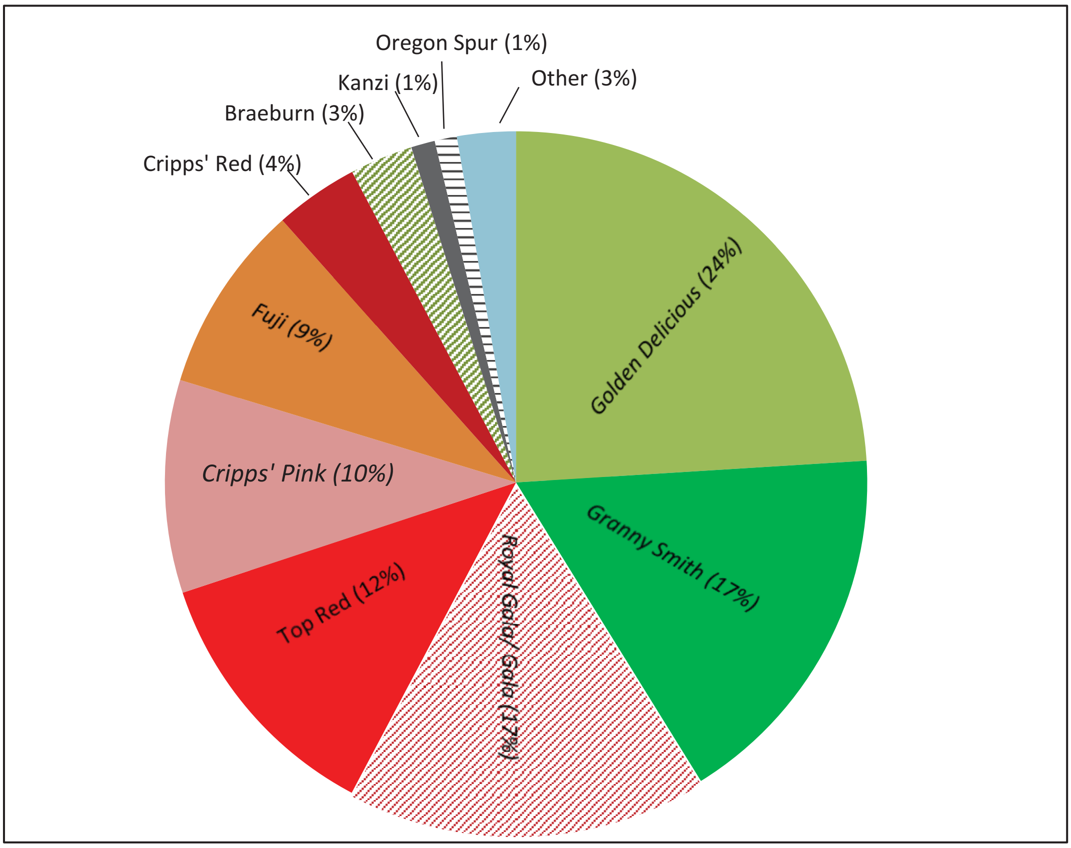


Fig. 2.1 Area planted to different cultivars in South Africa as a percentage of the total area under apple cultivation in 2016 (Hortgro, 2016).

Besides the ‘Cripps’ Red’ cultivar which is harvested in late April to early May, ‘Cripps’ Pink’, being harvested in mid to late April, has the second longest growing season of all the cultivars. The total area planted, as well as the seasonal water requirements per cultivar may impact the water requirements. This study intends to quantify the water use by ‘Golden Delicious’ (most popular cultivar, largest planted area) and ‘Cripps’ Pink’ (long growing season, strong market potential) apple trees under different microclimatic conditions in the major production regions in the winter rainfall area.

Modern apple orchard trees comprise two different genetic components i.e. a scion budded onto a rootstock. Figure 2.1 shows the major scions used in South African apple orchards. While several hundreds of rootstocks have been developed over the years, Table 2.3 lists some of the most commonly used ones in South Africa and their characteristics. Scions are selected for the quality and quantity of their fruit. Rootstocks on the other hand are selected for their ability to grow strong, persistent root systems and they are often characterized as “vigorous” or “dwarfing” depending on the vigour of the scion that grows on them (Cohen and Naor, 2002). Rootstocks also influence crop yields and the time to bearing of newly planted orchards with precocious rootstocks leading to early yields. Increasingly, selection is for precocious and productive dwarfing rootstocks. This study focused on the ‘Golden Delicious’ and selected red, blushed or bi-coloured cultivars budded preferably on the M793 rootstock which is high yielding and is compatible with a range of cultivars and is able to grow in a range of soil types. However, alternative rootstocks with similar attributes were also considered in situations where identifying suitable sites was difficult.

The age distribution of South African apple orchards for 2016 season are shown in Table 2.4 according to the Hortgro tree census. For sustainable and consistent supply of fruit to the markets, the replacement stock/ non-bearing orchards (0-3 years) should be kept at 10% or higher (DAFF, 2011). In 2016, this was down to about 8% which represents a 3% decline from the 2013 values. Older orchards (25 years and above) covered approximately 34% of the planted area compared to 33% in 2013. Young non-bearing orchards will contribute less to the total water use of apple plantings since they not only represent a lower percentage of the planted area, but they also have a smaller leaf area for transpiration.

Table 2.3 Common rootstocks used in South African apple orchards and their characteristics (StarGrow-Africa, 2013).

Name	Characteristics
MM109	Vigour: 100 - 110%. Wide adaptability. Low to medium potential soils and warmer areas. Recommended for spur type - poor soils and replant sites.
M25	Vigour: 80-100%. Very precocious and high production. Low to medium potential soils. Good tree structure for light penetration. Recommended for medium to poor soils and replant sites. Can get collar rot in poorly drained soils. Collar rot is controllable with chemical treatment.
M793	Vigour: 80-90%. High production. Wide adaptability. Recommended for a wide range of soils and cultivars.
MM106	Vigour: 60-70%. Very precocious and high production. Medium to high potential soils. Produces flat crotch angles. Give good fruit size. Can get collar rot in poorly drained soils. Collar rot is controllable with chemical treatment. But not common in RSA.
M7	Vigour: 60%. Precocious and high production. Wide adaptability. Not for spur types. Resistant to collar rot. Produces flat crotch angles.
M26	Vigour: 40-50%. Precocious and high production. High potential soils and colder climates. Produces burknots. Sunburn can be a problem in weak growing conditions. Mainly found in the highveld.
M9	Vigour: 30%. Very precocious and high production. High potential soils - colder climates. Produces flat crotch angles and large fruit. The smaller canopy leads to more fruit exposed to the sun and hence susceptible to sunburn.

Table 2.4 Distribution of orchard age groups in hectares (Hortgro, 2016).

Cultivar	0 - 3 yr.	4 - 10 yr.	11 - 15 yr.	16 - 25 yr.	25+ yr.
Golden Delicious	361	1 222	349	1 186	2 696
Granny Smith	189	436	195	601	2 733
Royal Gala / Gala	349	1 102	548	1 363	650
Topred / Starking	109	603	199	325	1 711
Cripps' Pink	188	765	162	1 232	26
Fuji	183	1 057	338	488	40
Braeburn	8	184	63	337	113
Cripps' Red	391	132	191	207	13
Oregon Spur	1	0	0	127	118
Kanzi	59	206	1	0	0
Other	163	202	89	129	71
TOTAL	**2 002**	**5 909**	**2 135**	**5 994**	**8 172**
% OF TOTAL AREA	**8%**	**24%**	**9%**	**25%**	**34%**

According to preliminary data, total production of apples peaked in 2015 at 924 162 tons while the 2016 season experienced a marginal drop to around 902 129 tons (Hortgro, 2016). In 2016, the bulk of the fruit (44%) was destined for export as fresh fruit, whereas 26%, 30% and 0.0% was for domestic consumption, processing and drying, respectively.

Previous production trends show that the export and processing markets have been increasing for the past few years while the volumes sold in the local markets have been declining (DAFF, 2011, Hortgro, 2016). Major export markets for South Africa's apples in 2016 are the Far East and Asia and Africa, which accounted for 29% of the total fresh fruit exports. The UK's share decline to around 18% while the EU and Russia accounted for 11%, Middle East, about 10%, USA, Canada and others at 3%.

2.3 Factors affecting yield and quality of apples

Intensification of fruit production in commercial orchards in the past decades has primarily been driven by economic factors and the need to increase orchard efficiency (Fereres et al., 2012) (Robinson et al., 2007). Increasing the productivity of orchards to get higher yields of good quality fruit at minimum costs and use of scarce water is a priority for sustainability given the rising production costs and pressure on water resources. Many factors determine the yield and quality of apple orchards. These include, among others: the genetic potential of the cultivars and rootstocks planted, water stress, soils, environmental factors, management practices, and nutrition. However, no single factor or resource controls the variation in yield and quality of the fruit. Instead, it is the complex combination of these factors which is important and we will describe the role of a few selected key factors. Important fruit quality attributes for apples include; 1) fruit size, 2) skin colour, 3) flesh firmness, 4) total soluble solids, 5) titratable acidity, 6) aroma volatiles, 7) physiological disorders, 8) dry matter content, and 9) fruit mass, among others (Costa et al., 1997, Fouché et al., 2010, Mpelasoka, 2001).

2.3.1 Cultivars and rootstocks

Cultivar evaluation trials have shown that different apple cultivars have different yield potentials even under similar growing conditions (Amarante et al., 2008, Crassweller et al., 2005, Masabni and Wolfe, 2007, Miller et al., 2004) (Masabni and Wolfe., 2007). Crassweller et al. (2005) compared the performance of 20 cultivars grafted on the same rootstock (M9) at 13 sites across the USA over four growing seasons. They found significant differences in tree size, yields, number of fruit per tree, fruit size, pre-harvest fruit drop, and alternate bearing tendencies while Miller et al. (2004) noted differences in the quality of fruit. High yielding apple cultivars grown in South Africa include, among others, 'Golden Delicious', 'Braeburn', 'Gala' and 'Granny Smith'. The cultivar trends in South African orchards (Fig. 2.1) may, apart from the high yields required, be explained by consumers' preference for a more diverse selection of high quality apples, the low rate of return of traditional cultivars, an expanded world market that has increased competition and consumer awareness, and a desire to reduce the use of fertilizers and pesticides, among others (Miller et al., 2004).

Rootstocks are one of the most important factors influencing orchard productivity as they affect tree growth, leaf nutrition, yield and fruit quality. They differ in resistance to soil borne pests and diseases and response to environmental factors (Fallahi et al., 2002, Tworkoski and Miller, 2007, Kosina, 2010). Selecting the wrong rootstock may therefore adversely affect productivity throughout the lifetime of an orchard. In South Africa, as elsewhere in the world, the trend in apple growing is to plant more trees per hectare than in the past (Cook and Strydom, 2000, Univer et al., 2006). Careful selection of rootstocks is critical to ensure early returns on investment - given the high costs associated with establishing high density orchards and to control excessive vigour. In this regard, rootstocks that produce the desired size (dwarfing or semi-dwarfing) of the trees and promote high yields early in the orchard's life are ideal.

2.3.2 Water stress

The imbalance between tree water use and water application is a common cause of yield decline in orchards. This can be a result of not enough or too much water. Water stress can be detrimental to production by reducing growth and net photosynthesis rates per unit leaf area (Landsberg and Jones, 1981; Flore and Lakso, 1989). The amount of radiation intercepted by the canopy, leaf photosynthesis rate and the allocation of assimilates to fruits controls the actual fruit yield (Wünsche, 1993). The partitioning of assimilates to fruit as opposed to vegetative sinks is strongly dependent on radiation distribution in the canopy and on crop load (Wünsche, 1993). Advanced foliar damage and/or leaf senescence caused by water stress can limit carbohydrate availability for growth and development. This in turn has an adverse effect on fruit bud formation, fruit set and fruit size (Wünsche, 1993).

Yield is a function of the number of fruit on trees as well as fruit size. The critical processes to achieve the yield potential of the current year are therefore initial and final fruit set and fruit growth, assuming adequate fruit bud formation and flower density (Wünsche, 1993). Early season water stress of apple trees reduced fruit set, resulted in less fruit per cluster (Powell,

1974) and interfered with flower bud morphogenesis (Landsberg and Jones, 1981), while limiting irrigation increased fruit drop (Assaf et al., 1974, Assaf et al., 1975). The effects of water deficit on yield are more pronounced during budburst and flowering, the beginning of rapid shoot growth and the beginning of fruit fill (Fig. 2.2). Large numbers of flowers and fruit-lets drop when subjected to water stress during the early season (ca. first 50 days) causing low yields at the end of the season.

Although controlled levels of water stress outside the sensitive phases can be beneficial and lead to significant water savings as demonstrated by some deficit irrigation trials (Fallahi et al., 2010, Mpelasoka, 2001), deficit irrigation is in general not well suited to the apple growth habit (Lakso, 2003). Since apple has an ‘expo-linear’ fruit growth pattern by weight (Lakso et al., 1995) and fruit growth is already sensitive to water stress early in the season, there is no suitable period to limit extension shoot growth through controlled water deficits without affecting fruit size. Several researchers found that deficit irrigation decreased apple fruit size (Landsberg and Jones, 1981, Lötter et al., 1985, Ebel et al., 2001, Mpelasoka, 2001). Deficit irrigation could even further reduce fruit size of trees which already have limited carbohydrates available due to high crop load (Lakso, 2003). Fruit size distribution of several apple cultivars under deficit irrigation tended to favour smaller fruit sizes (Lötter et al., 1985, Mpelasoka, 2001, Leib et al., 2006), although high crop load can cause a similar trend (Mpelasoka, 2001, Naor et al., 1997, Naor et al., 2008, Naschitz and Naor, 2005).

Both the level and timing of water deficit influence fruit quality attributes such as fruit size and total soluble solids, although the effects on firmness, skin colour and mineral concentration are inconclusive or not well documented (Mpelasoka, 2001, Naor et al., 1997). In general, mild water deficits during fruit development advance fruit maturity, increase total soluble solids content and firmness and may improve red colour (Naor et al., 1997). Physiological disorders related to water stress such as water core (Lötter et al. 1985), scald (Guelfat'Reich et al., 1974, Lötter et al., 1985) and bitter pit (Guelfat'Reich et al., 1974, Lötter et al., 1985, Irving and Drost, 1987) also occur in apple. Water stress also increases fruit cracking (Goode et al., 1975, Irving and Drost, 1987), as well as russeting (Irving and Drost, 1987) and sunburn of ‘Granny Smith’ and ‘Cripps’ Pink’ fruit (Lötter et al., 1985, Makeredza et al., 2013).

Fig. 2.2 The growth cycle of pome fruit.

According to Naschitz and Naor (2005) the response of crop yield to the availability of soil water, given a certain number of flowering buds, follows a sigmoid pattern as illustrated in Fig. 2.3. There is a minimum soil water availability (A) below which trees might die. A-B represents soil water availability where the proportion of fruit set and the surviving fruitlets increase with increasing water availability due either to improved turgor potential or assimilate availability which may reduce fruit drop. Region B-C is typical of the situation in most orchards. Here the assimilate availability (see next section) for fruit expansive growth and potential fruit size limits crop yield.

In general, severe water deficits imposed by lack of or poor irrigation practices not only reduce the current year's yields, but it also affects production in subsequent years (Ebel et al., 2001; Fereres et al., 2008). Water stress exacerbates alternate bearing and the intensity of this phenomenon is more pronounced in some cultivars e.g. Golden Delicious, Fuji and Braeburn than in others. During periods of prolonged droughts water stress can damage or kill trees and therefore adequate water supply is crucial for sustained yields. Too much water in the root zone is just as damaging to production as water deficit. Excess soil water content leads to anaerobic conditions in the soil resulting in severe injury to the root system. The roots in waterlogged soils stop growing, mineral uptake ceases, leaves turn yellow and remain small and eventually the roots begin to die. Besides the primary damage to the tree and fruit, the root system becomes more susceptible to infections. Often apple trees in poorly drained areas are infected by *Phytophthora* (crown rot), and the orchard condition slowly declines over one or more years.

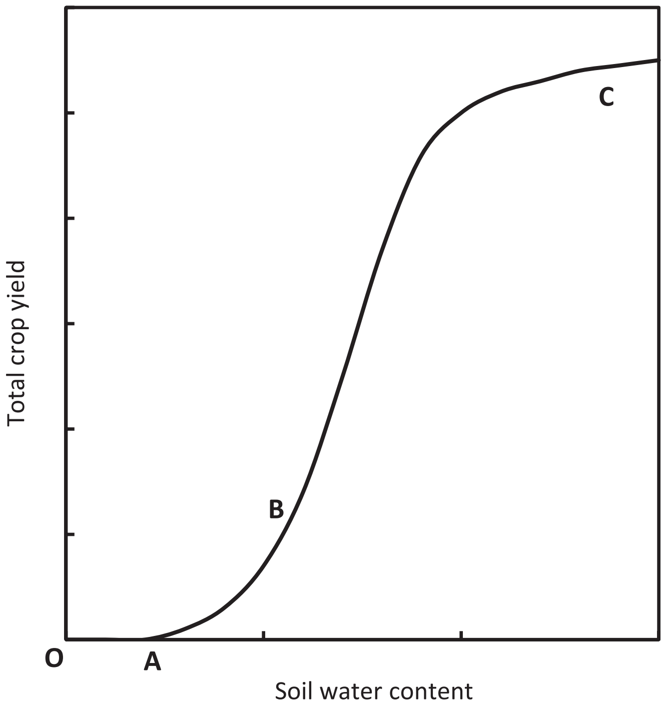


Fig. 2.3 Schematic representation of the relationship between soil moisture availability and crop yield (after Naschitz and Naor, 2005).

2.3.3 Environmental factors and management practices

While some apple cultivars and rootstocks are susceptible to cold injury (frost), excessive radiation (and hence temperature), hail and wind damage are other common environmental factors reducing yield in South African orchards. Strong winds can cause trees to lean over or even be uprooted particularly for trees on dwarfing or semi-dwarfing rootstocks such as the M7 which tend to be brittle. Shade nets are becoming increasingly popular in recent years to minimize wind, hail and sunburn damage to apple fruit. Gindaba and Wand (2007) found that increases in leaf temperature from 35-40 °C in field grown 'Cripps' Pink' trees reduced photosynthesis by up to 70%. Therefore, excessive solar radiation and temperature can reduce both yield quality and quantity of apples. Each year, sunburn substantially reduces the amount of marketable yield in South African orchards. A number of local studies have investigated the effectiveness of various technologies (e.g. shade nets, kaolin particle sprays and evaporative cooling) in reducing yield loss due to excessive radiation. Smit (2006) found that the response of yield quantity and quality to shade netting seemed to be cultivar specific although sunburn defects were reduced for all apple cultivars. Gindaba and Wand (2005) observed that evaporative cooling treatments increased the fruit mass of ‘Royal Gala’ but not the ‘Cripps’ Pink’ apples.

Despite the adverse effects described above, interception of adequate solar radiation is a critical factor in apple production (Palmer, 1997, Wünsche and Lakso, 2000). As a result, most orchard designs and management practices aim to enhance tree canopy radiation interception and distribution in order to maximize yields. According to Wünsche and Lakso (2000) there are only two possible means to improve fruit yield and quality in cases where other limiting factors like frost, disease, drought and nutrient deficiency are well managed. These are: 1) increasing total dry matter yield, and 2) increasing the magnitude of partitioning of dry matter (DM) towards fruit development. Factors affecting dry matter production (DM) in apples can be summarized by the relationship

$$DM = PAR \times \%Int. \times \varepsilon - RESP \qquad (2.1)$$

where PAR is the quantity of incident photosynthetically active radiation, %Int is the percentage of PAR intercepted by the trees, ε is the photosynthetic conversion of radiation into biomass (typically 5-10% due to the inefficiency of the photosynthesis process) and RESP is the respiratory carbon loss.

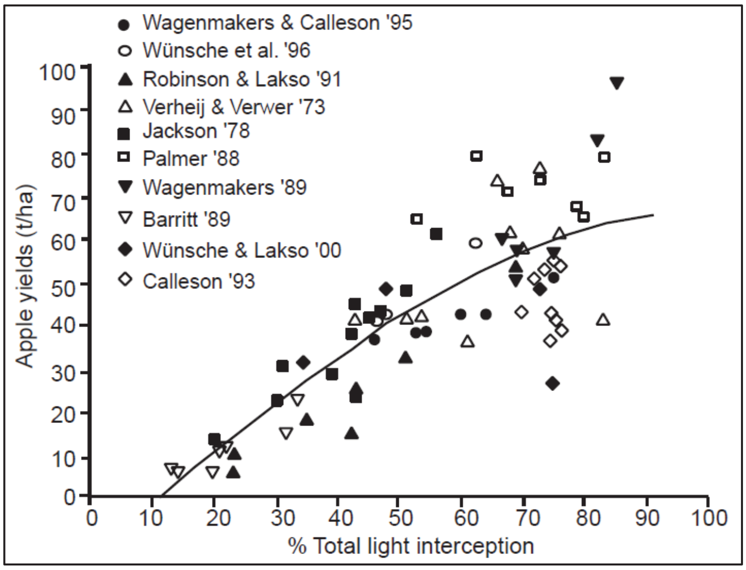


Fig. 2.4 Summarized relationship between apple fruit yield and mid-season percent total orchard radiation interception from several reports in literature (after Wűnsche and Lakso., 2000).

The amount of radiation intercepted, and hence the actual yield, depends on various orchard design factors such as planting system, tree spacing, tree shape, row orientation, and canopy management practices e.g. pruning that influence the leaf area index (leaf area per unit ground area),use shoot growth retardants such as Regalis®, and the length of the growing season.

The relationship between apple yields and the total intercepted radiation shown in Fig. 2.4 reveals a linear relationship up to about 50% radiation interception. Beyond the 50% interception, the relationship tends to be curvilinear and optimum apple yields are obtained at about 60 to 70% radiation interception according to Wűnsche and Lakso (2000). In South African orchards apple tree rows are usually planted in a north-south orientation to maximize radiation interception. Light distribution within canopies is increased by management practices such as pruning, spreading or tying down branches to a horizontal position.

The shift towards high density plantings in South African orchards reflects a decrease in between-row and within-row spacing and increased orchard leaf area indices, which may increase radiation interception. South African high-density plantings appear to have stabilized at around 1 500 trees per hectare (Hortgro, 2016). However, plant densities exceeding 4 000 plants per hectare are not uncommon in some orchards. High density plantings have the major advantage that yields are increased substantially and the high yields are reached early in the orchard life span (Costa et al., 1997, Eccher and Granelli, 2006, Robinson et al., 2007). Average yield per tree declines because of the smaller tree size, but the overall yield per hectare increases because of the large number of trees per unit area (Costa et al., 1997). Full production was reached as early as the fourth year in high density orchards compared to between six and seven years for normal plantings in Italy (Eccher and Granelli, 2006). With respect to fruit quality, high plant densities tended to produce smaller size fruit in Italian orchards (Costa et al., 1997, Eccher and Granelli, 2006) while changes in total soluble solids, fruit firmness and other attributes have also been reported with significant variations between cultivars.

In addition to improved orchard management practices (i.e. irrigation, nutrition, pests and disease control etc.) in South African orchards there are other factors that contribute to the exceptionally high yields in some orchards. For example, less thinning result in high crop loads usually associated with smaller sized fruit (Mpelasoka, 2001; Naschitz and Noar, 2005). However, the availability of a ready market for smaller sized fruit, especially in the emerging African markets, is seen as a major driver encouraging exceptionally high yields with minimum thinning.

2.4 Water resources and irrigation of apples

According to the second National Water Resources Strategy for South Africa (NWRS 2, 2013), irrigated agriculture is cited as one of the most inefficient industries with respect to water use. It estimates that between 30 and 45% of water allocated for irrigation is wasted either through leakages, poor irrigation scheduling or other causes. Recommended actions to increase agricultural water productivity according to this report include, among others: 1) the need for accurate quantitative information on crop water use under different production practices, and 2) the adoption of precise irrigation technologies. Irrigation infrastructure in the South African apple industry is already modernized. Most fruit is produced under the high pressure irrigation systems mainly micro-sprinkler. In addition, water saving practices such as mulching is the norm in the deciduous fruit industry (Trevor Abrahams, pers. comm.), while some growers reap water saving benefits through the use of shade nets.

According to Fereres et al. (2012) the challenges that fruit farmers face to maximize their sustained productivity require: i) knowledge of the irrigation requirements to meet the full tree needs; ii) determining the irrigation schedule that will be best in terms of net profits, which may include a moderate reduction in applied water relative to the maximum needs determined in (i); iii) tailoring that schedule to their own conditions and monitoring the tree response to the water applied, and; iv) knowledge on the orchard response to a reduction in irrigation water below that needed for maximum net profits, which may be caused by droughts or other restrictions. It is apparent therefore that there exists an optimal water supply situation for specific orchards. Ideally irrigation should be applied as close to that optimum as possible to remain competitive.

2.5 Orchard water requirements

The water requirement of orchards depends on environmental factors which drive the evaporative demand and transpiration, salinity, and electrolyte composition in the soil solution, the resistance of the soil to root penetration and moisture transport, soil aeration, tree hydraulic architecture (including rootstock) and crop load (Naor, 2006, Dzikiti et al., 2017). With the intensification of fruit production in recent years, the water requirements of orchards have also increased (Fereres et al., 2012, Batchelor et al., 2014). This change has resulted in greater irrigation water use, but increased production as well. While the accuracy of water use estimates for tree crops has increased in recent years little is known about the water requirements of high yielding apple orchards. It is therefore important to address this information gap for sustainable fruit production, especially in water limited areas. In general crop water requirements (CWR, in $m^3\ ha^{-1}$) can be estimated as:

$$CWR = \sum_{i=1}^{n} A_i (ET_i - P_{eff}) \times 10 \qquad (2.2)$$

where A_i is the area planted to apple cultivar i, ET_i is the actual evapotranspiration of the orchard, P_{eff} is the effective rainfall and the factor of 10 converts the result from millimeters to cubic meters of water per hectare. Effective rainfall is however, negligible in the major apple growing regions of South Africa given that most rain falls outside the growing season. Therefore, ET can be considered as the net irrigation requirement allowing for losses due to irrigation inefficiency.

Orchard evapotranspiration is commonly measured using the soil water balance approach (Rallo et al., 2014, Rallo et al., 2017, Volschenk, 2017), micrometeorological techniques such as the eddy covariance (Gush and Taylor, 2014, Dzikiti et al., 2017), combining micro-lysimeter derived soil evaporation and transpiration (Bonachela et al., 2001, Testi et al., 2004), and using the surface energy balance method (Cammalleri et al., 2010, Consoli and Papa, 2013, Dzikiti et al., 2011). These methods are however, not suited for routine use in orchard water management. Instead, simple crop coefficients (K_c) are widely used to estimate ET from reference evapotranspiration (ET_o) ($ET=K_c \times ET_o$), using the guidelines provided in FAO paper number 56 (Allen et al., 1998). Whilst these have proven robust in a number of annual crops, they have been shown to be very site specific for perennial orchard crops where crop coefficients can vary according to variety, rootstock, tree spacing, canopy cover, microclimate and irrigation method (Naor et al., 2008). As a result, published K_c values can often result in poor estimates of water use for orchard crops. There is therefore a need for more mechanistic models which can provide reliable estimates of ET under a wide range of climatic conditions and management practices which can then be used to derive site specific K_c values for improved on-farm water resources management. However, in cases where the soil water content falls below threshold values, plants experience water stress and K_c can be adjusted for the stress according to:

$$ET = (K_{cb} \times K_s + K_e \times K_r) ET_o \qquad (2.3)$$

where K_{cb} and K_e are the basal and soil evaporation coefficients, K_s and K_r are the transpiration and evaporation reduction coefficients described in detail by Allen et al. (1998) and Rallo et al. (2017).

In micro-irrigated orchards, ET has four main components namely transpiration from the trees (T), transpiration from the weeds and cover crops (T_c), evaporation from wet soils in the zones wetted by irrigation (E_{wz}), and evaporation from the dry soil in the un-irrigated parts (E_{dz}) (Fig. 2.5). Whole orchard evapotranspiration is then calculated as the algebraic sum of all the evaporation components using the equation

$$ET = T + T_c + E_{wz} + E_{dz} \tag{2.4}$$

Several empirical models exist for calculating the different components of ET in equation 2.4.

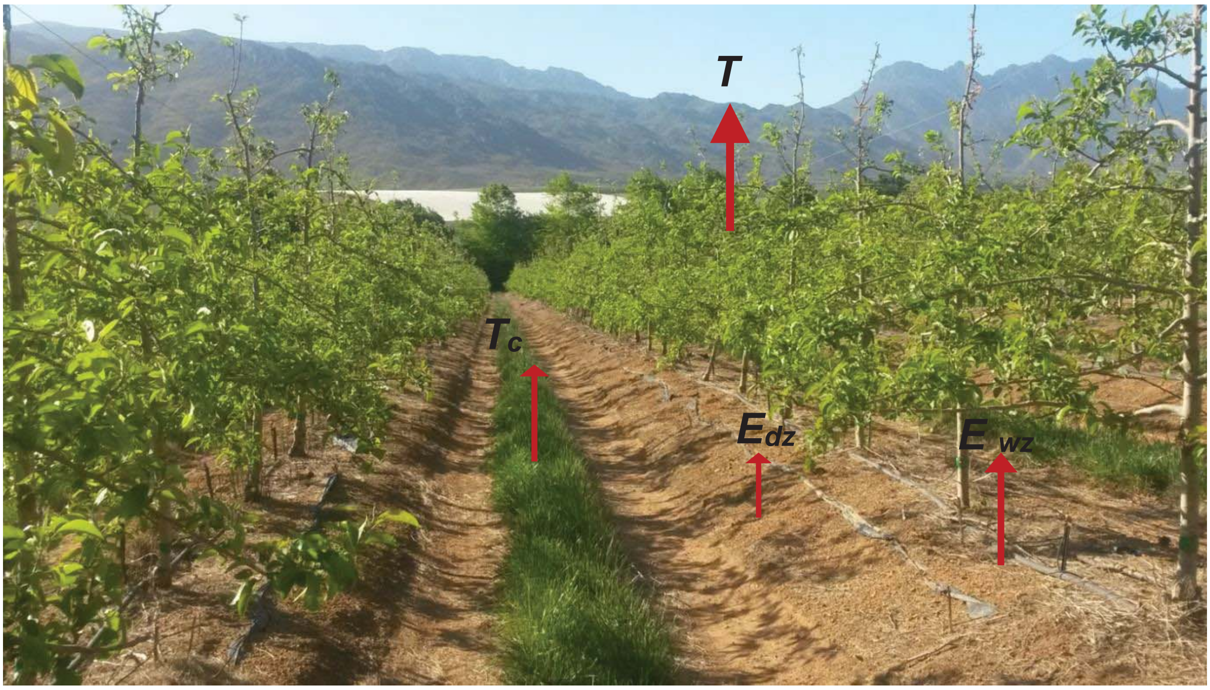


Fig. 2.5 Evapotranspiration components from an orchard under micro-irrigation. T represents the tree transpiration, T_c is the cover crop transpiration, E_{dz} and E_{wz} is the evaporation from the dry and wet soil zones.

2.6 Water relations, water use and water productivity of apple orchards

Main factors determining apple tree water consumption are the: 1) atmospheric evaporative demand, 2) canopy size, and 3) crop load (FAO irrigation and drainage paper 66). Canopy size determines the amount of energy intercepted by the tree and this influences the transpiration rates (Monteith and Unsworth, 1990, Jones, 2013). Irrigation requirements of young orchards are therefore different from those of mature trees. In addition, Robinson and Lakso (1991) observed that the canopy size and radiation interception in apple orchards varied with the training system and with cultivars while Cohen and Naor (2002) noted that different rootstocks influenced the hydraulic properties and hence transpiration rates of apple trees. These findings suggest that the effects of canopy size, cultivars, rootstocks and row orientations on transpiration and therefore on irrigation levels should be evaluated for each specific orchard.

2.6.1 Canopy size and transpiration of apple trees

There are few reports in literature that presented results of orchard transpiration by field grown apple trees (Dragoni et al., 2005, Green et al., 2003) and none of them have reported on water use in high yielding orchards (>100 t ha^{-1}). In a study on the transpiration rates of 14 year old ‘Cripps’ Pink’ apple orchards on M793 rootstock in the Koue Bokkeveld region of South Africa, (Gush and Taylor, 2014) recorded mean annual transpiration rates of about 690 mm using the heat ratio sap flow method for an orchard yielding approx. 60 t ha^{-1}. Maximum leaf area index of the orchard was around 2.74 with the average leaf area of each tree being approximately 15.8 m^2. Transpiration by individual trees peaked at about 42 L per day in summer (Table 2.5). In another study, Green et al. (2003) using the compensation heat pulse velocity sap flow method measured the maximum transpiration rates of 20 L per day on ‘Braeburn’ trees on a dwarfing M9 rootstock with a small canopy of about 8.65 m^2 in Australia. However, they observed water use rates of between 60 and 70 L per day on the Splendour cultivar on a vigorous MM106 rootstock with a large canopy of approximately 45 m^2.

Dragoni et al. (2005) used a combination of a whole tree gas exchange system and the compensation heat pulse velocity sap flow system to quantify transpiration rates in ‘Empire’ apple trees on the dwarfing M9 rootstock in the USA. Average canopy area was approximately 14 m^2 and transpiration rates were in the range of 40-50 L per day for each individual tree. This data shows a clear relationship between canopy size and water consumption with larger sized trees using-as expected-more water. Differences in the maximum daily transpiration rates could be attributed to differences in microclimatic conditions, equipment and analytical errors.

2.6.2 Effect of crop load on transpiration and fruit quality

The presence of fruit on trees influences the trees' water requirements (Berman and DeJong, 1997; Lakatos, 2003, Naor, 2006) and two considerations are worth noting. The first relates to the direct influence of cropping on stomatal conductance and hence transpiration and water consumption. The second relates to the increased demand for assimilates under high crop loads (Naor, 2006). High crop loads on fruit trees have been observed to increase leaf photosynthesis rates and stomatal conductance due to the increased sink strength for assimilates (Hansen, 1971; Dejong, 1986; Wibbe and Blanke, 1995). The accumulation of dry matter requires photo-assimilates and the higher the number of fruits the higher the demand for the assimilates (stronger sink). To maintain high photosynthesis rates (to meet the high demand for assimilates) a high influx of CO_2 needs to be maintained which is achieved by opening of stomata.

Stomatal opening significantly increases the stomatal conductance of water vapour leading to increased transpiration rates (Naor, 2006). This suggests that higher irrigation rates will therefore be required to produce large crop loads in high yielding orchards. This possibility is supported by the experiments by Lenz (1986) who directly demonstrated that the tree water consumption of fruiting apple trees was 25 to 50% greater than that of non-fruiting trees in a controlled environment. In another study Wünsche et al. (2000) recorded up to 36% higher transpiration in trees with a high crop load relative to de-fruited field grown apple trees using whole-tree gas exchange systems.

Lysimeter experiments by Girona et al. (2011) in Spain with fully grown apple trees showed that crop coefficients (K_c) increased in proportion with canopy size after bud break reaching a peak at maximum canopy cover 60 days after full bloom. However, a rapid drop in K_c values was observed after harvest and this was attributed to the removal of fruit from the trees as there was no evidence of leaf senescence. This suggests that harvesting fruit from the trees resulted in lower transpiration rates, consistent with the observations by Wűnsche et al (2000) and others. Besides increases in the stomatal conductance, Naor et al. (1997) realized that the midday stem water potential decreases (more negative) as the crop load of apple trees increased. This provides further evidence that high irrigation levels are required to meet the water requirements of trees with high crop loads.

Table 2.5 Comparison of canopy area and maximum daily transpiration of individual apple trees.

Cultivar	*Rootstock*	*Maximum leaf area (m^2)*	*Maximum transpiration (L day^{-1})*	*Method*	*Country*	*Reference*
Cripps' Pink	M793	15.8	42	Heat ratio heat pulse velocity sap flow	South Africa	Gush et al. (2014)
Braeburn	M9	8.65	20	Compensation heat pulse velocity sap flow	Australia	Green et al. (2003)
Splendour	MM106	35.5	60-70	Compensation heat pulse velocity sap flow	Australia	Green et al. (2003)
Empire	M9	14	40-50	Compensation heat pulse velocity and canopy gas exchange	USA	Dragoni et al. (2005)
-	-	20.6*	59.7	Stem heat balance	France	Pereira et al. (2011)
-	-	15.7*	45.5	Stem heat balance	France	Pereira et al. (2011)
-	-	4.7*	22.6	Stem heat balance	France	Pereira et al. (2011)
-	-	7.5*	13.9	Stem heat balance	France	Pereira et al. (2011)
Fuji	-	37.95*	50-70	Compensation heat pulse velocity	China	Gao et al. (2014)
Golden Delicious	M793	4.62	7.7	Compensation heat pulse velocity sap flow	South Africa	Volschenk et al. (2003)
Golden Delicious	M793	17.01	14.1	Compensation heat pulse velocity sap flow	South Africa	Volschenk et al. (2003)
Golden Delicious	M793	28.54	21.0	Compensation heat pulse velocity sap flow	South Africa	Volschenk et al. (2003)
Cripps' Pink	M793	11.74	13.2	Compensation heat pulse velocity sap flow	South Africa	Volschenk (unpublished data)

**Cultivar and/or rootstock not mentioned in source.*

According to Naschitz and Naor (2005), optimal irrigation is expected to maintain a well-balanced tree structure (i.e. roots, branches, shoots, leaves and flower buds) that can provide the fruit with enough assimilates at an adequate rate for them to reach commercial fruit size and to ensure enough fertile flower bud formation to enable consistent commercial crop production. Numerous studies have shown that excessive crop loads upset the tree balance and leads to the production of smaller sized fruit (Berman and DeJong, 1996, De Salvador et al., 2006, Naschitz and Naor, 2005, Naor et al., 2008, Mpelasoka, 2001) as demand for assimilates exceeds supply. According to Fig. 2.6, high irrigation levels are required to maintain fruit size of apples above the threshold of 70 mm (required for export to most EU markets) as the number of fruit on the tree increases.

Besides fruit size, high crop loads also affects other quality attributes of fruit. For instance (Palmer et al., 1997) observed that low crop loads in ‘Braeburn’ trees on the M26 rootstock significantly advanced fruit maturity as indicated by the background colour, starch/iodine score and soluble solids. In this experiment, high crop load also reduced the vegetative growth of the trees. De Salvador et al (2006) observed that the fruit from trees of ‘Golden Delicious’ and ‘Red Chief’ with high crop loads in Italy were smaller, firmer and had a higher total soluble solid content.

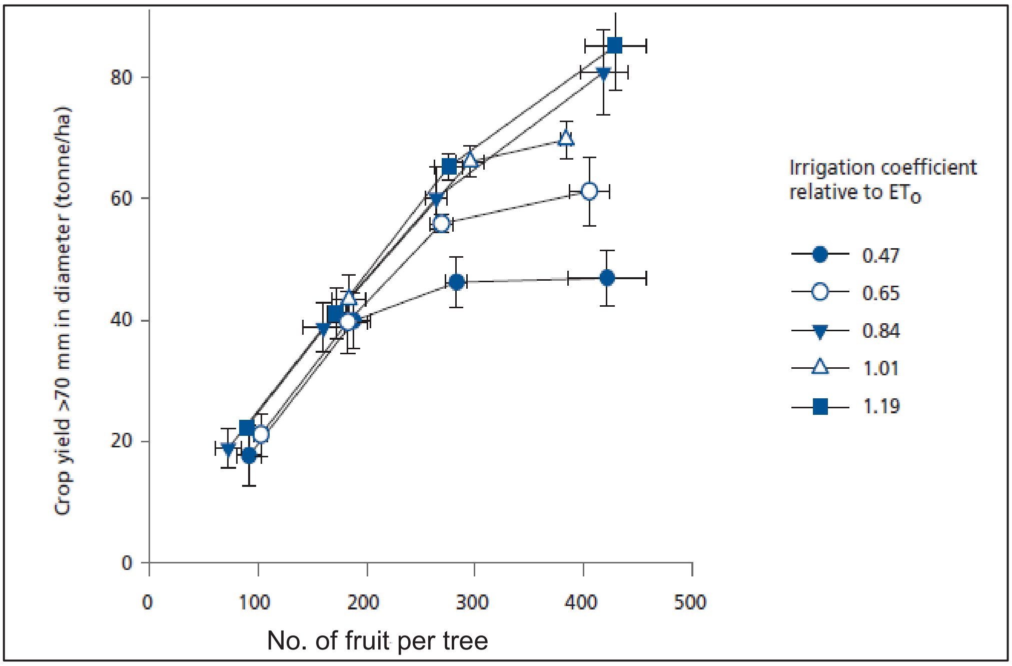


Fig. 2.6 Effect of the number of fruit per tree on apple fruit size (>70 mm in diameter) at different irrigation levels (Naor et al., 1997).

2.6.3 Water use efficiency and water productivity of apple orchards

As with transpiration, few studies have quantified the evapotranspiration and water productivity of apple orchards globally. Of the few existing studies, none have been done in high yielding orchards. In this report we distinguish between water use efficiency and water productivity (WP, kg m^{-3}) of the orchards. Physical water use efficiency (WUE) refers to the actual amount of yield (Y_a - in kg) produced per cubic meter of water consumed (ET_a in m^3);

$$WUE = \frac{Y_a}{ET_a} \tag{2.5}$$

Water productivity (WP) on the other hand is similar to water use efficiency, but it takes fruit quality into account. The study by Gush and Taylor (2014) on 'Cripps' Pink' orchards in the Koue Bokkeveld region of South Africa showed actual annual evapotranspiration rates of 952 and 966 mm for the 2008/2009 and 2009/2010 periods. The corresponding yields were 54 and 69 tonnes of fruit per hectare, respectively. The water use efficiency for each of the growing seasons were therefore 5.67 and 7.14 kilograms of fruit produced per cubic meter of water evapotranspired. Average water use efficiency for the two years is 6.40 kg m^{-3}. The evapotranspiration information includes data collected during the winter dormant period. Therefore, the water use efficiency could be even higher if water use is considered only for the active growing season (September to May). This average water use efficiency for the 'Cripps' Pink' apples in South Africa is much higher than the value of 2.58 kg m^{-3} observed for apple orchards in California (Renault and Wallender, 2000). In the California study, annual evapotranspiration was about 1 037 mm while average yield was only 26.8 tonnes per hectare.

In the next Chapter first, we discuss the water use and growth patterns of young apple orchards in prime apple producing regions of the Western Cape. Orchards with medium and high canopy cover are discussed in subsequent chapters.

2.7 Summary

In this chapter we provide a review of apple production in South Africa and we summarize information on the water requirements of the orchards. However, no studies have so far investigated the water use of high yielding apple orchards, and to understand the key drivers of water use, growth, yield and fruit quality. This study therefore seeks to close this information gap and to provide insights on the sustainability of high yielding apple orchards in South Africa given the limited water resources.

CHAPTER 3

WATER USE OF YOUNG APPLE ORCHARDS

3.1 Introduction

South African apple orchards are irrigated throughout their life cycles. There is need for accurate quantitative information on orchard water use from planting to full-bearing age. Besides the research by Volschenk et al (2003), few other studies have directly quantified the water use of young apple orchards although a number of studies exist for other fruit types mainly citrus (Consoli et al., 2006, Consoli et al., 2014). An important requirement in young orchards is the need to achieve optimal tree growth by giving the trees the right amount of water when they need it. Sustained water stress reduces tree growth as a result of lower photosynthesis rates. This prolongs the time to reach commercial fruit bearing which affects the grower's economic returns.

The trees may also suffer stress and stunted growth as a result of over-irrigation (Jones, 2013). Excess water in the root zone causes water logging which leads to anaerobic conditions due to lack of aeration. This affects root health and hence the uptake of certain nutrients leading to reduced growth or even death of the trees. The low canopy cover in young orchards means that large proportions of the orchard floor are exposed to the atmosphere. So, evaporative losses from the orchard floor can be very high estimated to exceed 50% of ET in some instances (Dzikiti et al., 2017, Liu and Luo, 2010). For this reason, farmers are encouraged to use irrigation techniques that reduce the wetted soil fraction e.g. using narrow range micro-sprinklers, drip irrigation and mulching to reduce soil evaporation. The root volume of young trees is smaller than that of mature trees. Thus, the irrigation depth should be carefully managed to avoid drainage beyond the root zone. Careful irrigation scheduling is therefore essential in young orchards to ensure trees reach maturity quickly. Currently, there are no clear guidelines in South Africa on the water requirements of young apple orchards. However, it is thought that substantial water wastage occurs in these orchards due to a lack of information to guide irrigation scheduling.

The aim of this chapter was to quantify the actual water use (transpiration) and evapotranspiration in young non-bearing apple orchards growing in the KBV and EGVV production regions. These trees have a low fractional vegetation cover (<30%) calculated according to the method proposed by Allen et al (1998). Focus is on the Golden Delicious, Golden Delicious Reinders, and the red cultivars, three or four years after planting. We also collected detailed data on the physiological responses of the young trees to environmental variables and to changes in the orchard water balance. These data will be useful in developing irrigation guidelines for young apple orchards and for optimal orchard management.

3.2 Materials and methods

3.2.1 Study sites and plant material

3.2.1.1 Non-bearing orchards with low canopy cover in the Koue Bokkeveld

The two young orchards studied in KBV during the 2014/15 season comprised a three-year-old ‘Golden Delicious Reinders’ orchard (NBGR) in Block LW03A at Lindeshof farm (Fig. 3.1). The orchard was 3.2 ha in size and tree spacing was 4.0 m x 1.5 m (i.e. 1 667 trees ha^{-1}). One in every ten trees was a ‘Granny Smith’ pollinator. The rootstock was the industry standard M793. Average tree height was about 2.7 m with a canopy diameter about 0.90 m and about 19% canopy cover. The cover crop was a dense indigenous grass layer intermixed with various weed species in a strip approx. 1.2 m wide in the middle of the row. The orchard was on flat terrain on deep sandy soils of the Clovelly form with stone content increasing with depth. There was a layer of mulch comprising course wood chips (Fig. 3.1).

The second orchard was a 4-year-old ‘Rosy Glow’ (NBRG) which was 6.0 ha in size. The orchard was at Paardekloof farm, about 30 km to the South of Lindeshof. Tree spacing was 3.5 m x 1.25 m (i.e. 2 285 trees per ha). Tree height was about 3.0 m with an average canopy diameter of about 0.9 m and canopy cover of about 26%. The rootstock was the MM109 which is a precocious and high production rootstock like the M793, but with slightly more vigour. We could not find suitable young ‘Cripps’ Pink’ orchards on M793 in KBV. Cover crop was a dense indigenous grass similar to the one at Lindeshof. The trees were planted on ridges covered with heavy mulching from course wood chips. Soils were deep sandy soils of the Fernwood form with no stones.

Irrigation of both orchards was via a micro-sprinkler system with one sprinkler per tree delivering about 30 L h^{-1}. The wetted radius was about 0.8-1.0 m from the micro-sprinkler. The trees were irrigated roughly once or twice a week at the beginning of the season in October-November when there was still residual moisture from the winter rains. This translated to about

50 m^3 ha^{-1} h^{-1} at Lindeshof and 69 m^3 ha^{-1} h^{-1} at Paardekloof. Typically, each irrigation event lasted between one and one and half hours. Irrigation frequency increased to about once every two days during the hot summer weather in January and February.

Fig. 3.1 A typical non-bearing 'Golden Delicious Reinders' orchard at Lindeshof on 14 December 2014.

3.2.1.2 Non-bearing orchards in EGVV

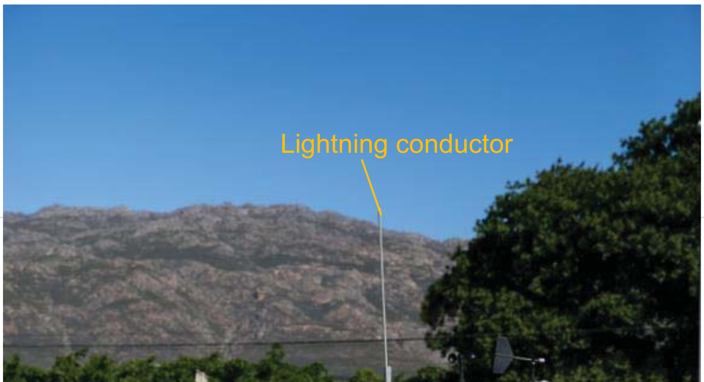
During the 2015/16 season, data were collected in two non-bearing orchards in EGVV. These comprised a four-year-old 'Golden Delicious' orchard in Block 24 at Vyeboom farm in Vyeboom. Orchard size was 6.0 ha and the trees were planted on the vigorous MM109 rootstock. Tree spacing was 4.0 m x 2.0 m translating to 1 250 trees per hectare which was sparse compared to the orchards in KBV. Mean tree height was about 2.5 m with an average canopy diameter of approx. 0.69 m and a canopy cover of about 14%. The pollinator was 'Granny Smith' while the soil type was the koffee klip with a high stone content (7-24%). The trees were planted on ridges in rows with a north-south orientation under a micro-sprinkler irrigation system. The cover crop was a short indigenous fynbos maintained at about 10-15 cm height. The slopes in the orchard were non-uniform typical of the terrain in EGVV.

As in KBV, it was also difficult to find a suitable non-bearing ‘Cripps’ Pink’ orchard in EGVV with the right attributes i.e. rootstock, soil type, orchard size etc. For this reason, we selected a non-bearing ‘Cripps’ Red’ (NBCR) also at Vyeboom farm. Like its close relative Cripps’ Pink, Cripps’ Red is also a red cultivar but with a slightly longer growing season. The orchard (Block 14) was three years old and it was 5.0 ha in size. The rootstock was the MM109 and the trees were planted on ridges in rows with a north-south orientation. Tree spacing was 4.0 m x 2.0 m giving 1 250 plants per hectare. Average height of the trees was about 2.6 m with a mean canopy diameter of about 0.8 m. Canopy cover was approx. 16%. Soil type was the dark sandy loams with about 1.0% stone content although there were bigger boulders in some portions of the orchard. The cover crop was a mixture of fescue and a variety of indigenous grass species. Irrigation frequency was similar to KBV only that the trees received 37.5 m^3 ha^{-1} for each hour of irrigation.

3.2.2 Orchard microclimate

Weather data were recorded using an automatic weather station (Fig. 3.2) located close to each of the study sites. The station was installed on open spaces with a uniform short grass cover. The equipment comprised a pyranometer (Model: SP 212 Apogee Instruments, Inc., Logan UT, USA) which measured the solar irradiance. Air temperature and relative humidity was measured using a Vaisala HMP60 temperature and humidity probe (Vaisala, Vantaa, Finland).

A wind sentry (model: 03001, R.M. Young; Campbell Scientific, Inc., Logan UT, USA) was used to measure wind speed and direction at 2.0 m above the ground, while rainfall was recorded using a tipping bucket rain gauge (model: TE525-L; Texas Electronics, Dallas, TX, USA) installed at 1.2 m above the ground. All the sensors were connected to a Campbell Scientific CR1000 data logger programmed with a scan interval of 10 s and the output signals were processed at hourly and daily intervals. Reference evapotranspiration (ET_o) was determined for a short grass using the FAO Penman-Monteith equation (Allen et al. 1998).



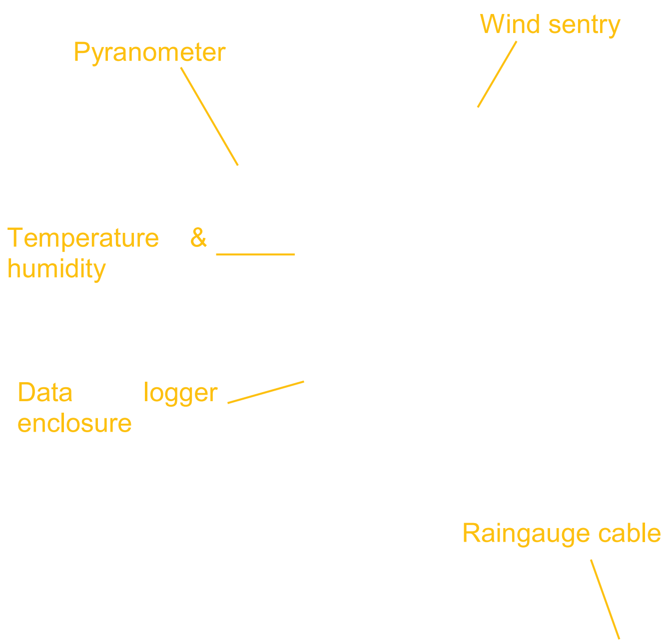


Fig. 3.2 Automatic weather station measuring basic weather elements close to the study sites. The rain gauge is out of view further to the right.

3.2.3 Soil properties, soil water content and irrigation

3.2.3.1 Soil physical properties

Soil samples were taken in the KBV and EGVV in November 2014 and October 2015, respectively, at the sap flow instrumented trees and pooled for chemical and five fraction particle size analyses (PSA) at a commercial laboratory. The sampling depth increments were representative of soil layers in which soil water monitoring equipment were installed or of the root zone.

To determine soil water retention properties, tensiometers were placed at a tree adjacent to where the soil water content monitoring equipment was installed or at a representative tree near the sap flow installation. Manual tensiometers were placed 0.5 m perpendicular to the centre of the tree trunk – in the tree row as well as perpendicular to the tree row in the clean cultivated area. At the 'Golden Delicious' and 'Cripps' Red' orchards tensiometers were installed at 300, 600, and 800 mm depths. At the ‘Rosy Glow’ orchard tensiometers were installed at 300, 600, and 900 mm depths. Gravimetric soil water content samples were taken for a range of soil matric potentials at selected soil depths to determine soil water characteristic curves *in situ* in each orchard. Soil matric potential was read from tensiometers.

3.2.3.2 Soil water content and irrigation

The orchards were not all instrumented with soil water content sensors (model: CS616- Campbell Sci. Inc., Logan, UT, USA) to the same degree because of equipment limitations. Two orchards were selected for detailed soil water balance measurements, whereas soil water content measurements in the upper soil horizon were recorded in the other orchards using CS616 sensors attached to HPV systems.

In the KBV ‘Golden Delicious Reinders’ (Lindeshof) orchard in October 2014, thirty soil water content sensors (model: CS616- Campbell Sci. Inc., Logan, UT, USA) and custom-made T-type thermocouples were installed at a tree comparable to and next to sap flow instrumented trees. The soil water monitoring equipment and thermocouples were connected via two multiplexers (model AM16/32B: Campbell Sci. Inc., Logan, UT, USA) to a CR1000 logger. The logging equipment and a 12 V lead calcium battery power supply were enclosed in a security box. The CS616 sensors (length of probe head - 85 mm, rods - 300 mm, nonflexible cable - 40 mm) were installed horizontally at selected depths at eight measurement positions in the soil according to a configuration which represents both the tree row and work row areas (Appendix A: Fig. A1).

Eight soil profiles per tree included two in the tree row with sensors orientated perpendicular to the tree trunk (North and South), four on the clean-cultivated strip with sensors oriented 45° from the tree row and perpendicular to the tree trunk (North West, South West, North East and South East) and two in the work row (East and West) (Appendix A: Fig. A1, Table A1). The work row soil profile was parallel to the tree row and sensors orientated perpendicular to the middle of the work row with sensor prongs centred on the tree trunk. In the soil profiles thermocouples were installed c. 200 mm away from the CS616 sensors to minimise the possibility of electromagnetic interference during measurement. Cable length limitations in some cases required alternative placement of thermocouples.

Fig. 3.3 Installation of CS616 sensors (black wires) and thermocouples (blue wires) in sandy soil in the low canopy cover 'Golden Delicious Reinders' orchard at Lindeshof in 2014/15. The measuring tape indicates centimetres.

Soil water content sensors and thermocouples were installed in relatively uniform sandy soil profiles in the root zone at 150, 300, and 600 mm from the soil surface and below the root zone at the 800 mm soil depth (Fig. 3.3). A gravel layer occurred beyond the 800 mm depth but surfaced shallower in the western work row below the 600 mm depth. No installations were done below the root zone in the work rows due to limited equipment. In the EGVV 'Cripps' Red' orchard soil water monitoring equipment were installed in a c.500 mm high ridge having sandy loam soil intermixed with stones. The soil was ripped to 800 mm depth and cultivated up to a depth of 600 mm. Tree roots extended in the centre of the ridge to a depth of 800 mm, and cover crop roots in the work row to c. 600 mm. A trench was made between two trees and CS616 sensors and thermocouples were installed at these trees at different depths in the centre of the ridge, in the slopes and work row (Appendix A: Fig. A2). Due to limited equipment, sensors were installed only at one tree in the tractor row at 150 mm. The purpose of this measurement is to detect whether runoff of water occurs from the slope to the work row area. Soil water content could not be measured representative of the root zone in the work row nor below the root zone due to limited equipment. Thermocouple cable length limitations prevented measurement of temperature in all positions at both trees.

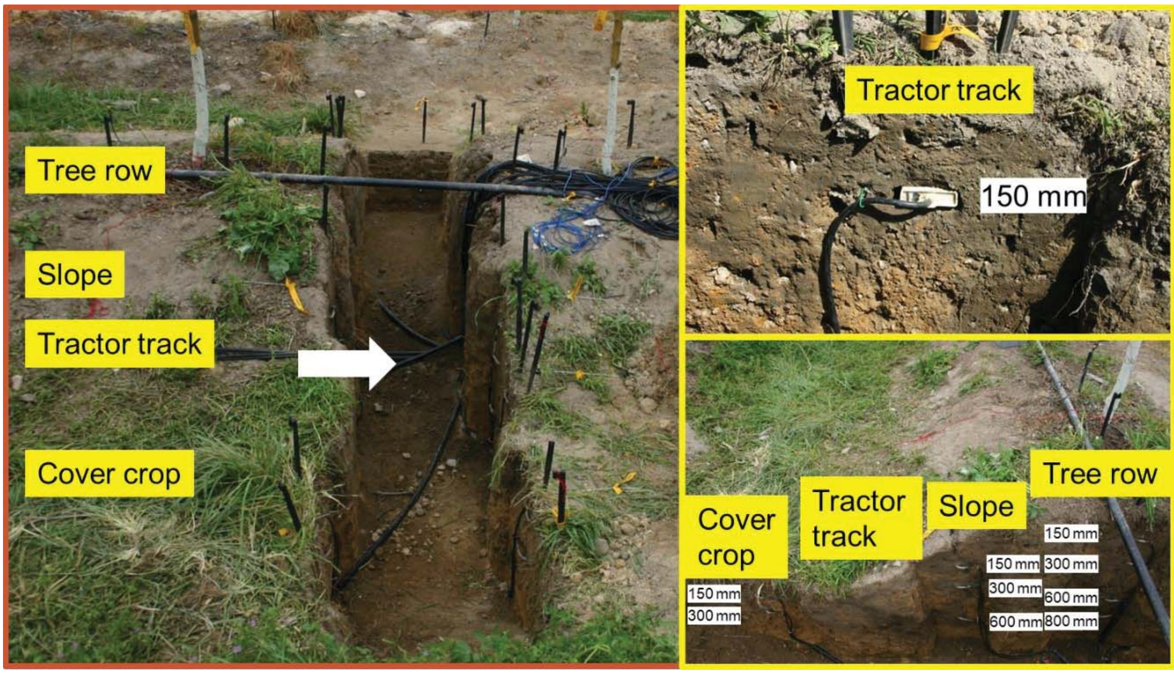


Fig. 3.4 Soil water balance equipment installed at two trees in sandy loam soil intermixed with stones in a ridged low canopy cover 'Cripps' Red' orchard at Vyeboom Boerdery in 2015/16. The relative positions and installation depths of the CS616 sensors in the tree row, slope, tractor track and work row area with cover crop is indicated.

Soil water content equipment were calibrated in both orchards to check the accuracy of the CS616 sensors in the soils. This was done by taking gravimetric soil samples for a range of soil water contents at selected depths to facilitate *in situ* calibration of the probes in each orchard. Statgraphics was used to obtain the mathematical relationships for the soil water characteristic curves and CS616 sensor calibration equations. Data points were considered as potential outliers if they deviated by more than two standard deviations from the model fitted and was only removed after careful inspection of the data. Irrigation applied was monitored using electronic water flow meters with a resolution of 10 litres per pulse installed on the irrigation lines (Fig. 3.5). The amount of irrigation received by each tree was calculated as the ratio of the volume of water that passes through the flow meter divided by the number of trees downstream of the flow meter.

3.2.4 Eco-physiology

3.2.4.1 Leaf gas exchange and stem water potential

In each orchard, five trees were marked in the same row as the instrumented trees, but further into the row and leaving three to five trees between the first marked tree and the last instrumented tree. Another five trees were marked in the next row on the opposite side of the tree row, to give a total of ten trees per orchard. Two leaves were measured per tree for all parameters. Measurements were performed throughout the growing season until harvest.

Fig. 3.5 Water flow meter measuring irrigation levels.

Stem water potential was measured using a pressure chamber (model 615, PMS Instrument Company, Albany, OR, USA) and using the enclosed leaf method. Leaves were enclosed in the morning using zip-lock silver reflective stem water potential bags (prune bags) (PMS Instrument Company, Albany, OR, USA) to allow the leaf water potential to equilibrate with stem water potential. They were then measured at midday (12:00-13:00). Leaf gas exchange (net CO_2 assimilation rate [A], stomatal conductance [g_s] and transpiration rate [E]) were measured using an infra-red gas analyser (IRGA) Model LI-6400 XT (Li-Cor, Lincoln, Nebraska, USA). Sensors inside the cuvette monitored leaf surface temperature (T_{leaf}) and the leaf-to-air vapour pressure deficit (VPD_{leaf}). We then derived instantaneous photosynthetic water use efficiency [WUEi] from A/E, as well as intrinsic photosynthetic WUEi from A/g_s. Spot measurements were taken in the morning (09:30-12:00) and afternoon (14:00-15:30) on two sun-exposed leaves per tree. The environmental conditions in the cuvette were: ambient temperature; saturating photosynthetically active radiation (PAR) (1500 µmol m^{-2} s^{-1}) provided by the internal red/blue LED lamp; constant cuvette CO_2 concentration (390 µmol mol^{-1}) provided by an external CO_2 canister.

Correlations were established between parameters using the seasonal spot measurements data set of gas exchange and stem water potential to establish key drivers of stomatal response and water use in the young trees. The influence of solar radiation on the measured parameters and their correlations was not analysed since PAR in the IRGA cuvette was kept constant during the gas exchange measurements. However, the influence of PAR as a key driver of photosynthesis and stomatal conductance is well-established in the scientific literature and in previous work conducted in the two production regions.

3.2.4.2 Diurnal stem diameter fluctuations

Continuous information on the water status of fruit trees can be obtained by monitoring stress on the plants themselves using devices such as dendrometers (Fig. 3.6). Jones (2004) provided a detailed review of different plant-based methods for scheduling irrigation and changes in the stem or fruit size is one option for fruit trees. Dendrometers can quantify plant water stress from changes in the maximum daily shrinkage (MDS) or the diurnal growth (DG) patterns. In this study the dendrometer (model DEX 70, Dynamax, Inc. Houston, USA) measured hourly changes in stem size by monitoring the change in the electrical resistance of a strain gauge that forms part of a four-wire bridge circuit. Figure 3.7 shows the relationship between stem diameter changes and tree water uptake (represented by the sap velocity) over a period of 24 hours.

Fig. 3.6 The dendrometer used for monitoring stem diameter fluctuations.

When transpiration commences at sun rise, the stem diameter shrinks (Fig. 3.7a) as the trees use their internally stored water for transpiration (Fig. 3.7b). It takes a while for the water potential gradient to develop across the transpiration stream and for root water uptake to commence to replenish the depleted internal storage reserves. The time lag between the commencement of transpiration and root water uptake can be of the order of magnitude of several hours depending on tree size and the hydraulic architecture of the transpiration stream. From late afternoon onwards, root water uptake catches up and later exceeds transpiration leading to a recharge of the internally stored water (Fig. 3.7b) leading to a recovery of stem size (Fig. 3.7a).

Tree water status was continuously measured in the two non-bearing apple orchards studied in 2015-2016 in the EGVV region: NBGD EGVV and NBCR EGVV. Results of this component are excluded from this report as the data has not been fully analysed. Rather the results will be presented as part of a student's PhD study linked to this project.

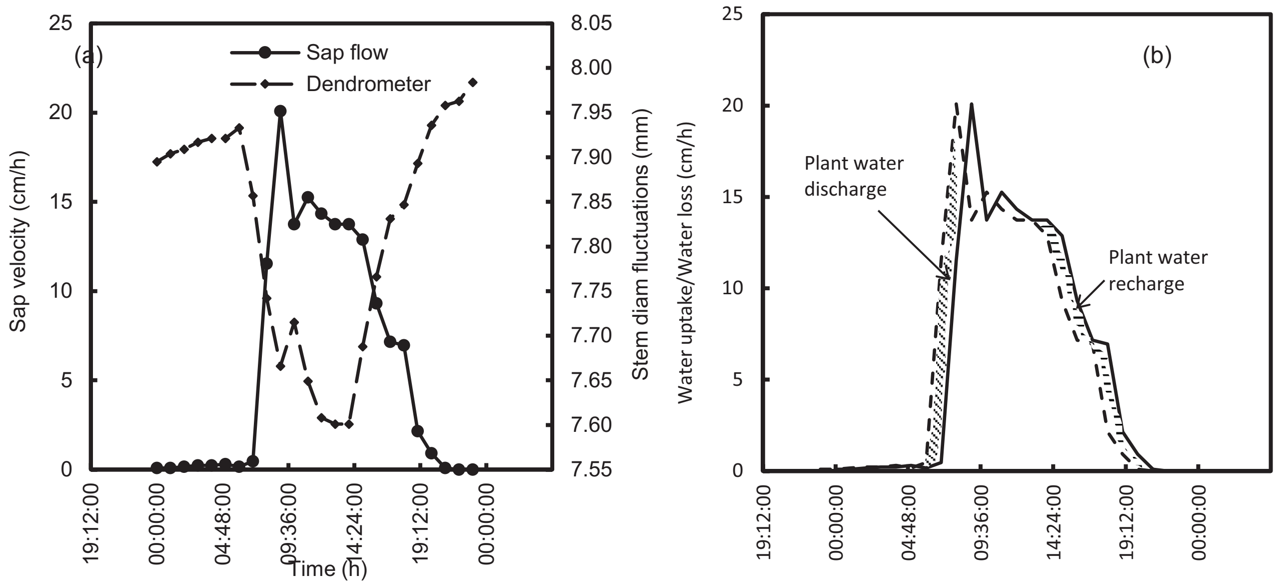


Fig. 3.7 (a) Diurnal trunk diameter fluctuations and stem sap velocity (in phase with sap flow) recorded in a 'Golden Delicious' apple tree; (b) The relationship between tree water uptake (continuous line) which is in phase with stem sap flow and water loss (dotted line) which is in phase with tree transpiration. The water uptake and loss is depicted by the sap velocities and similar trends are expected for the actual volumetric water uptake.

3.2.5 Tree transpiration

Transpiration by the young trees was measured using Granier probes (model: TDP 10, Dynamax Inc., Houston, USA) (Granier, 1987) (Fig. 3.8). Three trees were instrumented per orchard and the average sap velocity was determined in the depth range 0 to 10 mm of the stems. The average stem diameter at the point of sensor installation was about 30 mm for the 'Golden Delicious Reinders' at Lindeshof and up to 40 mm for the 'Rosy Glow' at Paardkloof. Mean stem diameter was about 52 mm for the 'Golden Delicious' and 48 mm for the 'Cripps' Red' at Vyeboom. The sensor probes sampled the 0-10 mm depth range. This ensured that the bulk of the TDP sensing probes sampled the sapwood and not the air and/or heartwood which would lead to a substantial under estimation of transpiration as reported for this technique in literature (Steppe et al., 2010, Dzikiti et al., 2011).

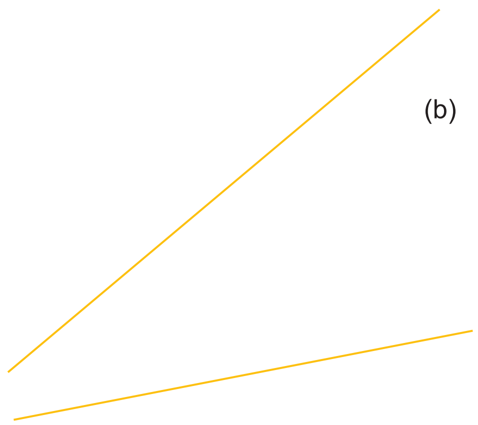


Fig. 3.8 (a) Measurement of transpiration in young orchards using Granier probes. (b) Granier probe installation using 10 mm sensors.

The sensors were installed at a height between 50 and 75 cm from the ground to eliminate errors due to the cold sap especially early in the morning. Installing the sensors at the recommended 1.0 m height above the ground was not feasible because the trees branched close to the ground. A double layer of aluminium bubble wrap was wrapped around the sensors (Fig 3.8a) to minimize the effects of exogenous heating on the sap temperature gradients. The TDP sap flow data was collected at hourly intervals throughout the study period i.e. October 2014 to June 2015 in KBV and from October 2015 to June 2016 in EGVV.

3.2.6 Orchard evapotranspiration

3.2.6.1 Eddy covariance

Evapotranspiration (ET) from the orchards was quantified using two open path eddy covariance systems (Fig. 3.9). These were deployed during specific window periods due to commitments on other projects. The systems comprised sonic anemometers (model: CSAT3, Campbell Sci. Inc., Utah, USA) which measured the wind speed in 3 dimensions (*u, v, w*). The concentration of atmospheric water vapour and carbon dioxide were measured using infrared gas analysers (IRGA) (model: LI-7500A, LI-COR Inc., Nebraska, USA). One eddy covariance system was connected to a CR3000 data logger while the other used the CR5000 data logger, both manufactured by Campbell Scientific. The high frequency data, collected at 10 Hz, were stored on 2.0 GB memory cards. Additional sensors included a one component net radiometer (model: CNR1, Kipp & Zonen, The Netherlands) on the CR5000 station and a four-component net radiometer (model: CNR 4, Kipp & Zonen, The Netherlands) on the CR3000 station. Two clusters of soil heat flux plates (model: HFP01, Hukseflux, The Netherlands) were installed at 8 cm depth below the surface to measure the soil heat fluxes under the canopies and between the rows in each station. Soil averaging thermocouples (model: TCAV, Campbell Sci. Inc., Utah, USA) were installed above the soil heat flux plates at 2 and 6 cm depths from the surface to correct the measured fluxes for the energy stored by the soil above the plates. Soil water content was measured using time domain reflectometers (model: CS616, Campbell Sci. Inc., Utah, USA).

At the Lindeshof site, the IRGA and sonic were installed at a height of about 1.6 m above the canopies and the tower was situated downwind of the prevailing wind direction. This gave a fetch of between 150 and 200 m upwind of the tower. In the bigger orchards at Paardekloof and Vyeboom, the tower was located in the middle of the orchard. Sensor height above the canopies was about 2.0 m which gave a fetch of at least 200 m round the tower. Separation of the IRGA and sonic was between 10 and 20 cm. The high frequency data was further processed using EddyPro v 5.2.1 (LI-COR, Nebraska, USA) to correct for water vapour density fluctuations, sensor tilt (coordinate rotation), sensor separation, and time lags, among others. The data was further corrected for the lack of surface energy balance closure. If R_n is the net irradiance absorbed by the orchard (treated as a flat surface), and G is the soil heat flux, then the shortened surface energy balance equation for the orchard can be written as:

$$R_n - G = H + \lambda E \qquad \text{(W m}^{-2}\text{)} \qquad (3.1)$$

where H is the sensible heat flux and λE is the latent heat flux, which is the energy equivalent of evapotranspiration. λ is the latent heat of vaporization? The ratio of the sensible to the latent heat flux is called the Bowen ratio (B). Substituting the Bowen ratio into equation 3.1 and re-arranging the equation gives the latent heat flux as:

$$\lambda E = \frac{R_n - G}{1 + B} \qquad \text{(W m}^{-2}\text{)} \qquad (3.2)$$

This relationship was used to correct the ET data for lack of energy balance closure which has been widely reported for the eddy covariance method. The measurement schedule at the various sites is shown in Table 3.1.

Fig. 3.9 Open path eddy covariance system deployed in a young apple orchard.

Table 3.1 Measurement schedule for the eddy covariance campaigns in the Koue Bokkeveld. NBGR – non-bearing 'Golden Delicious Reinders'; NBRG – non-bearing 'Rosy Glow'; NBGD – non-bearing 'Golden Delicious', and; NBCR – non-bearing 'Cripps' Red'.

Season		**Orchard**		
	NBGR	***NBRG***	***NBGD***	***NBCR***
Spring	16-25/10/2014 & 07-27/11/2014	17/09/2014 to 10/10/2014	ND	ND
Summer	04-17/12/2014 & 27/01/2015 to 27/02/ 2015	16-27/03/2015	22/01/2016 to 18/02/2016	20/12/2015 to 14/01/2016
Autumn	ND	02-11/04/2015	ND	ND
Winter	ND	ND	ND	ND

ND- not determined.

3.2.6.2 Soil water balance

Soil water content and temperature were measured hourly by means of CS616 soil water content sensors and T-type thermocouples connected to data loggers. In order to calculate the soil water balance the CS616 soil water content measurements at specific installation depths were weighted to represent different depth increments to obtain the soil profile water content. The field capacity per CS616 sensor was determined by inspection of data after heavy rainfall during a period of minimal tree water use. Evapotranspiration was calculated according to the universal soil water balance on a daily basis (Allen et al., 1998) using the soil water content logged at 00:00. The rainfall was measured by a representative weather station.

Irrigation volumes were measured for a section of trees using one automated flow meter per orchard. The irrigated amount (mm) was calculated as (Volume applied/Wetted area). The runoff and drainage components of the soil water balance were not measured. It was assumed that runoff would be negligible on the sandy soils irrigated according to best practice. The drainage was estimated from soil water content, irrigation and rainfall data. The ET was calculated per sensor position and weighted according to representative area to calculate ET of the different orchard components. Orchard ET was calculated by adding the volumes of ET of the different components and expressing it over the full orchard surface area. A data set was selected which excluded data reflecting non steady-state conditions after irrigation (negative values, crop coefficients > 1.4, excessive drainage). The ratio of actual ET to reference ET according to Allen et al (1998) was also calculated.

At the NBGR (Lindeshof) the sensors at 150, 300, 600 and 800 mm depths, respectively represent soil depth increments for 0 to 225, 225 to 450, 450 to 700 and 700 to 800 mm in the soil profile. The ET was calculated separately for the irrigated tree row (2.3 m width) and non-irrigated work row (1.7 m width). A wetted radius of 1.15 m was used for the micro sprinkler. In the NBCR orchard, ET was calculated separately for the irrigated and non-irrigated area and the cover crop. The effective root depth used for the tree row on the ridge, slopes and cover crop were 800, 700 and 600 mm, respectively. A depth of 150 mm was used for the non-irrigated area (top of ridge, slopes and tractor row). The wetted area on top of the ridge was estimated as a capsule, and that on the slopes as a segment of a circle. A wetted radius of 1.0 m was used for the micro sprinkler. The micro sprinkler was located c. 200 mm west of the tree and 100 mm South of the tree row. This offset from the centre of the tree row was not taken into account in the estimation of the wetted area on the slopes.

3.2.6.3 FruitLook remote sensing

FruitLook is a remote sensing-based ET product whose services were available to the Western Cape farmers during the course of the project. It is based on the ETLook model developed by

Bastiaansen et al (2012). In this study, the FruitLook data were downloaded at weekly intervals for the period October to April on the website: www.FruitLook.co.za and compared with the eddy covariance and the modelled ET.

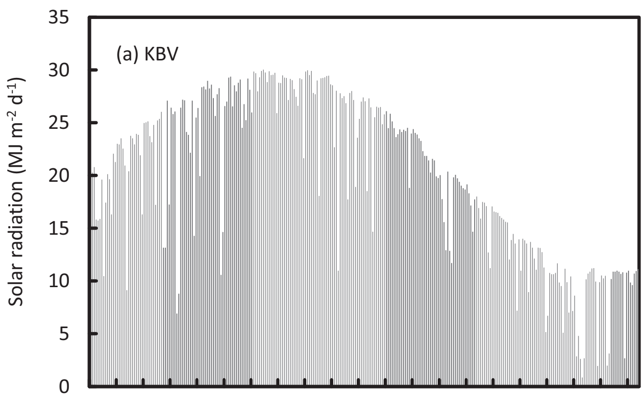
3.3 Results and discussion

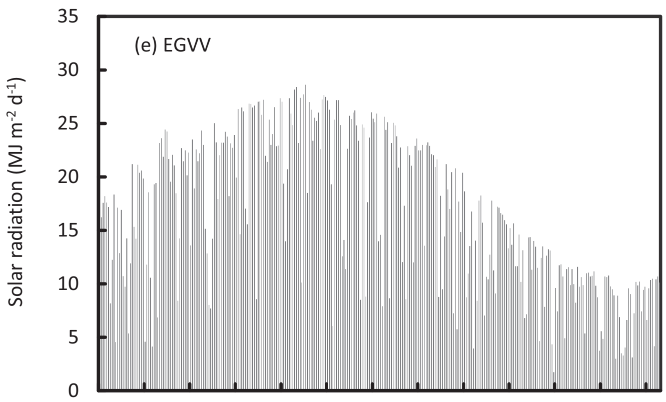
3.3.1 Seasonal dynamics of climatic conditions

The daily trends of key climatic variables during the 2014/15 season in KBV and 2015/16 in EGVV are shown in Fig. 3.10 while Table 3.2 provides the monthly summary. The daily maximum solar radiation for the season in KBV was 28.5 MJ m^{-2} which was higher than in EGVV where it peaked at 24.0 MJ m^{-2} and Fig. 3.10 a, e shows the higher incidence of cloud cover in EGVV which moderated weather conditions in that production region. Average seasonal (October to June) temperature in KBV was 17.3 °C with a peak of 37.3 °C reached in March 2015 and minimum temperature of 1.4 °C in June 2015.

For EGVV, the mean seasonal temperature was slightly higher than in KBV being 18.3 °C, with a maximum of 39.7 °C recorded in December 2015 and a minimum of 2.3 °C in June 2016. The atmospheric evaporative demand, depicted by the VPD, was on average higher in KBV than EGVV (Fig. 3.10 c, g) due to the hotter and drier conditions in KBV with the minimum relative humidity dropping to below 10% in KBV while the lowest in EGVV was about 13%. The daily reference evapotranspiration peaked at 8.8 mm in KBV and it was only 7.3 mm in EGVV. The seasonal total reference evapotranspiration (ET_o) was higher in KBV being 1 264 mm in 2014/15 compared to 1 064 mm in EGVV in 2015/16.

The main drivers for the low reference evapotranspiration in EGVV were the higher incidence of cloud cover (see Fig. 3.10 a & e) and the comparatively higher relative humidity. There were no substantial differences in the maximum air temperatures for the two seasons. The Koue Bokkeveld received 281 mm of rainfall in 2014/15 compared to 247 mm in EGVV during 2015/16 and this was approximately 20% of ET_o for both regions during the growing season. The long-term annual precipitation in KBV is 350-510 mm while EGVV has higher rainfall (>510 mm).





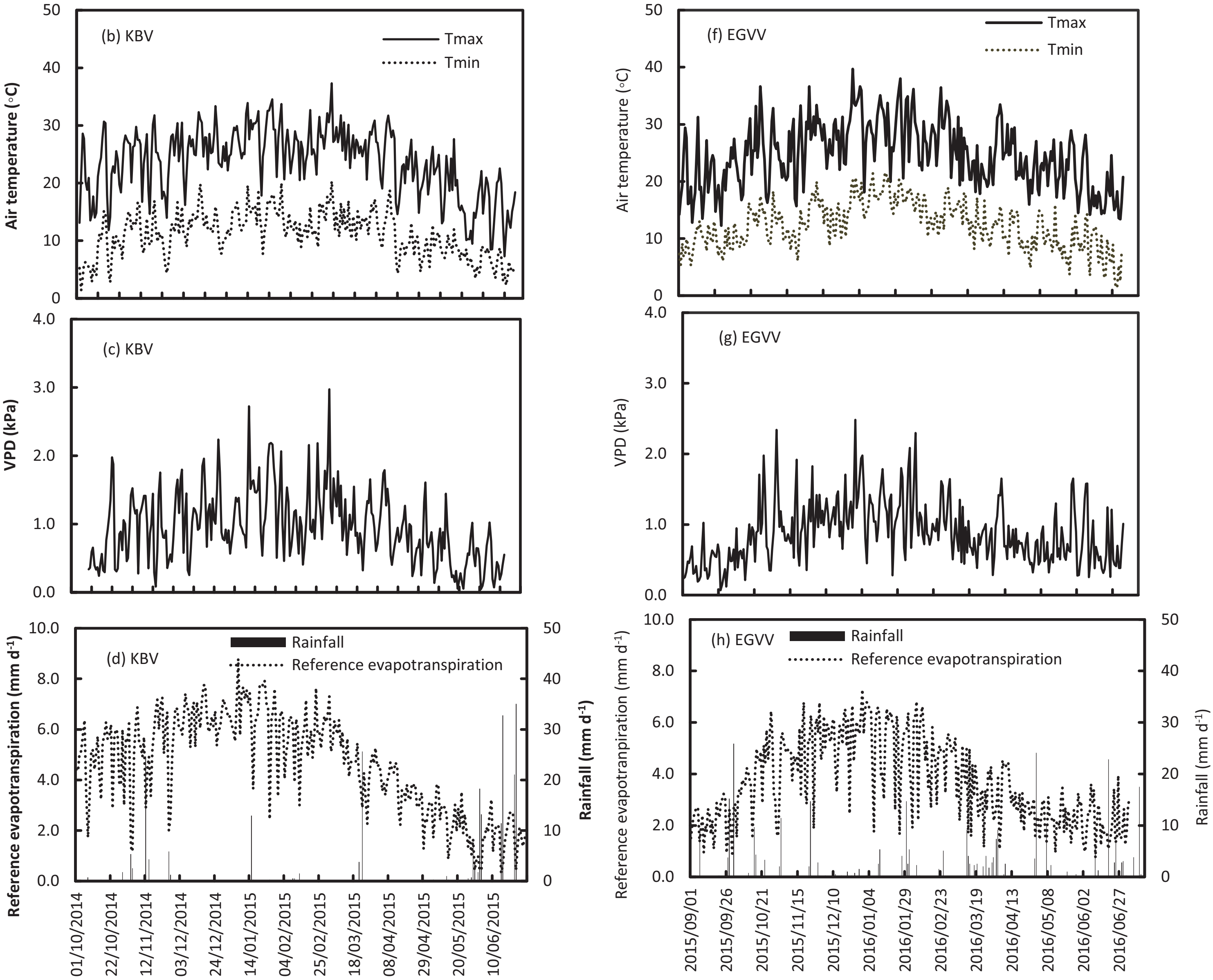


Fig. 3.10 Hourly climatic conditions during the 2014/15 and 2015/16 seasons in KBV and EGVV, respectively. (a, e) represents the daily total solar radiation; (b, f) represents the maximum and minimum temperatures; (c, g) represents the vapour pressure deficit; and (d, h) represents the daily short grass reference evapotranspiration and rainfall.

Table 3.2. Monthly summary of the daily mean solar radiation (R_s); maximum (T_{max}), minimum (T_{min}) and average air temperature (T_{avg}); maximum (RH_{max}) and minimum (RH_{min}) relative humidity; short grass reference evapotranspiration (ET_o), and rainfall in the Koue Bokkeveld (KBV) in 2014/15 and in EGVV during 2015/16. KBV and EGVV represent the Koue Bokkeveld and Elgin/Grabouw/Villiersdorp/Vyeboom production regions, respectively.

	KBV	**EGVV**	**KBV**	**EGVV**	**KBV**	**EGVV**	**KBV**	**EGVV**	**KBV**	**EGVV**	**KBV**	**EGVV**	**KBV**	**EGVV**	**KBV**	**EGVV**
Month	**R_s (MJ m^{-2} d^{-1})**	**R_s (MJ m^{-2} d^{-1})**	**T_{max} (°C)**	**T_{max} (°C)**	**T_{min} (°C)**	**T_{min} (°C)**	**T_{avg} (°C)**	**T_{avg} (°C)**	**RH_{max} (%)**	**RH_{max} (%)**	**RH_{min} (%)**	**RH_{min} (%)**	**ET_o (mm)**	**ET_o (mm)**	**Rain (mm)**	**Rain (mm)**
Oct	21.9	19.4	30.7	36.6	2.8	6.1	17.1	17.3	96.0	99.9	11.2	15.3	150.3	118.0	2.8	20.3
Nov	24.0	22.0	31.8	36.6	4.4	6.1	17.4	17.8	95.9	93.5	13.3	5.4	154.9	143.2	43.9	31.8
Dec	28.5	24.0	33.4	39.7	7.8	8.7	20.2	21.2	95.2	94.7	12.2	11.5	201.8	169.8	0	5.1
Jan	26.9	22.2	34.6	36.6	7.7	13.4	21.7	23.1	95.9	94.3	11.1	18.0	203.2	166.4	13.5	34.5
Feb	24.9	19.8	32.7	38.0	8.9	10.3	19.3	21.2	95.4	93.3	9.3	12.9	161.0	136.9	2.5	9.1
Mar	20.5	15.0	37.3	34.1	10.1	8.1	20.3	18.9	95.9	94.2	9.3	25.0	154.0	110.3	29.5	52.1
Apr	15.7	13.0	31.7	33.5	4.4	6.2	16.4	17.0	95.1	95.8	14.7	18.6	108.7	88.6	0.25	40.4
May	10.2	9.8	27.6	28.9	4.6	3.7	13.3	15.3	96.3	96.0	12.3	13.3	71.1	70.4	14.5	4.3
Jun	8.6	7.8	22.6	28.1	1.4	2.3	9.9	12.9	96.7	94.3	18.5	11.0	51.7	60.9	133.6	49.5
Total													**1 264.1**	**1064.4**	**280.7**	**247.1**

3.3.2 Soil properties, soil water content and irrigation

3.3.2.1 Soil physical properties

Soils classed according to particle size (Soil Classification Working Group, 1991) indicated that the low canopy cover orchards included sand (NBRG Paardekloof), sandy loam (NBGR Lindeshof; NBCR Vyeboom Boerdery Block 14) and very stony sandy clay soil (NBGD Vyeboom Boerdery Block 24) (Table 3.3). The soil from Paardekloof had almost no stone, while at Lindeshof and Vyeboom Boerdery Block 14, the coarse fraction (>2 mm) in the soil tended to increase with depth, having up to almost 30% stone below the root zone (Appendix B: Table 1).

The soil surfaces of all these orchards had a mulch of coarse wood fragments in the tree row. *In situ* determination of the bulk density (P_b) according to the core method (Blake & Hartge, 1986) was not feasible in the EGVV non-bearing 'Golden Delicious' orchard or the 'Cripps' Red' orchard due to the high stone content of the soils. A value of 1600 kg m^{-3}, typical of sandy soils was used to convert mass based gravimetric soil water content to volumetric soil water content.

Table 3.3 Profile averaged soil texture classes and particle size analysis for the soils at the low canopy cover orchards.

Orchard	Profile depth (mm)	Texture class	Clay	Silt %	Sand	Stone (m^3 m^{-3})
Lindeshof W03	900	Sandy loam	15.7	3.3	81.0	12.2
Paardekloof	1050	Sand	6.0	2.0	92.0	2.7
Vyeboom Boerdery Block 14	900	Sandy loam	11.7	6.9	81.4	13.5
Vyeboom Boerdery Block 24	900	Sandy clay	48.9	35.4	15.7	n.a.[1]

[1] Laboratory analysis indicated no stone although field observation indicated stone content higher than that of Vyeboom Boerdery Block 14.

Soil chemical analysis of the KBV orchards confirmed that - based on fertilization norms for deciduous fruit trees-growth and therefore water use of trees would not be adversely affected by any soil related nutrient deficiencies/ imbalances or salinity (Appendix B: Table 2). Although initial analysis indicated a potential aluminium toxicity problem at the NBRG (Paardekloof) orchard, analysis of a second soil sample did not indicate any such problems. Soil chemical status of the NBCR orchard (Vyeboom Boerdery Block 14) was acceptable except for high sodium levels in the 225-700 mm depth increment. The pH of the EGVV NBGD orchard (Vyeboom Boerdery Block 24) soil was low and needed adjustment to prevent potential nutrient uptake problems in future (Appendix B: Table 2). Levels of nutrients appeared to be adequate up to 450 mm in the soil but became low in the 450- 700 mm increment. The analysed data were sent to farm management for consideration in their soil management programme and the anomalies brought to their attention.

The *in situ* determined *soil water retention curves* of the low canopy cover orchards are shown in Fig. 3.11 (a-c). The curve for Paardekloof (Fig. 3.11b) is represented only by a limited range of soil matric potentials even though gravimetric soil samples for establishment of the soil water retention curves were taken on ten occasions. For the NBGD orchard at Vyeboom (Block 24) there was no correlation between the gravimetric soil water content and soil matric potential read from the tensiometers (data not shown) as extremely stony soil prevented accurate gravimetric sampling. Refer to Table 1 in Appendix C for statistics of the *in situ* determined soil water retention curves for various depths per orchard.

According to estimates from the soil water retention curves (Fig. 3.11) the soil water holding capacity between -5 and -1500 kPa was 134, 83 and 103 mm m^{-1} for the NBGR at Lindeshof, NBRG at Paardekloof and NBCR at Vyeboom, respectively. It is estimated that at a soil matric potential of -20 kPa - c. 44%, c. 75% and c. 84% of the plant available water (PAW) between -5 kPa and -1500 kPa is depleted in the soils of these orchards. To refill the soil to field capacity to a 600 mm root depth in the respective orchards one would have to apply 35, 37, and 52 mm of irrigation. Since between 50 and 60% depletion of TAW is recommended before irrigation is applied to apple trees having roots up to a depth of 1-2 m (Allen et al., 1998) the soil matric potential at which irrigation is applied for the Paardekloof and Vyeboom orchards could be reduced.

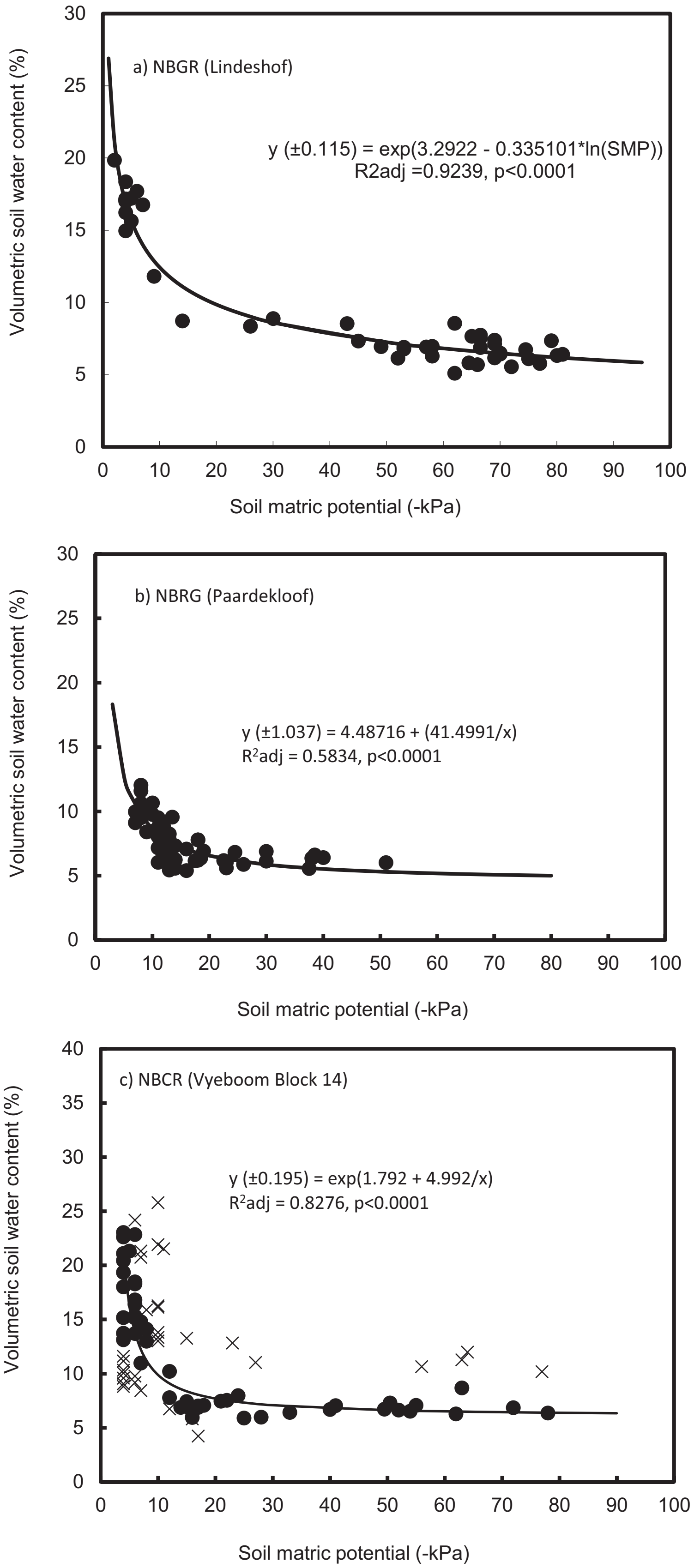


Fig. 3.11 Soil water retention curves of a) a sandy loam soil in the NBGR orchard at Lindeshof, b) sandy soil in the NBRG orchard at Paardekloof and c) sandy loam soil in the NBCR orchard at Vyeboom Boerdery. Outliers are indicated as crosses.

3.3.2.2 Soil water content and irrigation

The *CS616 in situ calibration* statistics for 30 sensors each at Lindeshof and Vyeboom (Appendix D:Tables 1 and 2) indicated that individual calibrations per sensor between gravimetrically determined volumetric soil water content and CS616 period per soil depth obtained accuracy equal to or better than the 2.5% indicated by the manufacturer. The period values were restricted to the low range between 17.4 and 24.9 µs. The standard error of the estimate increased if data were pooled per depth. Outliers removed were attributed to variation in spatial distribution of soil water along the length of the sensor prongs and/or variation in stone content of the sampled area vs sensor location. Comparison of volumetric soil water content calculated from the CS616 period using the manufacturer's calibration and actual soil water content at comparable CS616 periods indicated that the former underestimated the volumetric soil water content (Fig. 3.12 a & b).

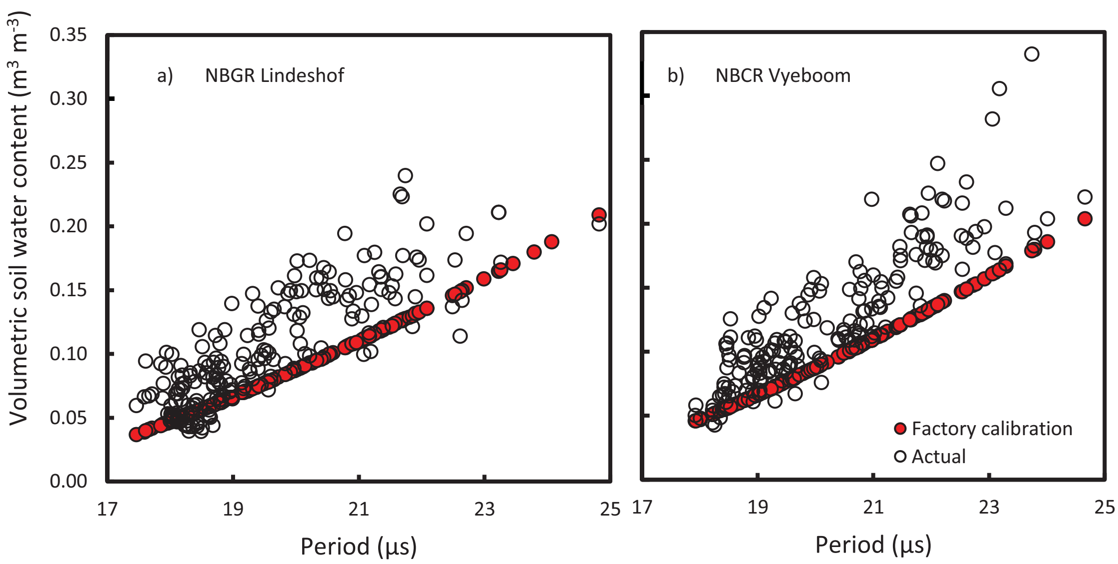


Fig. 3.12 Comparison of CS616 factory calibrated volumetric soil water content and actual volumetric soil water content sampled simultaneously at various CS616 periods at a) the NBGR (Lindeshof) and b) NBCR (Vyeboom) orchards.

Soil water dynamics at the NBGR at Lindeshof indicated that the volumetric soil water content in the tree row reflected irrigation and rainfall events, whereas the non-irrigated work row area responded to rainfall only (Figs. 3.13 & 14b). The orchard was over-irrigated during November and January until 6 February and received at times irrigation amounts exceeding 32 mm per event on the wetted area (19 mm expressed over the full surface area) (Table 3.4).

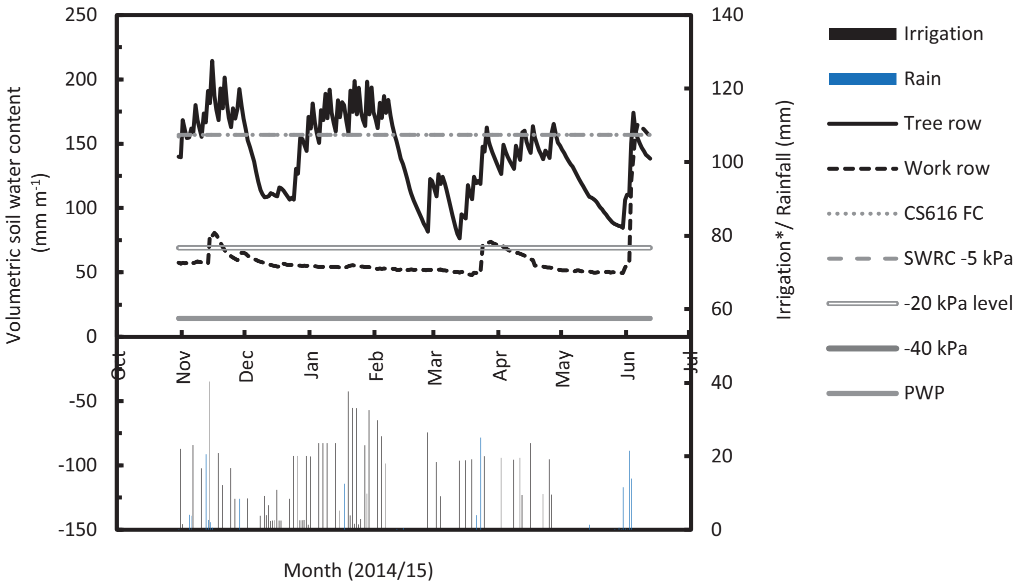


Fig. 3.13 Seasonal changes in volumetric soil water content in the tree row and work row areas of a non-bearing 'Golden Delicious Reinders' orchard at Lindeshof during the 2014/15 season. The amount of irrigation applied in the tree row and rainfall received are indicated on the Y-axis.

Table 3.4 Monthly mean amount, number and interval of irrigations applied to non-bearing 'Golden Reynders' and 'Cripps' Red' orchards at Lindeshof (2014/15) and Vyeboom (2015/16), respectively. Irrigation applied on the wetted area is indicated as mm per full surface area.

Month	Irrigation amount (mm d^{-1})				Number (n)		Interval (d)	
	NBGR[1]		NBCR[2]		NBGR	NBCR	NBGR	NBCR
	Mean	Stdev	Mean	Stdev				
Oct	14.9	-	8	-	1	1	31	14
Nov	11.8	7.8	4.2	0.6	8	7	3.8	4.3
Dec	4.5	4.4	2.9	1.7	20	7	1.5	4.3
Jan	12.6	8.6	2.9	1.4	16	6	1.9	5.0
Feb	16.9	3.4	5.4	2.0	4	8	7.0	3.6
Mar	11.8	2.8	6	3.8	6	5	5.2	6.2
Apr	11.0	3.8	5.2	0.0	8	2	3.8	15.0

[1] *Divide by 0.58 to obtain amount applied per wetted area*
[2] *Divide by 0.5 to obtain amount applied per wetted area*

Lower irrigation applications during December, almost no irrigation during the later part of February and a longer irrigation interval in March, allowed the soil profile to become drier, but it remained above the -20 kPa refill level (Fig. 3.13, Table 3.4).

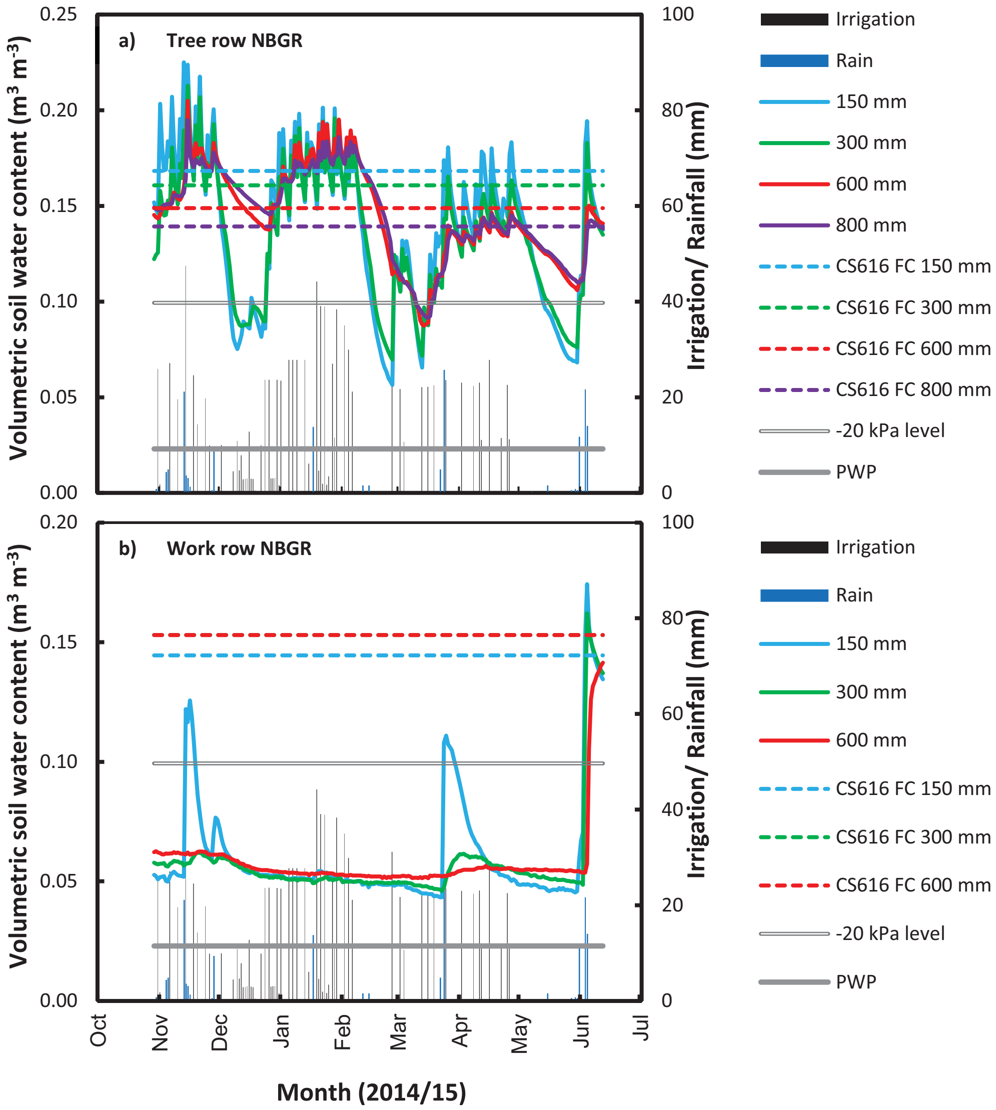


Fig. 3.14 Seasonal changes in volumetric soil water content at selected depths in a) the tree row and b) work row of a non-bearing 'Golden Delicious Reinders' orchard at Lindeshof during 2014/15. The amount of irrigation applied in the tree row and rainfall received are indicated on the Y-axis.

The irrigation interval and amounts were adjusted to address exceptionally wet conditions deeper in the soil profile (Fig. 3.14a), which could deter deep root development of the young trees. Soil water content in the top 450 mm of the root zone reached its lower limits on 10 December 2014 and in 2015 on 25 February, 14 March and 30 May (Fig. 3.14). On these respective dates the estimated soil matric potential at the 150 mm depth reached -38, -80, -50 and -32 kPa, being less at the 300 mm depth (-21, -41, -40 and -27 kPa, respectively) (Fig. 3.14a). During the period of tree water potential measurement between 17 and 19 February the estimated soil matric potential ranged from -23 to -33 kPa and -17 to -23 kPa at the 150 and 300 mm depths, respectively.

In the NBCR orchard, volumetric soil water dynamics in the ridge indicated that, although the -20 kPa refill level was not exceeded, under-irrigation may have occurred between middle December 2015 and end March 2016 (Fig. 3.15). During this period, the soil profile water content never reached the field capacity level. The tractor track and cover crop were drier than the ridge and in general had comparable wetness. At times the cover crop area was drier than the tractor track, most likely due to water use of the non-irrigated cover crop.

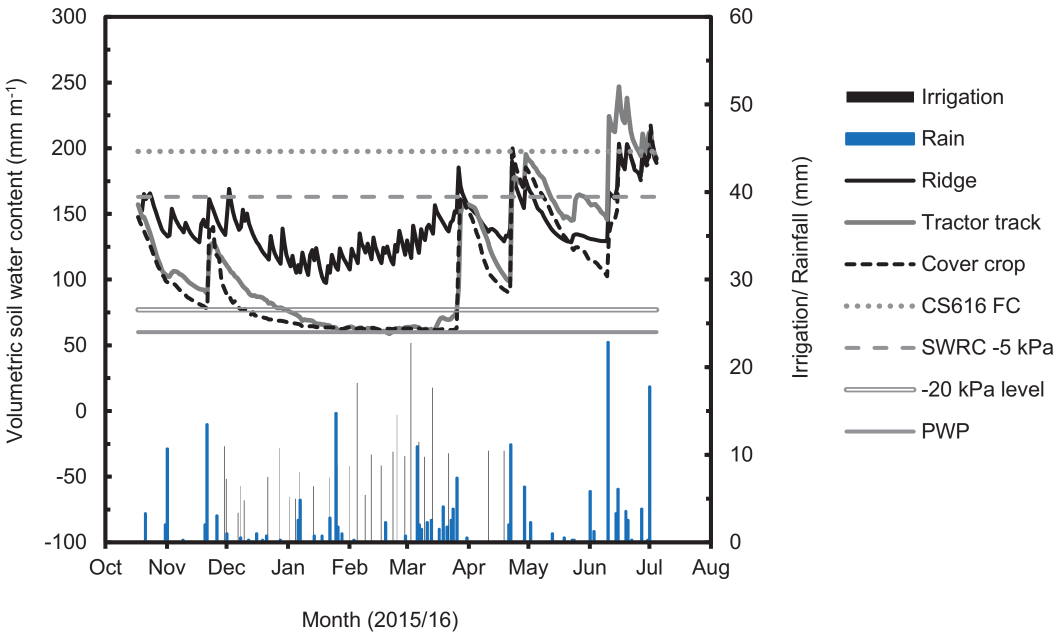


Fig. 3.15 Seasonal changes in volumetric soil water content in the ridge, tractor track and cover crop areas of a non-bearing 'Cripps' Red' orchard at Vyeboom in EGVV during the 2015/16 season. The amount of irrigation applied to the ridge and rainfall received are indicated on the Y-axis.

The downward trend in volumetric soil water content in the tree row centre on the ridge during December and January (Fig. 3.16a) confirmed conditions of under-irrigation, which improved towards the end of the season. There were large oscillations in soil water content at the 150 and 300 mm depths, whereas trees started using water during December from the 600 and

800 mm depths. Soil water content at the 300 mm depth approached the -20 kPa refill level (i.e. c. 84% TAW depletion), which for this soil may be too high.

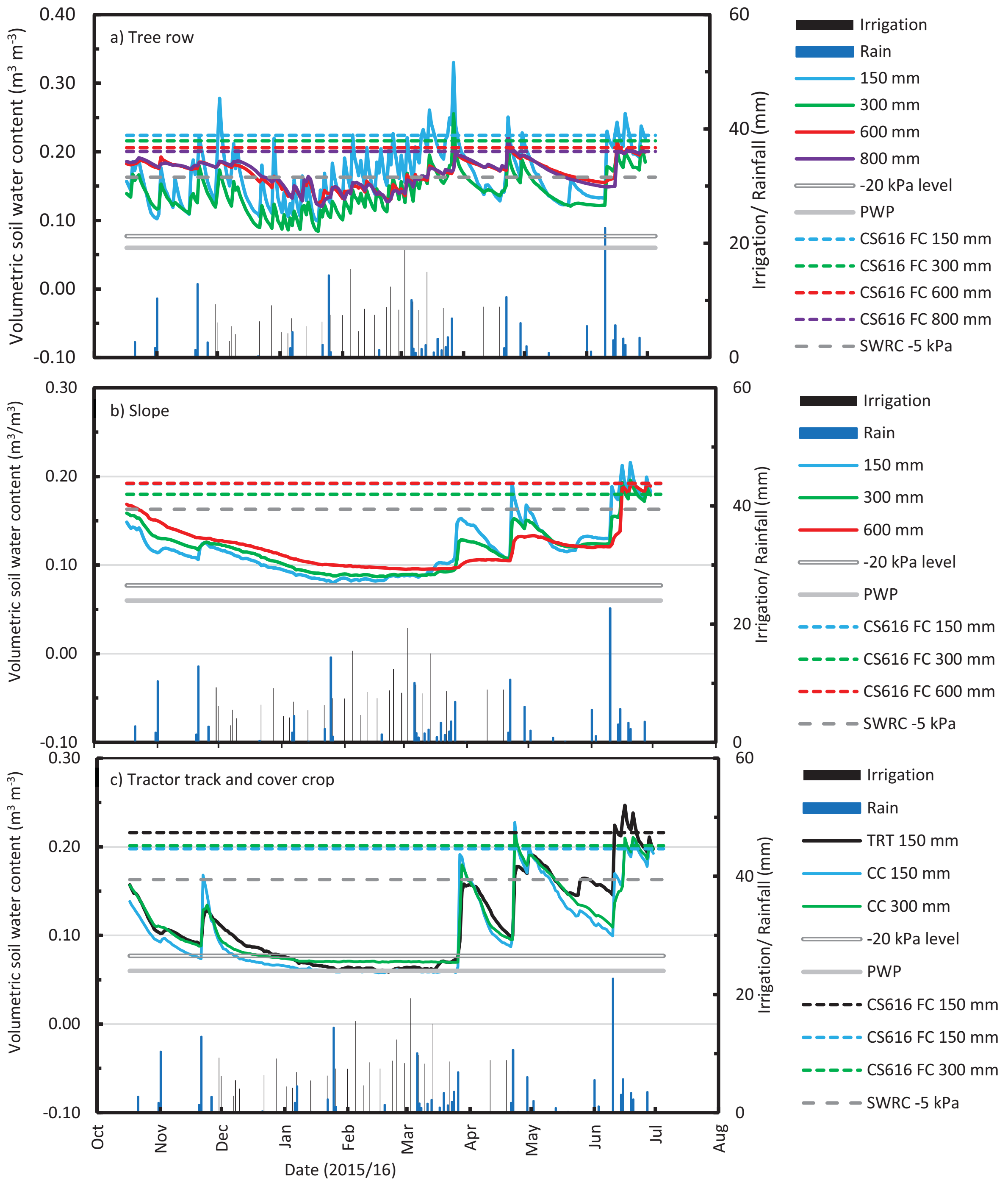


Fig. 3.16 Seasonal changes in volumetric soil water content at selected depths in a) the tree row, b) slope and c) tractor track and cover crop of a non-bearing 'Cripps' Red' orchard at Vyeboom in EGVV during 2015/16. The amount of irrigation applied on the ridge and rainfall received are indicated on the Y-axis.

The slopes of the ridge tended to be drier than the centre tree row, but the soil water content remained within the -20 kPa level limit even at the 150 mm depth (Fig. 3.16b). The soil water content in the cover crop area approached permanent wilting point in the top 150 mm during summer (Fig. 3.16c). The tractor track did not reflect irrigation of between 5.8 (±3.4) and 10.8 (±4) mm applied on the ridge (Table 3.4) clearly during summer, which could indicate that minimal runoff occurred from the slopes during this period.

3.3.3 Plant water relations and growth

3.3.3.1 Leaf gas exchange and stem water potential

In the four non-bearing low canopy cover orchards, stem water potential and gas exchange values (Tables 3.5-3.7) did not indicate unusual trends, except in the case of the NBRG KBV orchard and possibly also the NBCR EGVV orchard. Stem water potential values below -2 MPa are generally indicative of water stress. Many factors can influence stem water potential including irrigation levels and the prevailing microclimatic conditions.

The NBRG KBV orchard showed signs of significant water stress on 14 January 2015 (Table 3.5) under conditions of very high VPD_{leaf} and leaf surface temperature (T_{leaf}). This subsequently led to very low leaf transpiration rates (E), stomatal conductance (g_s), net CO_2 assimilation rate (A), and very low midday stem water potential (Ψ_{stem}) (Table 3.5). The stress was independently confirmed by the sap flow and soil water content data. The stress was caused by inadequate irrigation due to a faulty irrigation system. The stress was relieved on 16 January 2015 when the problem was rectified. Water use measurements were subsequently corrected using basal crop coefficients (T/ET_o) derived before the onset of stress in early December 2014. On 24 November 2014, this orchard showed typical reductions in A, g_s and E in the afternoon, compared to the morning (Table 3.5), linked to a moderate VPD_{leaf} and a moderate midday Ψ_{stem}. This trend was not seen in the NBGR KBV orchard on 26 November 2014, a very mild day with low VPD_{leaf} (Table 3.5). In this orchard, values of A were very high at around 20 µmol m^{-2} s^{-1} and E increased in the afternoon as stomata opened up. A very high midday Ψ_{stem} supports the conclusion that this orchard was well-watered and not experiencing stress at the time of measurements. The high A values could also reflect a strong carbon sink (demand for assimilates) in the young Golden Delicious Reinders trees and the maximising of carbon assimilation under very mild conditions.

Table 3.5 Leaf gas exchange and midday stem water potential of low canopy cover non-bearing trees of 'Rosy Glow' and 'Golden Delicious Reinders' apple orchards in the KBV production region. No measurements could be taken during the afternoon of 16/01/2015 owing to rainfall. AM = morning; PM = afternoon.

Parameter	Non-bearing Rosy Glow (KBV)				Non-bearing Golden Delicious Reinders (KBV)					
	24/11/2014		14/01/2015		26/11/2014		16/01/2015		19/02/2015	
	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
A (µmol m^{-2} s^{-1})	14.90	10.29	1.12	1.16	20.16	19.92	16.50	-	13.63	10.72
g_s (mol m^{-2} s^{-1})	0.20	0.11	0.02	0.01	0.16	0.51	0.35	-	0.21	0.15
E (mmol m^{-2} s^{-1})	4.92	3.18	0.87	0.88	2.27	3.95	3.34	-	4.02	3.97
VPD_{leaf} (kPa)	2.40	2.74	5.01	5.62	1.34	0.83	0.99	-	1.99	2.77
T_{leaf} (°C)	29.5	29.8	36.30	37.7	17.30	18.2	18.10	-	25.30	28.90
Instantaneous WUEi (mmol CO_2 mol^{-1} H_2O)	3.03	3.24	1.29	1.32	8.90	5.04	4.94	-	3.39	2.70
Intrinsic WUEi (µmol. CO_2 mol^{-1} H_2O)	74.30	95.20	73.0	84.00	125.20	38.80	47.60	-	66.60	73.50
Stem water potential (MPa)	-1.30		-2.78		-0.48		-0.79		-1.47	

Table 3.6 Leaf gas exchange and midday stem water potential of low canopy cover non-bearing trees of a 'Golden Delicious' apple orchard in the EGVV production region.

Parameter	Non-bearing Golden Delicious (EGVV)							
	16/12/2015		27/01/2016		10/02/2016		16/03/2016	
	AM	PM	AM	PM	AM	PM	AM	PM
A (µmol m^{-2} s^{-1})	17.34	13.31	16.38	14.48	14.55	9.41	17.41	14.25
g_s (mol m^{-2} s^{-1})	0.29	0.20	0.26	0.19	0.31	0.15	0.30	0.20
E (mmol m^{-2} s^{-1})	4.37	3.76	1.67	1.86	8.00	6.96	3.32	3.39
VPD_{leaf} (kPa)	1.56	1.92	0.71	1.06	2.72	4.59	1.18	1.69
T_{leaf} (°C)	26.70	27.90	24.6	27.70	35.6	38.40	28.00	28.3
Instantaneous WUEi (mmol. CO_2 mol^{-1} H_2O)	3.97	3.54	9.82	7.80	1.82	1.35	5.25	4.21
Intrinsic WUEi (µmol. CO_2 mol^{-1} H_2O)	58.90	67.00	64.30	78.10	46.90	61.90	58.3	69.90
Stem water potential (MPa)	-0.97		-0.70		-1.69		-1.21	

Table 3.7 Leaf gas exchange and midday stem water potential of low canopy cover non-bearing trees of a 'Cripps Red' apple orchard in the EGVV production region.

Parameter	Non-bearing 'Cripps' Red' (EGVV)							
	16/12/2015		27/01/2016		10/02/2016		16/03/2016	
	AM	PM	AM	PM	AM	PM	AM	PM
A (µmol m^{-2} s^{-1})	15.92	12.05	15.30	12.70	5.52	5.81	16.26	12.69
g_s (mol m^{-2} s^{-1})	0.23	0.14	0.17	0.16	0.07	0.08	0.28	0.17
E (mmol m^{-2} s^{-1})	3.11	2.83	1.14	1.45	3.44	4.54	2.81	3.25
VPD_{leaf} (kPa)	1.43	2.01	0.68	0.96	4.65	5.43	1.06	1.94
T_{leaf} (°C)	25.50	27.40	24.8	25.60	39.00	40.00	26.00	30.90
Instantaneous WUEi (mmol CO_2 mol^{-1} H_2O)	5.12	4.26	13.41	8.77	1.60	1.28	5.79	3.91
Intrinsic WUEi (µmol CO_2 mol^{-1} H_2O)	70.50	85.80	90.60	81.00	78.00	72.00	58.70	74.90
Stem water potential (MPa)	-1.30		-1.14		-1.98		-1.35	

On a warmer day on 19 February 2015, afternoon reductions in g_s and A were measured, in the young 'Golden Delicious Reinders' orchard with E remaining constant and midday Ψ_{stem} was moderately low. This could be related to the period of some water stress in late January to 26 February 2015 (see Section 3.3.4.1) when irrigation was withheld. No afternoon measurements were obtained on 16 January 2015, but the morning gas exchange and midday Ψ_{stem} measurements reflected the very mild day (with rain in the afternoon).

The results for the non-bearing 'Golden Delicious' (NBGD) EGVV orchard (Table 3.6) show that on three of the four measurement days, relatively mild conditions were experienced, with VPD_{leaf} between around -0.8 and -2.0 kPa. A and g_s were high in the morning, decreasing in the afternoon, with E remaining relatively stable from morning to afternoon. Midday Ψ_{stem} values were high on 16 December 2015 and 27 January 2016, and moderate on 16 March 2016. On 10 February 2016, very high temperatures and VPD_{leaf} were experienced, especially in the afternoon. Nevertheless, A and g_s were relatively high in the morning (with high transpirational water loss), decreasing in the afternoon (with reduced but still high E) but not indicating significant water stress. This was supported by the moderately low midday Ψ_{stem}.

The climatic conditions and general trends of gas exchange and stem water potential described above for the measurement days in 2015-2016 also apply to the non-bearing 'Cripps' Red' (NBCR) EGVV orchard (Table 3.7). Measurement days in December 2015, January 2016 and March 2016 were mild and measured values of A, g_s and E indicated normal unstressed responses of apple trees under well-watered conditions. However, g_s and E values were lower in this orchard compared to the NBGD EGVV orchard. On the very hot day (10 February 2016), trees in this orchard reduced their g_s significantly in the morning and afternoon, which led to low A values. E was still significant, rising slightly in the afternoon, and midday Ψ_{stem} was low at -1.98 MPa. This orchard experienced occasional water stress as discussed in section 3.3.4.4 and elsewhere in this report, and received less seasonal irrigation compared to the other orchards.

Some general differences were observed between non-bearing orchards in KBV compared to EGVV. A and g_s were usually higher in EGVV than KBV. This can be explained by differences in climatic conditions, with ETo being higher in KBV (section 3.3.1), leading to stronger stomatal closure. This helped to control E and led to higher WUE, with apparent acclimation of xylem hydraulic properties. Since individual trees in KBV and EGVV had very similar total seasonal transpiration (see section 3.3.4, with the exception of NBCR EGVV which was under-irrigated), the conclusion is that stomatal regulation of transpirational water loss at leaf level, together with possible acclimation of xylem hydraulic properties, resulted in similar tree-level water use in all the well-watered young orchards.

3.3.3.2 Diurnal stem diameter fluctuations

The maximum daily shrinkage (MDS) and daily growth (DG) values in all orchards were found to be strongly related to the volumetric soil water content. The maximum daily trunk diameter decreased as the soil became drier leading to negative DG values (Fig. 3.17). Non water stressed conditions are shown when the consecutive maximum daily trunk diameters increased as the soil water content increased. Generally, a decrease in the volumetric water content of the soil induced a reduction in stem growth which is an indication of water stress. So, the stem size change information can be used as a measure of tree water status although this data will not be discussed in this report.

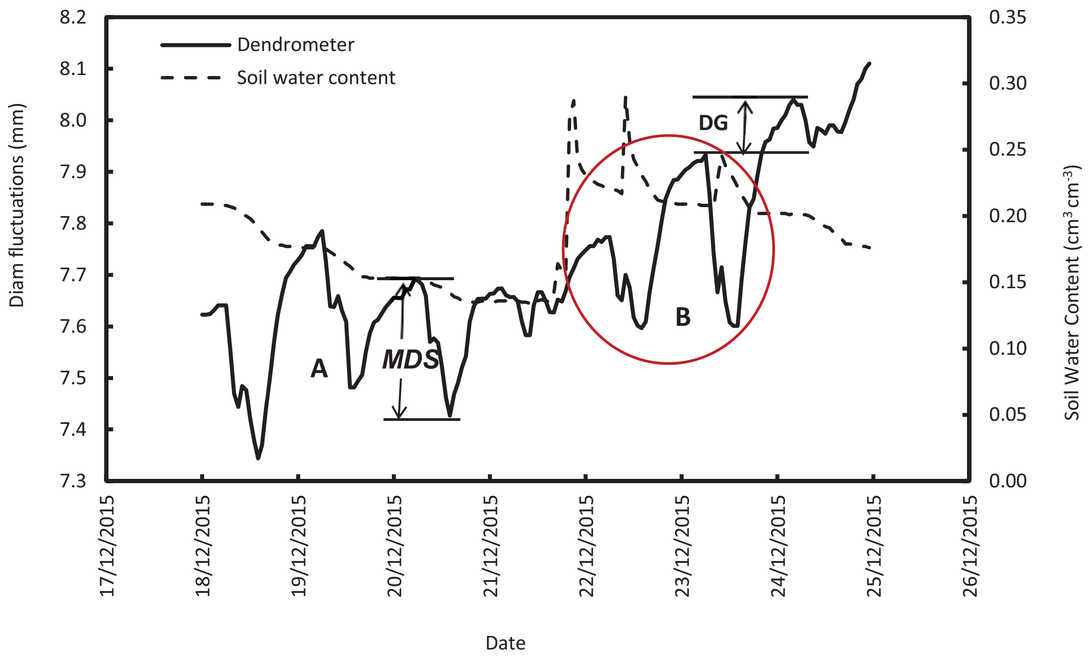


Fig. 3.17 Daily trunk diameter fluctuation of a tree in the FBGD EGVV orchard as a) as volumetric water content was decreasing and b) as volumetric water content was increasing. A representation of the quantification of maximum daily shrinkage (MDS) and daily growth (DG) is shown.

3.3.4 Tree and orchard scale transpiration rates

3.3.4.1 Non-bearing 'Golden Delicious Reinders' in KBV

Transpiration by a typical young 'Golden Delicious Reinders' tree at Lindeshof peaked at 9.9 L d^{-1} in January 2015 (Fig. 3.18). This is within the same range as that observed by Volschenk et al (2003) at Molteno Glen farm. In that study they recorded peak transpiration of about 8.4 L $tree^{-1}$ d^{-1} in four-year-old 'Golden Delicious' trees. The seasonal total transpiration in the present study for the period 01 October 2014 to 30 June 2015 was 1 184 L $tree^{-1}$. The transpiration was significantly lower than the ~ 3 080 L received by each tree through irrigation during the season.

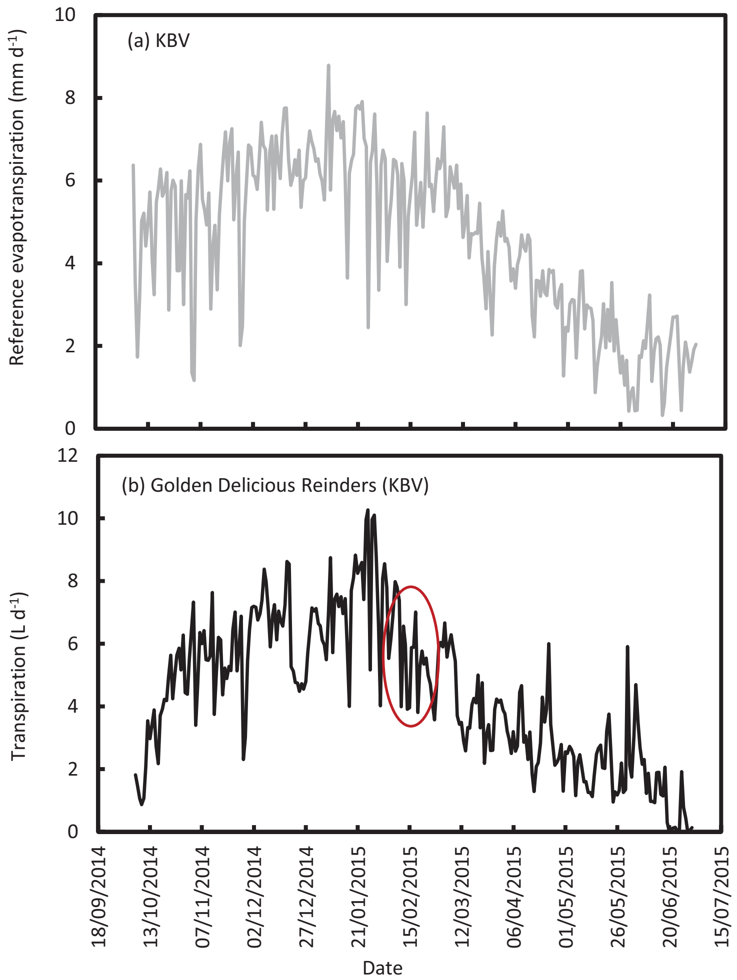


Fig. 3.18(a) Seasonal evapotranspiration trend in KBV during the 2014/15 season. (b) Daily transpiration dynamics of a young non-bearing 'Golden Delicious Reinders' from 01 October 2014 to 30 June 2015.Red circle indicate a period of water stress.

The trees experienced some water stress from late January to February 2015 (see red circle in Fig. 3.18b) when irrigation was withheld. This reduced the leaf transpiration rates as shown by the gas exchange measurements presented in section 3.3.3.1. An increase in transpiration was evident on 26 February 2015 when the stress was relieved. Expressed in equivalent depth units, daily transpiration of the young ‘Golden Delicious Reinders’ orchard peaked at 1.74 mm, reached on 23 January 2015. The seasonal total transpiration was about 199 mm translating to actual tree water consumption of around 2 000 m^3 ha^{-1} $season^{-1}$.

3.3.4.2 Non-bearing ‘Rosy Glow’ in KBV

Non-bearing ‘Rosy Glow’ trees at Paardekloof had a maximum daily transpiration of approx. 8.5 L $tree^{-1}$ (Fig. 3.19). An average tree transpired about 1 188 L for the entire season compared to about 1 600 L of irrigation. However, rather severe, albeit unintended, stress occurred in this orchard from around 09 December 2014 to about 16 January 2015 as reported in Section 3.3.3. During this period the daily maximum transpiration dropped by up to 70%. We corrected for the stress by deriving a basal crop coefficient (K_{cb}) for the orchard using data collected a few days before the onset of the stress in December. The corrected unstressed transpiration (T) was derived according to Allen et al. (1998) as $T = K_{cb} \times ET_o$ where K_{cb} was derived for clear days and when the soil water content was close to field capacity. The trees fully recovered from the stress when normal irrigation was resumed.

Peak daily transpiration of the orchard expressed in equivalent depth units was 2.02 mm, which was higher than that of the young ‘Golden Delicious Reinders’ at Lindeshof. The total transpiration for the ‘Rosy Glow’ orchard from 01 October 2014 to 30 June 2015 was about 271 mm translating to approx. 2 700 m^3 ha^{-1} season. The higher transpiration at Paardekloof was a direct consequence of the higher tree density (2 285 tree ha^{-1}) compared to 1 667 at Lindeshof. The number of trees per hectare influences orchard level transpiration rates in young orchards because of a greater sapwood area index (m^2 of sapwood per m^2 of ground area) and the sap velocities were similar given the similar canopy sizes. However, tree density driven transpiration rate variations are expected to disappear in mature orchards when the trees fill up their allocated space, but this should be confirmed by actual measurements.

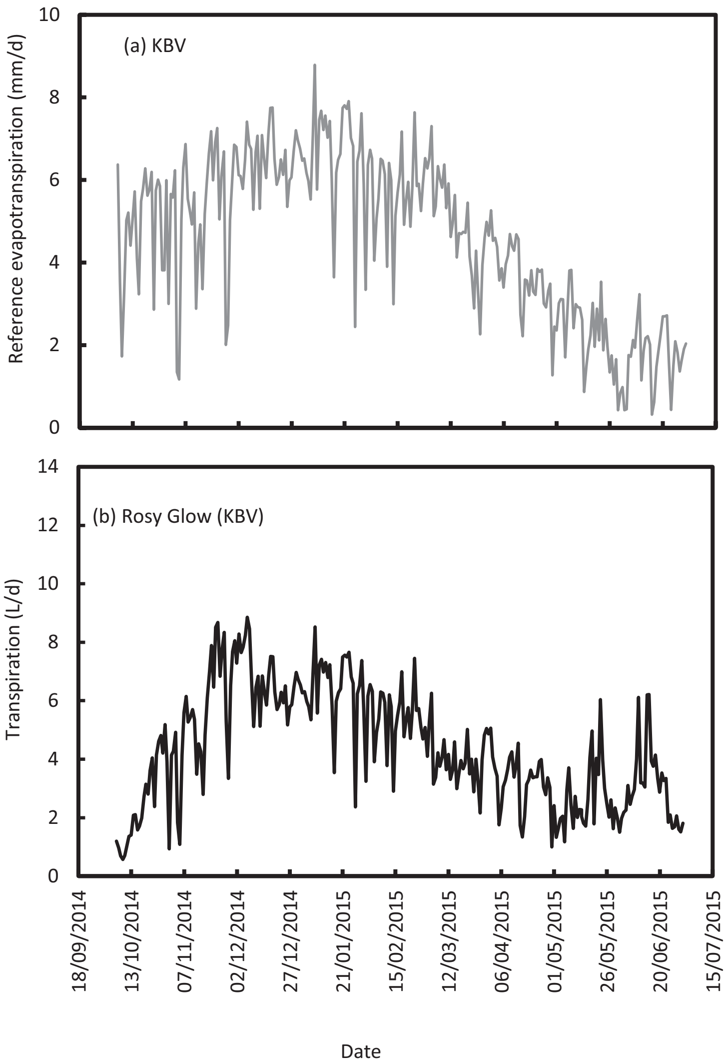


Fig. 3.19 (a) Seasonal evapotranspiration, and; (b) transpiration of a young non-bearing 'Rosy Glow' apple tree (in L d^{-1}) at Paardekloof farm.

3.3.4.3 Non-bearing 'Golden Delicious' in EGVV

The effect of the climate driving variables on the daily transpiration of the young 'Golden Delicious' trees in EGVV from 01 October 2015 to 30 June 2016 is shown in Fig. 3.20a. The daily maximum transpiration by a typical non-bearing 'Golden Delicious' tree peaked at around 11 L during the summer (Fig. 3.20b). The seasonal total transpiration of a single tree was approximately 1 195 L which was not substantially different from the 'Golden Delicious Reinders' or 'Rosy Glow' trees in KBV. Total irrigation per tree for the young 'Golden Delicious' orchard was about two times the seasonal transpiration at 2 430 L.

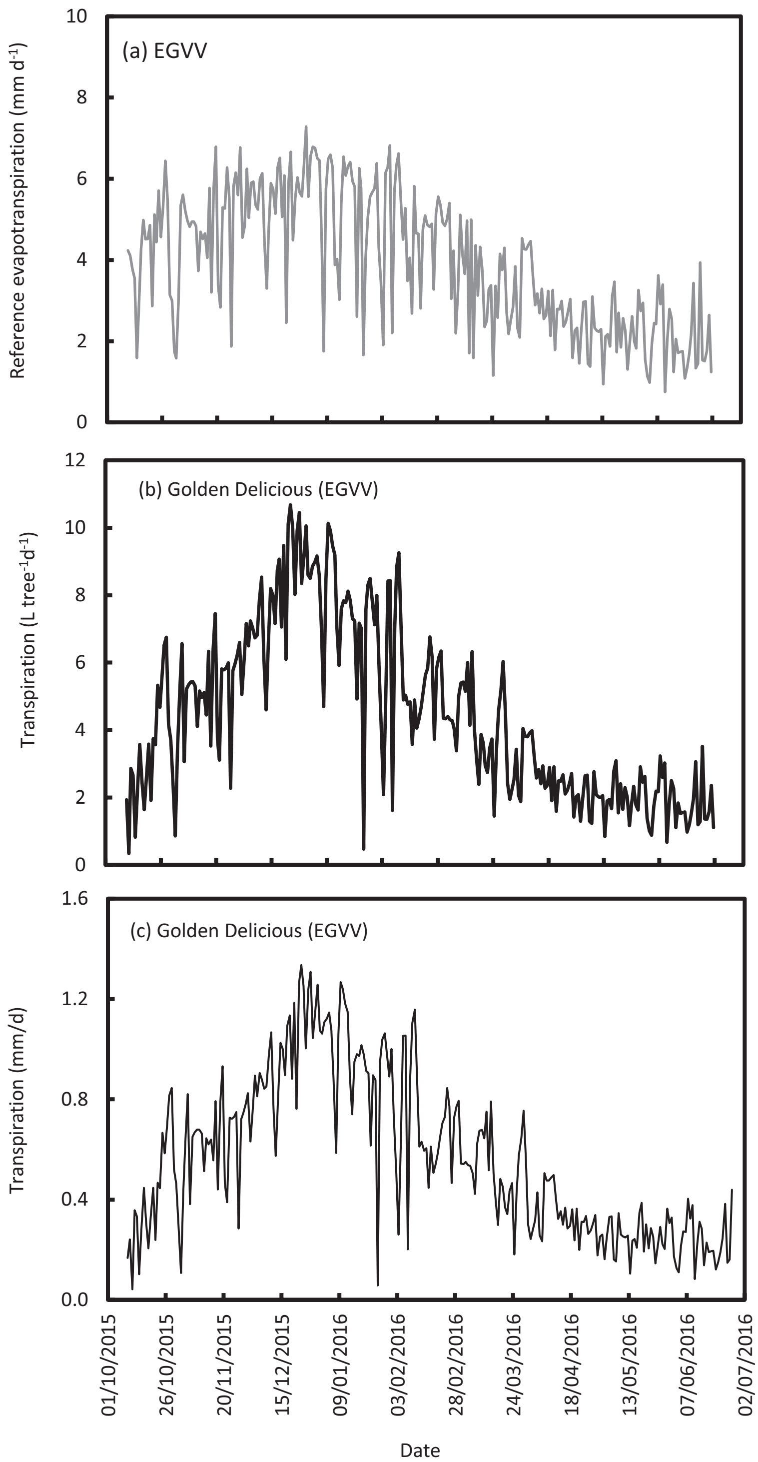


Fig. 3.20 Seasonal course of: (a) the daily reference evapotranspiration, (b) transpiration (in L d^{-1}), and; (c) transpiration (in mm/d) by the young Golden Delicious orchard in EGVV during the 2015/16 season.

Peak transpiration of the young ‘Golden Delicious’ orchard in EGVV expressed in depth units was about 1.3 mm d^{-1}. This was lower than that obtained for both orchards in KBV mainly because of the lower tree density in EGVV (1 250) compared to KBV (1 667-2 285). Differences in the climatic conditions between the two regions also play a part as evidenced by the higher total ET_o in KBV (Section 3.3.1). The seasonal total transpiration for the young ‘Golden Delicious’ orchard in EGVV was about 155 mm which was lower than the Golden Delicious Reinders in KBV. This transpiration value (1 550 m^3 ha^{-1} $season^{-1}$) is slightly lower than that recorded for a young non-bearing ‘Golden Delicious’ in EGVV by Volschenk et al. (2003) who recorded approximately 1 739 m^3 ha^{-1} per season in a four year old orchard in the same production region.

3.3.4.4 Non-bearing ‘Cripps’ Red’ in EGVV

Maximum daily transpiration by a young ‘Cripps’ Red’ tree in EGVV was relatively low compared to the other three orchards at just above 8 L (Fig. 3.21b). A single ‘Cripps’ Red’ tree transpired approx. 1 017 litres of water during the whole 2015/16 season. In equivalent depth units, peak transpiration of the ‘Cripps’ Red’ orchard was around 1.1 mm d^{-1} (Fig. 3.21c). The relatively low transpiration rates in the ‘Cripps’ Red’ orchard was partly a result of the smaller canopy size and also occasional water stress consistent with the soil water balance and eco-physiological measurements (Section 3.3.3). Each tree received about 1 150 L of irrigation which was quite low compared to the other orchards.

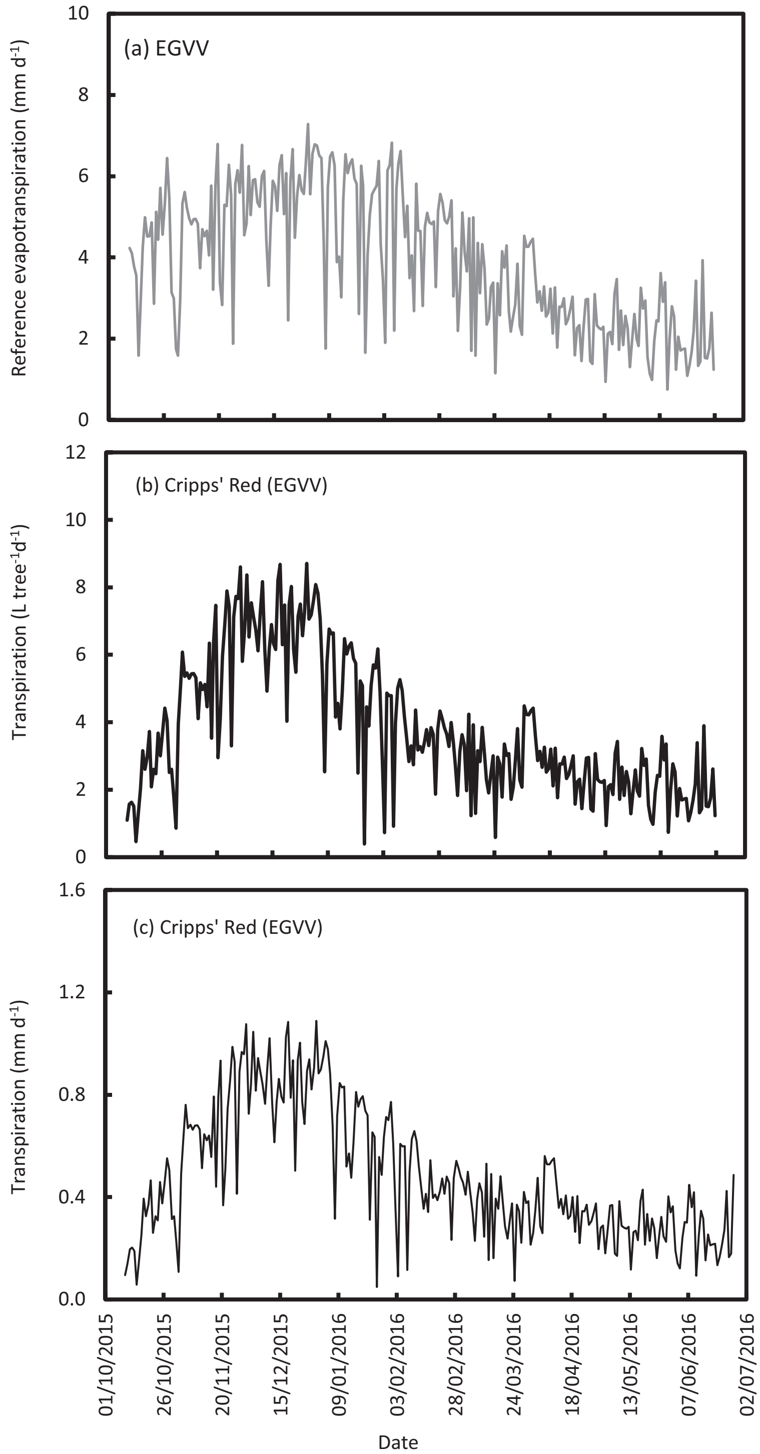


Fig. 3.21 Seasonal course of: (a) the daily reference evapotranspiration, (b) transpiration (in L d^{-1}), and; (c) transpiration (in mm d^{-1}) by the non-bearing 'Cripps' Red' orchards in EGVV.

3.3.5 Evapotranspiration in young apple orchards

3.3.5.1 Partitioning of energy in young orchards

The typical energy balance of a young non-bearing 'Golden Delicious Reinders' orchard that is well-watered at Lindeshof (KBV) is shown in Fig. 3.22. The data were collected over three cloudless days during the peak water use period from 19 to 21 February 2015. According to equation 3.1, the available energy (i.e. $R_n - G$) can be used to warm the air (i.e. converted to the sensible heat flux). It can also be used for evapotranspiration (i.e. converted to the latent heat flux) or both. In young orchards, a large proportion of the available energy is converted to sensible heat given that the transpiring leaf area is small and less energy is required for evaporation. In addition, the available energy also tends to be small compared, for example, to mature orchards given the high surface albedo of young orchards due to the large exposed bare soil fraction and also because a large proportion of the incoming energy (i.e. net radiation, R_n) is converted to the soil heat flux (G).

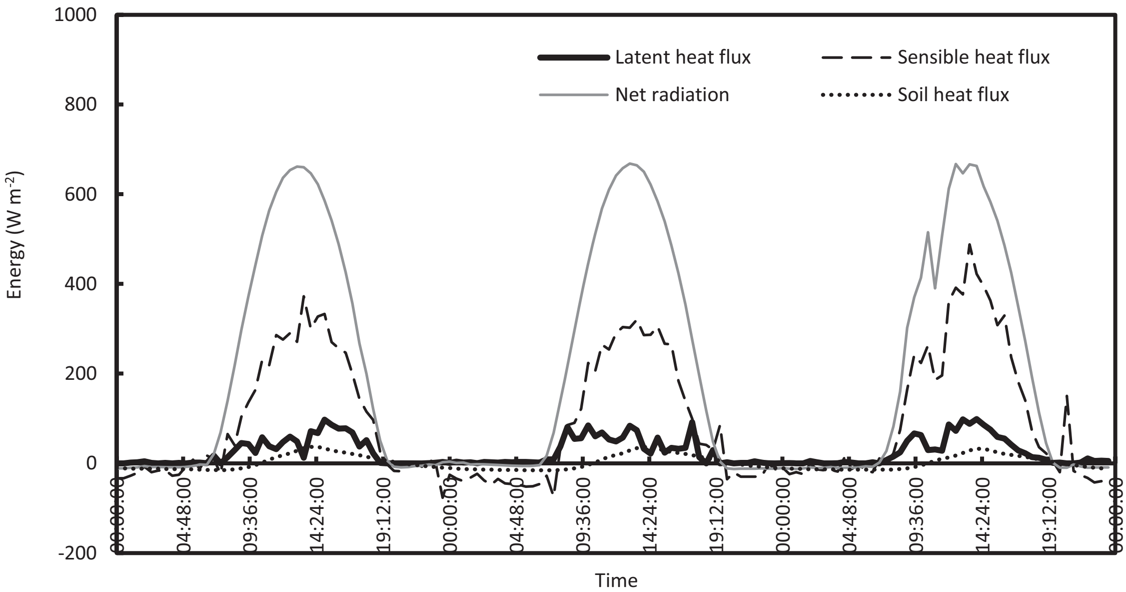


Fig. 3.22 The energy balance of a young non-bearing 'Golden Delicious Reinders' orchard from 19 – 21 February 2015 in the Koue Bokkeveld.

3.3.5.2 Energy balance closure in young orchards

Plotting the sum of the sensible and latent heat fluxes against the available energy for the young orchards using 30 min data collected during selected periods from 16 October 2014 to 27 February 2015 in the young 'Golden Delicious Reinders' orchard at Lindeshof shows a substantial lack of energy balance closure (Fig. 3.23). The dotted line depicts the one-to-one line. It is clear that at least 17% of the available energy was not accounted for by the sensible and latent heat fluxes. Similar trends were observed for the other young orchards in both production regions. Therefore the latent heat fluxes presented in this report were corrected for the lack of energy balance closure using the Bowen ratio approach presented in equations 3.1 and 3.2.

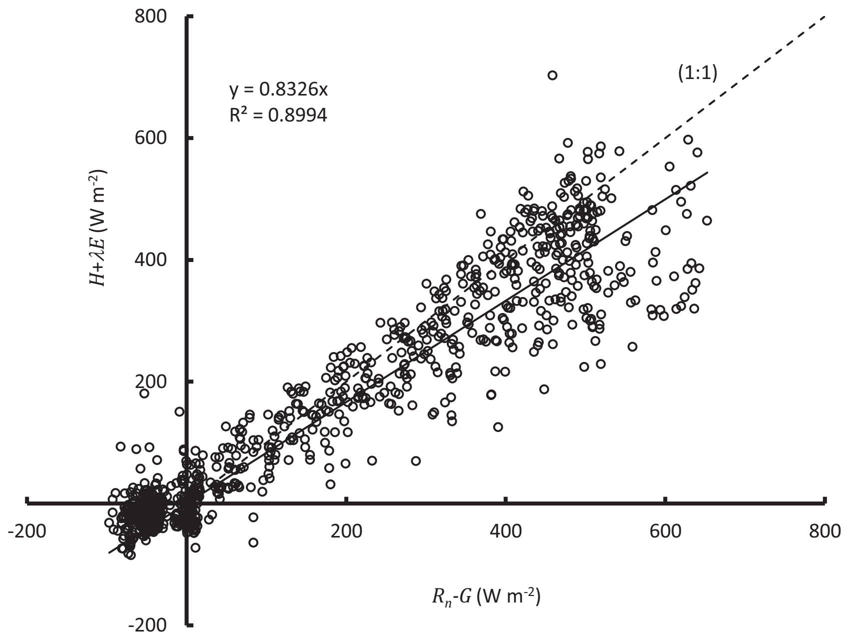


Fig. 3.23 Energy balance closure for a young non-bearing orchard in the Koue Bokkeveld from October 2014 to February 2015.

3.3.5.3 Evapotranspiration dynamics in young orchards

Typical seasonal time series for the measured reference evapotranspiration, actual evapotranspiration (ET), and transpiration in a young apple orchard are shown in Fig. 3.24. The measured ET was lower than the ET_o but higher than the measured transpiration for both KBV orchards. Similar orders of magnitude of the fluxes were observed in the young orchards in EGVV. There is an interesting trend however, in the 'Golden Delicious Reinders' ET data collected in February 2015 highlighted by the oval shape in Fig. 3.24a. It is clear that plant transpiration and orchard ET were much closer compared to any other period. This suggested that the contribution of the orchard floor evaporation to orchard ET was quite small at that time, while the trees continued to transpire, likely with water drawn from the deeper soil profiles as the orchard had experienced high irrigation levels earlier in the season. So, earlier campaigns in Fig. 3.24a from 05 November to 15 December 2014 show that the orchard floor evaporation accounted for a large proportion of ET when the orchard was well-watered. This observation is supported by micro-lysimeter soil evaporation measurements presented elsewhere in this report.

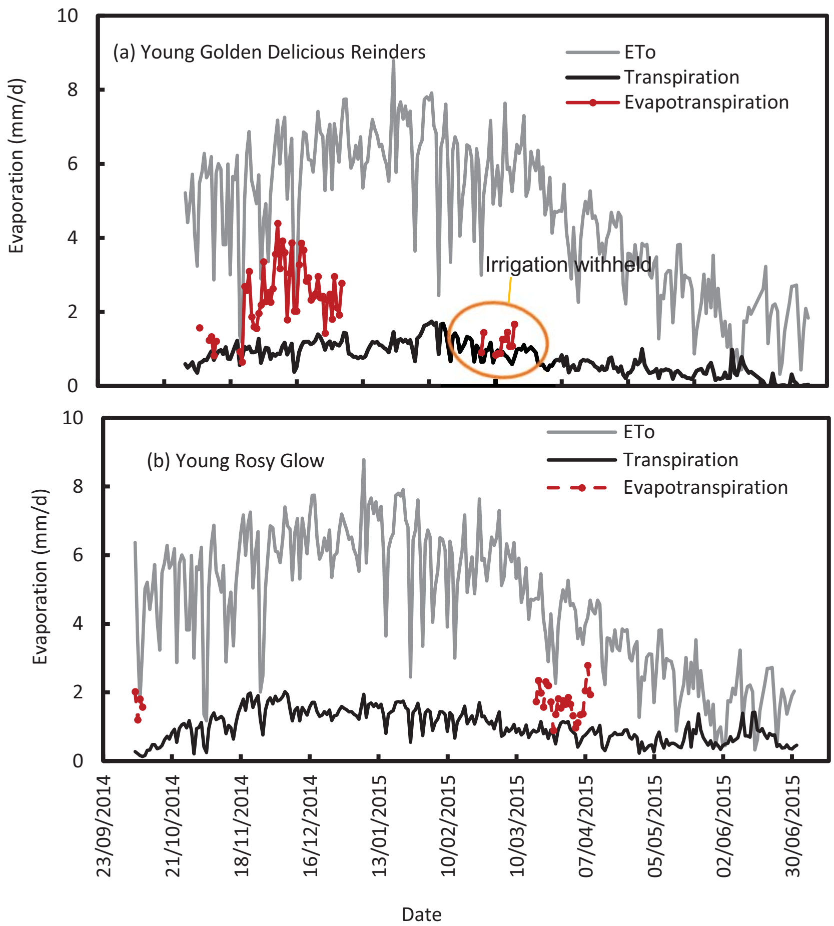


Fig. 3.24 Comparison of measured transpiration (bold black lines), actual evapotranspiration (red lines) and the short grass reference evapotranspiration (grey line) for: (a) young non-bearing 'Golden Delicious Reinders'; (b) young non-bearing 'Rosy Glow' orchards in KBV during the 2014/15 season.

The relationship between the measured ET and the reference evapotranspiration was generally linear (Fig. 3.25) suggesting that the climate variables were the main drivers of orchard ET when the orchards were well-watered. However, the scatter was high (low R^2) in orchards that experienced substantial water stress e.g. the ‘Cripps’ Red’ in EGVV (Fig. 3.25c) where partial stomatal closure may have occurred in response to the soil water deficit. Peak daily ET was in the range 4.0 to 4.8 mm in most orchards (Fig. 3.25).

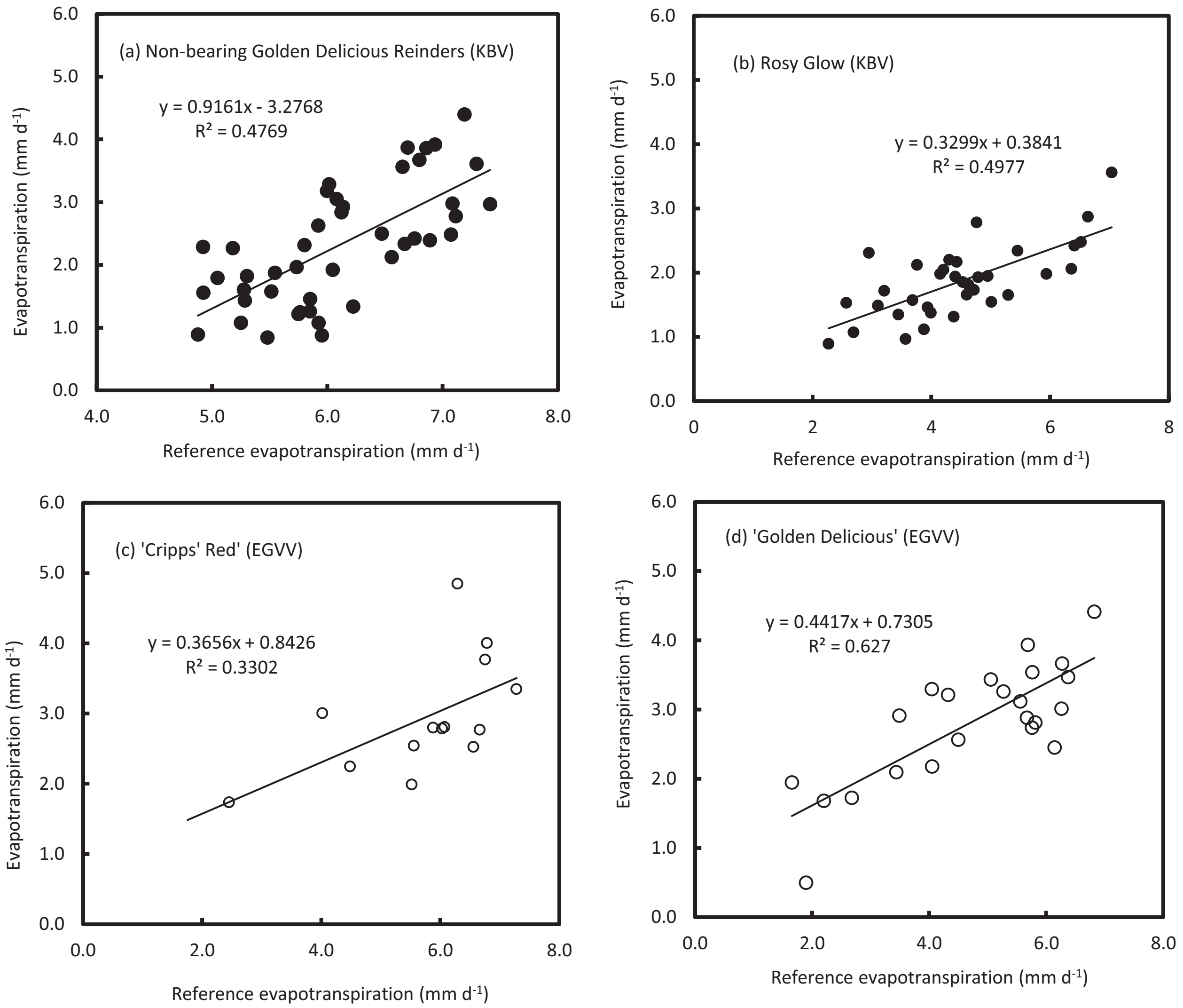


Fig. 3.25 Comparison of the evapotranspiration measured using the eddy covariance system with the reference evapotranspiration in young non-bearing (a) ‘Golden Delicious’ Reinders, (b) ‘Rosy Glow’, (c) ‘Cripps’ Red’, and; (d) ‘Golden Delicious’ orchard.

3.3.5.4 Evapotranspiration derived from the soil water balance method

At Lindeshof, overly wet conditions especially during November and January complicated calculation of evapotranspiration (ET) according to a daily soil water balance. The ET in general followed the trend of ET_o over the season (Fig. 3.26a).

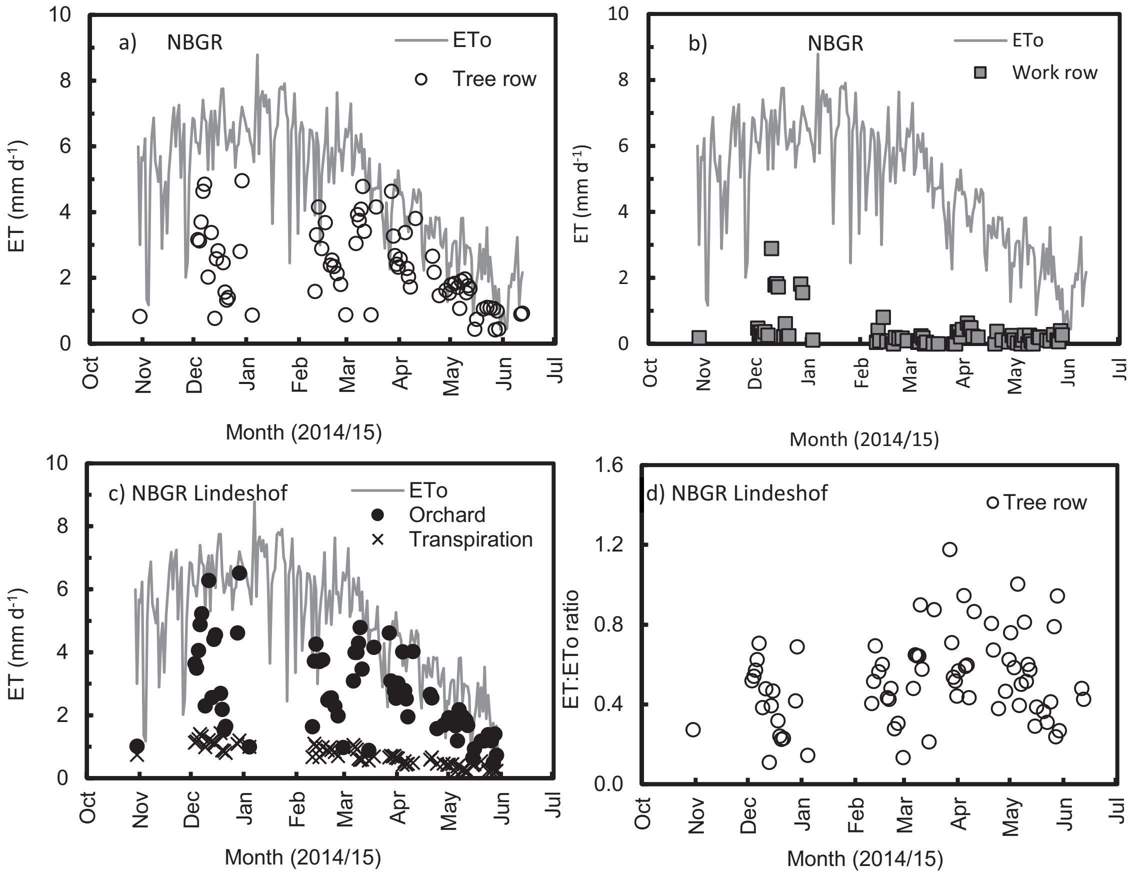


Fig. 3.26 Seasonal changes in reference evapotranspiration (ETo) and evapotranspiration (ET) of the a) tree row, b) work row and c) orchard of a non-bearing 'Golden Reynders' orchard at Lindeshof in the Koue Bokkeveld during the 2014/15 season. The amount of tree transpiration (T) relative to orchard ET and the ET: ET_o ratio for the irrigated tree row area is indicated in c) and d), respectively.

From the limited dataset available the maximum ET in the tree row from December to March was c. 4.8 mm d^{-1} (Fig. 3.26a). After end March the ET decreased almost linearly until June. The maximum water loss from the non-irrigated work row was 2.9 mm d^{-1} in December 2014, but the water use declined as the soil dried as the season progressed (Fig. 3.26b). A tree and work row weighted ET for the orchard reached a maximum of 6.5 mm d^{-1} for the season. However, an average of 4.6 mm d^{-1} seem to be a better estimate for the water use of the orchard until end March (Fig. 3.26c) consistent with the eddy covariance derived ET values. Higher water use in May and June may be attributed to the growth of grasses and weeds in the tree row. The ET decreased in between irrigations and based on the estimated soil matric potential it is possible that trees could have been subjected to water stress during February and March 2015. In February there was a clear tendency for ET and transpiration to decrease as the volumetric soil water content in the tree row decreased (data not shown). The ET:ET_o ratio for the irrigated tree row was c. 0.7 for the period until end February, after which it increased to between 0.87 and 1.18 in March (Fig. 3.29d). The increased ratio at the end of the season may be due to more available soil water to the tree (Fig. 3.13a), lower ET_o (Fig. 3.26a) and probably added water use of weeds in the tree row. The monthly averaged ET and ET: ET_o ratios of data available for the orchard and its components are summarized in Table 3.8.

Table 3.8 Monthly averaged orchard component and total orchard evapotranspiration (ET) and ET to Penman-Monteith reference evapotranspiration (ET_o) ratios for the non-bearing 'Golden Delicious Reinders' at Lindeshof in the Koue Bokkeveld in 2014/15. The number of days with reliable data are indicated (N).

Month	ET (mm d^{-1})			ET:ET_o ratio			N
	Tree row	Work row	Orchard	Tree row	Work row	Orchard	
Oct	0.8	0.2	1.0	0.27	0.06	0.34	1
Nov	-	-	-	-	-	-	0
Dec	2.8	0.9	3.8	0.43	0.14	0.57	16
Jan	-	-	-	-	-	-	1
Feb	2.5	0.2	2.7	0.44	0.04	0.47	11
Mar	3.4	0.1	3.5	0.66	0.02	0.68	12
Apr	2.3	0.3	2.6	0.63	0.08	0.72	11

The daily ET water balance calculations of the non-bearing 'Cripps' Red' NBCR orchard in EGVV indicated that the maximum ET that occurred from the irrigated area, cover crop and non-irrigated area during the season was 5.4, 1.7, and 1.6 mm, respectively (Fig. 3.27 a-c). In general, maximum summer water use from the irrigated area and orchard was about 3.4 and 3.9 mm, respectively and ET tended to decrease from end February (Fig. 3.27 a & d). The non-irrigated cover crop started using more water during April and May after rainfall occurred (Fig. 3.27b). Water losses from the non-irrigated area was primarily due to evaporation after irrigation events and water used by weeds (Fig. 3.27c). In general, the maximum ET:ET_o ratio for the irrigated area during December to February was about 0.75 (Fig. 3.27e). The monthly averaged ET and ET: ET_o ratios of data available for the orchard and its components are summarized in Table 3.9.

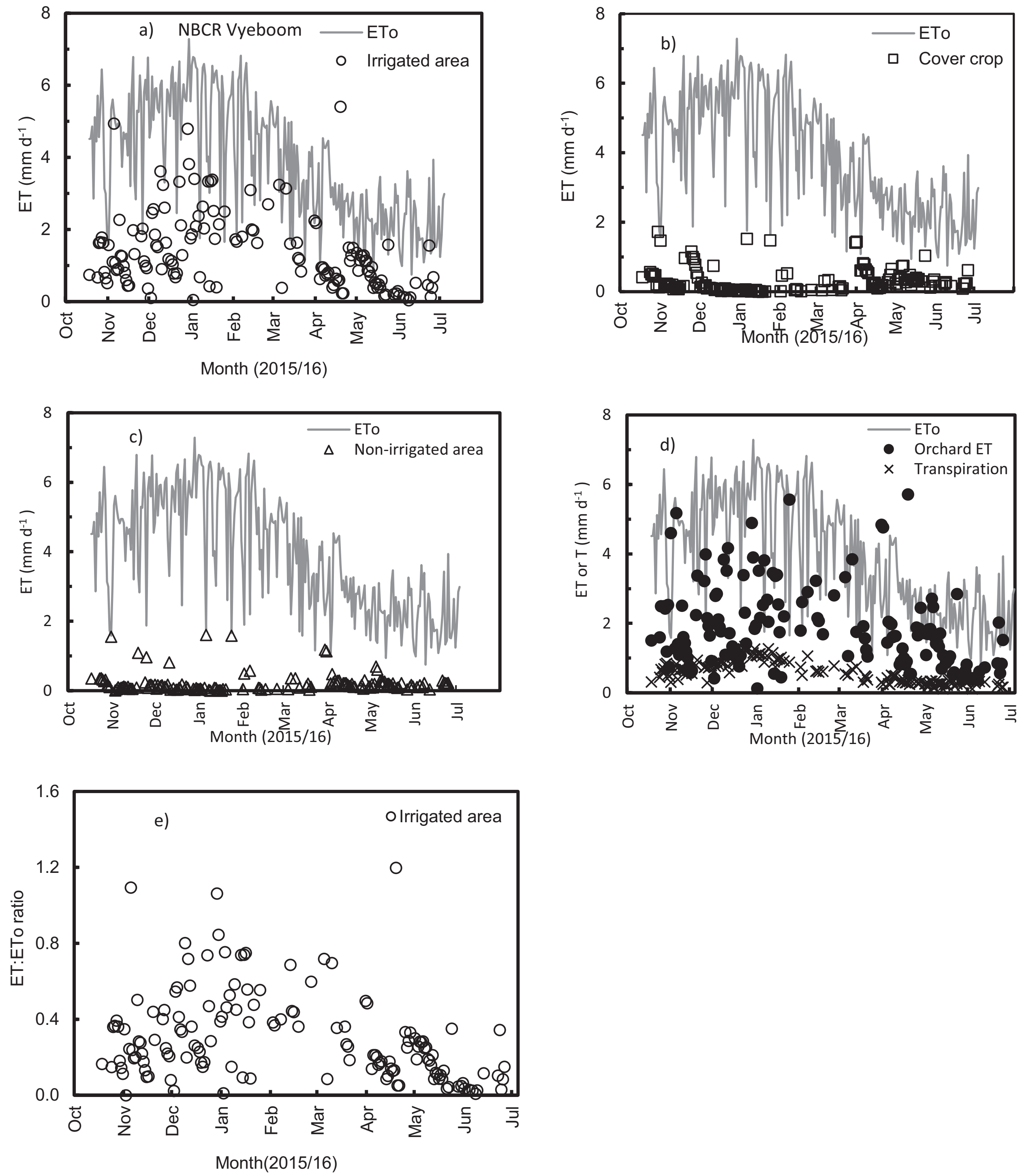


Fig. 3.27 Seasonal changes in reference evapotranspiration (ET_o) and evapotranspiration (ET) of a) the irrigated fraction of the ridge, b) non-irrigated cover crop, c) non-irrigated fraction of the ridge and tractor track and d) the orchard of a non-bearing 'Cripps Red' orchard at Vyeboom during the 2015/16 season. The amount of tree transpiration relative to orchard ET and the ET:ET_o ratio for the irrigated ridge is indicated in d) and e), respectively.

Table 3.9 Monthly averaged orchard component and total orchard evapotranspiration (ET) and ET to Penman-Monteith reference evapotranspiration (ET_o) ratios for the non-bearing 'Cripps Red' at Vyeboom in 2015/16. The number of days with reliable data are indicated (N).

Month	ET (mm d^{-1})				$ET:ET_o$ ratio				N
	Irrigated area	Non-irrigated	Cover crop	Orchard	Irrigated area	Non-irrigated	Cover crop	Orchard	
Oct	1.1	0.3	0.6	1.9	0.25	0.06	0.12	0.43	9
Nov	1.3	0.2	0.4	2.0	0.28	0.05	0.09	0.42	22
Dec	1.9	0.1	0.1	2.2	0.43	0.03	0.03	0.48	23
Jan	2.1	0.2	0.2	2.5	0.45	0.05	0.04	0.55	17
Feb	2.1	0.2	0.2	2.4	0.46	0.04	0.03	0.53	8
Mar	1.7	0.3	0.3	2.3	0.38	0.06	0.06	0.51	9
Apr	1.1	0.3	0.4	1.8	0.24	0.06	0.10	0.39	21
May	0.7	0.2	0.4	1.3	0.17	0.04	0.08	0.29	25
Jun	0.4	0.2	0.2	0.8	0.09	0.04	0.05	0.18	11

3.3.5.5 Evapotranspiration of young apple orchards from FruitLook

The FruitLook remote sensing product has been in use by the Western Cape farmers for the past few years. Here we compare its water use estimates with the measured ET data in the two young apple orchards in KBV. The measured ET data in EGVV was not sufficiently continuous, so we exclude it from this analysis. The performance of FruitLook was evaluated based on the root mean square error (RMSE) and the coefficient of determination (R^2). The predictive accuracy of the tool was established using the Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970) calculated as:

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^{n} (Y_i^{obs} - Y^{mean})^2} \right] \tag{3.3}$$

where Y_i^{obs} is the i^{th} observation of the daily ET, Y_i^{sim} is the i^{th} simulated ET, and Y^{mean} is the mean ET value and n is the total number of observations. The NSE ranges between -∞ and 1.0 with NSE = 1.0 being the optimal value and values between 0 and 1.0 are generally viewed as acceptable levels of performance (Moriasi et al., 2007). Values ≤0.0 indicate that the mean observed value is a better predictor than the simulated value which indicates unacceptable model performance.

There were 12 weeks of eddy covariance ET data in the young orchards during 2014/15 (Table 3.10). The root mean square error was quite low at ±1.9 mm week^{-1}. The coefficient of determination indicated a significant scatter between the FruitLook and eddy covariance derived ET (R^2 = 0.15). The Nash-Sutcliffe Efficiency was -0.73 which indicated difficulties of FruitLook in estimating ET in young orchards. A possible reason for the poor performance of FruitLook in young orchards includes uncertainties in the measured eddy covariance data. Most of the eddy covariance data was obtained from the 'Golden Delicious Reinders' orchard at Lindeshof which had a limited spatial extent. So, further validation of FruitLook in young orchards is required to confirm the observations made here.

Table 3.10 Comparison of the weekly eddy covariance derived ET ($ET_{\_ec}$) with the FruitLook predicted values ($ET_{\_FL}$) in two young apple orchards in KBV during the 2014/15 growing season.

Week ending	***ET_o (mm week^{-1})***	***$ET_{\_ec}$ (mm week^{-1})***	***$ET_{\_FL}$ (mm week^{-1})***	***Orchard***
11/11/2014	39.7	15.4	23.2	NBGR
18/11/2014	33.3	18.8	1.67	NBGR
25/11/2014	51.8	23.8	13.9	NBGR
02/12/2014	35.3	20.7	13.2	NBGR
09/12/2014	44.6	16.4	15.1	NBGR
16/12/2014	45.8	16.4	28.1	NBGR
24/02/2015	40.2	7.6	10.8	NBGR
24/03/2015	29.9	14.1	8.7	NBRG
31/03/2015	28.9	10.7	9.2	NBRG
07/04/2015	28.3	9.6	7.3	NBRG

3.4 Conclusions

The seasonal total transpiration of young apple orchards investigated varied from 1 500 to close to 3 000 m^3 ha^{-1}season^{-1}. Climatic factors, mainly the daily solar radiation and the VPD of the air were the main factors driving water use by the orchards under well-watered conditions. Plant density (no of trees per hectare) and soil water deficit also strongly influenced the transpiration rates of the young orchards. While the daily transpiration rates of individual trees were similar, orchards with larger number of trees per hectare had higher orchard level transpiration rates because of a bigger sap wood area index (m^2 of sap wood per m^2 of ground area). Some of the orchards e.g. the 'Rosy Glow' in KBV and the 'Cripps' Red' in EGVV experienced water stress during the course of the season. This inevitably affected the water use values although the other orchards were reasonably well-watered. Comparing the measured transpiration with the orchard ET measured by the eddy covariance method and by the soil water balance method, it is clear that under well-watered conditions, orchard ET was more than double the actual tree water use (transpiration). This suggests that significant amounts of water can be saved by reducing orchard floor evaporation in young orchards. The information generated can be used to improve irrigation scheduling in young orchards which is an important first step towards efficient water management.

CHAPTER 4

WATER USE AND ITS DRIVERS IN APPLE ORCHARDS WITH MEDIUM (30-44%) CANOPY COVER

4.1 Introduction

Orchards in the age range 4 to 10 years had the second largest area planted to apple trees in South Africa in 2016 accounting for 5 810 ha (or ~ 24%) (Hortgro, 2016). Many of these orchards have a medium canopy cover, defined in this study as an effective vegetation cover in the range 30 to 44% at solar noon when canopy size was maximum in summer (December-January). Trees that fall into this category (medium cover) can be young trees in the early stages of bearing. They can also be older trees nearing the full-bearing age but with canopies that are kept small e.g. through pruning or use of growth retardants. Since the goal of this study was to quantify how orchard water use varied from planting until full-bearing, it was necessary to identify orchards with attributes between the young non-bearing and the mature full-bearing orchards. Because crop load also influences orchard water use (Naor et al., 1997; Naschitz and Naor, 2005) our site selection criterion during the 2016/17 season involved identifying orchards that had; 1) a medium canopy cover as defined above, and; 2) expected yield in the range 30 to 50 t ha^{-1}.

Some studies have investigated the effect of canopy cover on water use by apple orchards (e.g. (Cohen and Naor, 2002, Li et al., 2002); McClymont et al., 2011). According to Li et al (2002), canopy structure enters orchard transpiration calculations through energy balance models (Consoli and Papa, 2013; Dzikiti et al., 2011) and combination equations such as the Penman-Monteith. Canopy size also influences the amount of radiation intercepted which influences yield quality and quantity. The fraction of the orchard floor covered by vegetation influences the partitioning of water use between tree transpiration and evaporation from the orchard floor (Kool et al., 2014). The aim of this chapter was to quantify the water use by apple orchards with a medium canopy cover and little information currently exists for these orchards. Tree physiological responses to environmental variables were investigated in order to understand the key drivers of water use and orchard productivity. Yield and fruit quality were also monitored, but these data are presented in Chapter 7.

4.2 Materials and methods

4.2.1 Study sites and plant material

4.2.1.1 Orchards with medium canopy cover in KBV

In KBV data was collected at Esperanto (S33.36527º; E019.32240º; 860 m asl) and Lindeshof farms (S32.95002º; E019.20737º; 820 m asl). At Esperanto, the orchard (Block 15) was planted to the Cripps' Pink cultivar on M793 rootstock. The orchard was planted in 2009 and it was 7 years old at the time of the study. The block was about 4.2 ha in size and it was irrigated with a wide range micro-sprinkler system with a wetted radius of about 1.5 m. There was one sprinkler per tree with a delivery rate of about 30 L h^{-1}. Irrigation was applied at least three times per week during most of the season, but more frequently (almost daily) during summer. The orchard floor had a dense cover crop dominated by the indigenous Eragrostis species (*Eragrostis capensis*) mixed with a complex assortment of weed species. The width of the cover crop strip was about 1.3 m on average. Tree spacing was 4.5 m x 2.0 m giving a tree density of ~1 111 trees per ha, of which 10% was the 'Granny Smith' pollinator. The trees were planted on ridges on deep sandy soils described in detail in section 4.2.2.

The 'Golden Delicious Reinders' orchard at Lindeshof was the same orchard that was used during the 2014/15 season. However, the orchard was now 5 years old during the 2016/17 season and it was in the second year of bearing. In contrast to the 2014/15 season, this time the orchard had no cover crop as the plants were removed as a drought mitigation measure to reduce water use. Irrigation was by short range micro-sprinklers (~ 1.15 m radius) with one sprinkler per tree with a delivery rate of about 30 L h^{-1}. Irrigation was scheduled in the same way as at Esperanto.

4.2.1.2 Orchards with medium canopy cover in EGVV

The orchard at Vyeboom Farm (in EGVV) was Block B6 (S34.06824º; E01911182º; 332 m asl) which was planted to the Golden Delicious Reinders cultivar. The orchard was 6 years old, planted in 2011 on ridges on M7 rootstock. We could not find an appropriate orchard on M793 in EGVV. Tree spacing was 4.0 m x 2.0 m (i.e. 1 250 trees per ha) with 10% 'Granny Smith' pollinators. There was a dense cover crop of tall fescue (*Festuca arundinacea*) which was kept short by regular mowing. The average width of the cover crop strip was about 1.2 m.

Irrigation was by a short range micro-sprinkler system with one sprinkler per tree delivering about 30 L h^{-1} with a wetted radius of about 1.0 m. On average irrigation was applied about three times a week during most of the season, but more frequently in hot summer weather. Trees were grown on ridges and the soils had a sandy loam texture with a high stone content.

The study orchard at Dennebos (Block 5) (S34.06273°; E019.11182°; 321 m asl) was 6 years old planted to the Cripps' Pink cultivar on an M7 rootstock. The size of the orchard was about 2.76 ha and it used a short range micro-sprinkler irrigation which wetted a radius of about 1.0 m and delivering about 30 L h^{-1}. Tree spacing was 4.0 m x 2.0 m (i.e. 1 250 trees per ha) with every 1 in 10 trees being a 'Granny Smith' pollinator. The soils were dark red clayey loam of the Tukulu soil form with a high stone content (Soil Classification Working Group, 1991). There were problems with water logging in a small section close to the middle of the orchard and the trees were grown on ridges. The cover crop comprised mainly of indigenous grass species on a 1.3 m wide strip. The orchard microclimate was monitored using two automatic weather stations one in each region as detailed in section 3.3.2.

4.2.2 Soil properties, soil water content and irrigation

4.2.2.1 Soil physical properties

Soil samples for chemical and five fraction particle size analyses (PSA) were taken in the KBV and EGVV in August 2016 and November 2016, respectively, according to the procedure described in Chapter 3. Soils at the KBV 'Golden Delicious Reinders' (Lindeshof) and the EGVV 'Golden Delicious Reinders' (Vyeboom Boerdery) orchards were sampled at depth increments of 0-300, 300-600, and 600-800 mm. Soils at the KBV 'Cripps' Pink' (Esperanto) orchard were sampled at depth increments of 0-450, 450-700, and 700-900 mm. At the EGVV 'Cripps' Pink' orchard (Dennebos) high stone content deeper in the soil profile restricted sampling and samples were only taken at depth increments of 0-300 mm and 300-450 mm.

To determine soil water retention properties at the KBV 'Golden Delicious Reinders' (Lindeshof) and 'Cripps' Pink' (Esperanto) orchards tensiometers were installed at 300 mm, 600 mm and 800 mm depths. At the EGVV 'Golden Delicious Reinders' orchard (Vyeboom Boerdery) tensiometers were installed only at 300 mm and 600 mm depths due to stony soil. No tensiometers were installed in the EGVV 'Cripps' Pink' orchard (Dennebos) as the extremely high stone content prevented accurate gravimetric sampling needed to determine *in situ* soil water retention curves.

Soil bulk density (P_b) values were determined *in situ* according to the core method (Blake & Hartge, 1986) at the KBV 'Golden Delicious Reinders' (Lindeshof) orchard at 150, 300, 600 and 800 mm depths in the clean cultivated tree row area and at 150, 300 and 600 mm in the middle of the work row. At the 'Cripps' Pink' (Esperanto) orchard bulk density was determined in the slope, the tractor track and the cover crop area. The P_b in the slope was determined at 150, 300, 600 and 800 m depths, in the tractor track at 150 mm and in the cover crop area at the 150, 300 and 600 mm depths.

4.2.2.2 Soil water content and irrigation

In 2016/17, the KBV orchards at Lindeshof and Esperanto were - based on favourable site and soil properties - selected for detailed soil water balance measurements. Soil water content measurements in the EGVV orchards at Vyeboom Boerdery ('Golden Delicious Reinders') and Dennebos ('Cripps' Pink') - having steep slopes and/or stony soils - were done only in the upper soil horizon using CS616 sensors attached to the sap flow systems described in section 4.2.3.

At Lindeshof soil water content equipment was installed in August 2016 in the 'Golden Delicious Reinders' orchard previously used for the low canopy cover measurements (2014/15), but in another orchard row (Fig. 4.1). The installation procedure was similar to that described in Section 3.2.3.2, except that 22-custom made T-type thermocouples were placed representatively and that the work row soil profile was now perpendicular to the tree row and sensors orientated parallel to the tree row (Appendix A: Fig. 3; Table 2). The sensor prongs were lengthwise centred on the tree trunk (i.e. 150 mm extended N and S of the tree trunk centre, respectively). The root system of the 'Golden Delicious Reinders' trees extended to between 0.8 m and 1 m in the tree row area. Tree roots extended beyond the irrigated area to the work row area. The equipment was installed in the root zone at 150, 300, 600 and 800 mm soil depths (Fig. 4.1), but only to a depth of 600 mm in the non-irrigated work rows. Soil water content could, due to limited equipment availability not be measured below the root zone. Gravimetric soil sampling for the purpose of soil water content equipment calibration in this orchard is similar to that described in section 3.2.3.2.

Fig. 4.1 Installation of CS616 sensors in sandy soil at 150, 300, 600 and 800 mm depths in the medium canopy cover 'Golden Delicious' orchard at Lindeshof in 2016/17. The measuring tape indicates centimetres.

At Esperanto soil water monitoring equipment were installed in the 'Cripps' Pink' orchard in a c. 250 mm high ridge having uniform sandy loam soil (Fig. 4.2). Tree roots extended in the centre of the ridge to a depth of 800 mm, and cover crop roots in the work row to c. 600 m. A trench was made between two trees and CS616 sensors and thermocouples were installed at these trees at different depths in the centre tree row, western ridge, eastern slope, tractor tracks and cover crop area (Appendix A: Fig. A4). Due to limited equipment, sensors were installed only at one tree in the tractor row and cover crop area. Thermocouple cable length limitations prevented measurement of temperature in all positions at both trees and thermocouples were installed at representative positions. Gravimetric soil sampling for the purpose of s*oil water content equipment calibration* and monitoring of *irrigation* applied in these orchards is similar to that described in section 3.2.3.2.

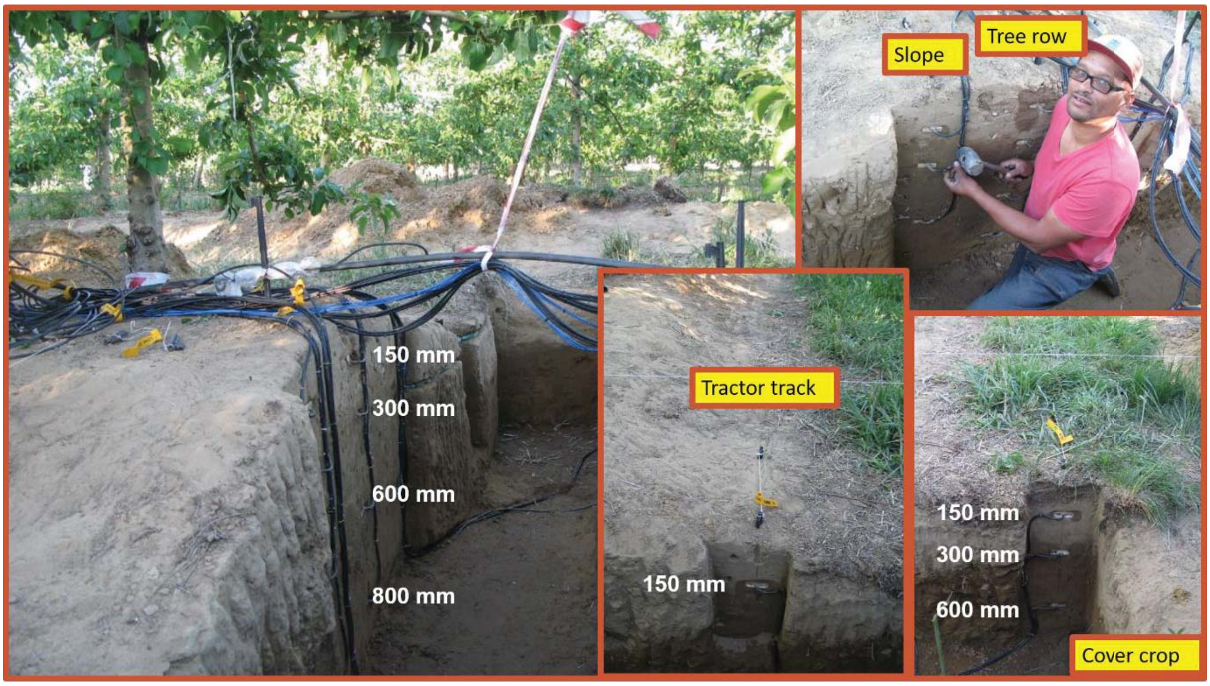


Fig. 4.2 Installation of CS616 sensors in sandy loam soil at various depths in the tree row, ridge, slope, tractor track and cover crop area in the medium canopy cover 'Cripps' Pink' orchard at Esperanto in 2016/17.

4.2.3 Eco-physiology: Leaf gas exchange and the water status

In each orchard, five trees were marked in the same row as the sap flow instrumented trees (see section 4.2.4), but further into the row and leaving three to five trees between the first marked tree and the last instrumented tree. Another five trees were marked in the next row on the opposite side of the tree row, to give a total of ten trees per orchard. Two leaves were measured per tree for all parameters using a similar approach to that detailed in Chapter 3. Measurements were performed throughout the growing season until harvest. Stem water potential and gas exchange measurements were taken monthly from November 2016 until March 2017 and again in June 2017, using methods described in Chapter 3.

4.2.4 Quantifying transpiration rates of trees with medium canopy cover

In all four farms, tree transpiration was measured using the heat ratio method (Burgess et al., 2001) of the heat pulse velocity (HPV) sap flow technique (Fig. 4.3). Three trees of varying stem diameters were instrumented in each orchard in EGVV and six trees in KBV. Sensors were installed 10-15 cm above the graft union away from the disturbed xylem vessels. A metal template with three holes spaced 5 mm apart was used to drill the holes in the stem of the trees to minimize probe misalignment. The HPV system comprised a heater implanted into the stem of the trees (Fig. 4.3) and connected to a custom-made relay control module which controlled the heat application. Two T-type thermocouples, installed at equal distances (~0.5 cm) up and downstream of the heater probe measured the sapwood temperature.

Fig. 4.3 Heat ratio method of the heat pulse velocity (HPV) sap flow technique. The grey security box contains the data logger, multiplexer, relay control module and battery. The insert shows a detailed view of the probes installed in the stems.

The thermocouples were connected to a multiplexer (model: AM16/32B Campbell Scientific, Logan UT, USA) which was in turn connected to a CR1000 data logger. Four sets of sensors were installed in the four cardinal directions around the stem on each of the trees at different depths into the sapwood as shown by the insert in Fig. 4.3. This was done to account for the circumferential and radial variation in sap velocity (Wullschleger and King, 2000). The depth of installation of the sensors ranged from about 0.7 to 4.2 cm below the bark depending on stem size. The HPV data was corrected for wounding due to sensor implantation at the end of the experiment according to the approach by Swanson and Whitfield (1981). The wounding width was determined by injecting a weak solution of methylene blue dye just below the probe insertion location. The flow paths around the drilled area were clearly visible (Fig. 4.4a). The same method was used to determine the extent of the conducting sapwood area where active xylem vessels were active (Fig. 4.4b).

Fig. 4.4 (a) A methylene blue dye trace illustrating the extent of the wounding width due to the implantation of sap flow probes in the stem. (b) Stem core showing the bark thickness and sapwood depth of an apple tree.

Whole-tree transpiration was derived as the sum of the sap flows in four concentric rings in the sapwood with flow in each ring calculated as the product of the sap velocity at each probe depth and the sapwood area represented by that probe as described by Dzikiti et al (2017). Sap flux density (U, in cm^3 cm^{-2} d^{-1}) was derived as the ratio of the daily sap flow rate of an individual tree and the conducting sapwood area. Orchard level transpiration (T, in mm/d) was calculated as the sum of the products of the sap flux density and the orchard sapwood area index (SAI = m^2 of sapwood per m^2 of ground area) for trees in different stem diameter classes as:

$$T = \sum_{i=1,3} SAI_i \times U_i \qquad (4.1)$$

where U_i is the average sap flux density in each size class and each of the instrumented trees was assigned to an appropriate size class.

Orchard evapotranspiration was measured using an open eddy covariance system described in Chapter 3. Leaf area index (LAI) was measured regularly throughout the season using a leaf area meter (model LAI 2000: LI-COR, Lincoln, Nebraska, USA). Stem growth was monitored using dendrometers (model: DEX 70, Dynamax, Huston, USA) installed on one tree per orchard as described in Chapter 3.

4.2.5 Determining evapotranspiration using the soil water balance method

Evapotranspiration was calculated for the KBV orchards at Lindeshof (‘Golden Delicious Reinders’) and Esperanto (‘Cripps’ Pink’) according to the universal soil water balance as described in Section 3.3.6.2. The orchard attributes used to calculate the soil water balance for the orchard and its components at the ‘Golden Delicious Reinders’ (IBGR) orchard at Lindeshof is similar to that used for the NBGR. However, at the IBGR orchard, soil water content was weighted to represent the 0-225, 225-450, 450-700 and 700-900 mm depth increments to obtain the average soil profile water content during the season. The soil water balance was calculated for the 0-900 mm depth increment in the tree row and 0-700 mm depth increment in the work row.

At the ‘Cripps’ Pink’ orchard at Esperanto soil water content was weighted to represent the 0-225, 225-450, 450-750 and 750-800 mm depth increments to obtain the average soil profile water content during the season. The soil water balance was calculated for the 0-800 mm depth increment in the tree row and ridge, 0-700 mm depth increment in the slopes and cover crop row and 0-225 mm in the tractor track. The ET was, as in the other orchards, calculated per sensor position and weighted according to representative area to calculate ET of the different orchard components. Ridge ET (tree row, western ridge and eastern slope), work row ET (tractor track and cover crop) and orchard ET was calculated by adding the volumes of ET of the different components and expressing it over the full orchard surface area.

4.3 Results and discussion

4.3.1 Seasonal climatic conditions

Seasonal total rainfall at Lindeshof for the period 01 October 2016 to 30 June 2017 was only 149 mm. As expected, June was the wettest month of the season receiving 111 mm since the area receives winter rainfall. Esperanto farm, on the other hand received slightly more rain (225 mm) over the same period. The 2016/17 season’s rainfall at Lindeshof was close to half of the 281 mm recorded over the same months in the 2014/15 season. Including the rainfall for the months of August and September 2016 for Lindeshof brought the total to about 237 mm from August 2016 to June 2017. This amount is quite low given that the long-term average annual rainfall in KBV is between 350 and 510 mm confirming the severe drought currently gripping the region. The seasonal (Oct-Jun) total grass reference evapotranspiration (ET_o) at Lindeshof was almost ten times higher than the rainfall, being 1 487 mm. Peak daily ETo exceeded 9.0 mm in the hot summer months. December 2016 had the highest average daily radiation (31.3 MJ m^{-2} d^{-1}) although it was not necessarily the hottest month. The maximum air temperature (35.1 °C) was measured in March 2017 while October 2016 recorded the lowest temperature of 2.6 °C. Seasonal average temperature was around 17.8 °C. Daily average wind speeds were fairly low ranging between 1.8 and 2.9 m s^{-1}. March 2017 was the driest month receiving no rainfall and it had the lowest relative humidity of 6%.

Seasonal rainfall in EGVV was 218 mm with June 2017 being the wettest month receiving 163 mm (Table 4.1). The same period in the 2015/16 season received 247 mm which was slightly more than what was received in the current season. Including the months of August and September 2016, total rainfall in EGVV in 2016/17 was about 323 mm. The long-term annual rainfall for the region is higher than 500 mm, again indicating the effects of the drought currently being experienced in the region. Overall EGVV seems to have received more rainfall than KBV during the 2016/17 season. Seasonal total reference evapotranspiration for EGVV was about 1 148 mm which was substantially lower than that of KBV. The average daily solar radiation (~27 MJ m^{-2} d^{-1}) was lower in EGVV than in KBV, although EGVV had a higher maximum temperature exceeding 40 °C. The minimum air temperature for EGVV was 2.3 °C which was similar to that experienced in KBV. Average temperature for EGVV during the 2016/17 season was around 19.5 °C. Wind speeds were fairly low varying from a daily average of 0.9 to 1.6 m s^{-1}.

4.3.2 Irrigation and soil water dynamics

4.3.2.1 Soil physical properties

According to *particle size distribution*, the soil at Lindeshof was sandy loam to sandy compared to the loamy sand at Esperanto, sand clay loam at Vyeboom and clay loam to clay soil at Dennebos (Table 4.2; Appendix B: Table B3).

Table 4.1 Monthly summary of the daily mean solar radiation (R_s); maximum (T_{max}), minimum (T_{min}) and average air temperature (T_{avg}); maximum (RH_{max}) and minimum (RH_{min}) relative humidity; reference evapotranspiration (ET_o), and rainfall in the Koue Bokkeveld (KBV) and EGVV during 2016/17.

	KBV	**EGVV**	**KBV**	**EGVV**	**KBV**	**EGVV**	**KBV**	**EGVV**	**KBV**	**EGVV**	**KBV**	**EGVV**	**KBV**	**EGVV**	**KBV**	**EGVV**
Month	**R_s (MJ m^{-2}d^{-1})**	**R_s (MJ m^{-2}d^{-1})**	**T_{max} (°C)**	**T_{max} (°C)**	**T_{min} (°C)**	**T_{min} (°C)**	**T_{avg} (°C)**	**T_{avg} (°C)**	**RH_{max} (%)**	**RH_{max} (%)**	**RH_{min} (%)**	**RH_{min} (%)**	**ET_o (mm)**	**ET_o (mm)**	**Rain (mm)**	**Rain (mm)**
Oct	23.2	21.1	31.5	36.7	2.6	4.1	15.2	17.4	91	91	10	8	134	131.5	4.6	3.3
Nov	28.9	24.8	31.9	36.8	4.8	7.4	18.7	19.8	92	93	10	13	204	153	4.6	10.9
Dec	31.3	27.3	34.9	40.4	8.8	12.6	20.9	23.1	91	90	10	9	232	189.2	6.1	1
Jan	30.2	26.4	34.4	38.7	9.3	12.2	21.6	22.8	91	88	9	10	234	181.2	8.1	3.3
Feb	28.6	25.1	34.9	38.6	9.4	13.1	21.9	23.4	89	90	10	11	222	155.8	4.1	2.5
Mar	23.2	19.8	35.1	38.9	8.5	10.0	20.4	21.6	90	92	6	9	187	137.4	0	6.1
Apr	17.1	13.8	30.7	34.9	2.9	8.2	18.4	19.3	91	94	8	15	136	89.3	5.8	20.5
May	13.0	10.2	28.2	29.9	3.7	6.5	14.8	16.0	92	95	12	15	94	63.7	4.6	7.4
Jun	8.2	8.0	15.4	29.2	3.5	2.3	8.7	11.8	99	94	48	19	44	46.5	111.3	163
Total													**1487**	**1147.6**	**149.2**	**218**

The coarse fraction of the soil at Lindeshof was low in the top 150 mm, but increased from on average c. 22% (v/v) between 225 mm and 700 mm to 33% (v/v) gravel at the bottom of the profile, whereas the soil at Esperanto did not contain any stone. The stone content of the orchard at Vyeboom Boerdery increased with depth to c. 38% (v/v), while the extremely stony soil at Dennebos contained between 45% and c. 75% stones (v/v) (Appendix B: Table 3). *Chemical analysis* indicated no apparent salinity or sodicity related problems in any of the orchards (Appendix B: Table 4). At Lindeshof, the profile averaged P_b in the clean cultivated tree row area and in the middle of the work row amounted to 1 614 and 1 597 kg m^{-3}, respectively (Table 4.3). At Esperanto, the profile averaged P_b in the slope (1 467 kg m^{-3}) and cover crop area (1 512 kg m^{-3}) was less than in the more compacted tractor track. The P_b of the ridged area was considered to be similar to that of the slope. *In situ* determination of the P_b according to the core method (Blake and Hartge, 1986) was not feasible in the EGVV orchards due to high stone content of soils.

Table 4.2 Profile averaged soil texture classes and particle size analysis for the soils at the medium canopy cover orchards.

Orchard	**Profile depth (mm)**	**Texture class**	**Clay**	**Silt %**	**Sand**	**Stone (v/v)**
Lindeshof W04	900	Sandy loam	6.5	8.1	85.4	20.8
Esperanto B15	900	Loamy sand	2.8	13.7	83.6	0.0
Vyeboom Boerdery B6	800	Sandy clay loam	26.5	15.3	58.3	14.2
Dennebos 13B	450	Clay loam	39.7	25.3	35.0	56.3

Table 4.3. Bulk density for different soil depth increments of the soils in the Koue Bokkeveld medium canopy cover orchards in 2016/17.

		Bulk density	**(kg m^{-3})**		
Orchard	**Lindeshof W04**		**Esperanto B15**		
Depth (mm)	**Tree row**	**Work row**	**Slope**	**Tractor track**	**Cover crop**
150	1683	1636	1407	1639	1432
300	1548	1615	1430	-	1518
600	1531	1619	1468	-	1548
800	1692	1519	1540	-	-

According to the *in situ* determined soil water retention curve at Lindeshof (Fig. 4.5a) the soil water holding capacity between -5 kPa and -1 500 kPa (TAW) was 115 mm m^{-1} of which 47 mm m^{-1} of water was available to a soil matric potential of -20 kPa (c. 41% of TAW). For the ridged loamy sand soil in the orchard at Esperanto (Fig. 4.5b) the TAW was 211 mm m^{-1} of which 95 mm m^{-1} of water is available to a soil matric potential of -20 kPa (c. 45% of TAW). The ridged clay loam soil at the Vyeboom orchard (Fig. 4.5c) had a soil water holding capacity between -10 kPa and -1 500 kPa of 172 mm m^{-1} of which 38 mm m^{-1} of water was available to a soil matric potential of -20 kPa (c. 22%).

To refill the soil from the -20 kPa level to field capacity for a 600 mm deep root zone one would have to apply 28, 57 and 23 mm of irrigation in the respective orchards. Refer to Appendix C (Table 2) for statistics of the *in situ* determined soil water retention curves for various depths per orchard. The *in-situ* soil water retention curves for the 'Cripps' Pink' orchard at Dennebos could not be established as the high stone content prevented accurate gravimetric sampling.

4.3.2.2 Soil water content and irrigation

The *CS616 in situ calibration* statistics for the 30 sensors each at the 'Golden Delicious Reinders' orchard at Lindeshof and the 'Cripps' Pink' at Esperanto are listed in Appendix D: Tables 3 and 4, respectively. Similar to the low canopy cover orchards, an individual calibration per sensor was needed to obtain the best accuracy (Appendix D: Tables 1 & 2). However, the 'Cripps' Pink' calibrations for some positions resulted in unrealistic soil water content estimations and raw data of selected depths per position were combined to obtain a combined calibration having a wider range of data (data not shown). The CS616 manufacturer's calibration again underestimated the actual (i.e. gravimetrically sampled) volumetric soil water content at similar CS616 periods sampled in the 'Golden Delicious Reinders' at Lindeshof soil (Fig. 4.6a). In the loamy soil without stone at the 'Cripps' Pink' orchard at Esperanto, data tended, despite considerable scatter, to have a more comparable trend (Fig. 4.6b).

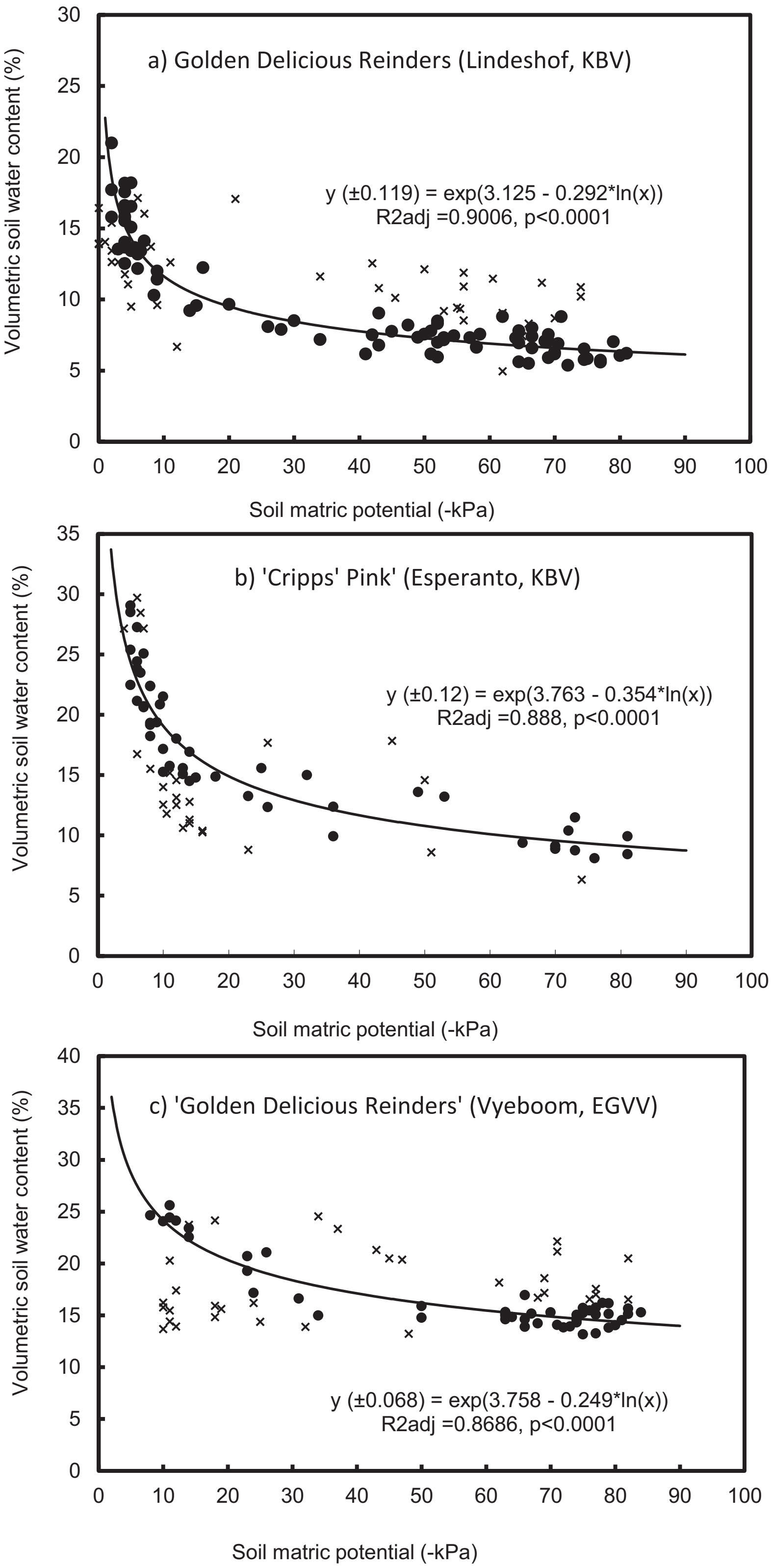


Fig. 4.5 Soil water retention curves of: a) a sandy loam soil in the Lindeshof orchard, b) loamy sand soil in the Esperanto orchard and; c) sandy clay loam soil in the 'Golden Delicious Reinders' orchard at the Vyeboom orchard. Outliers are indicated as crosses.

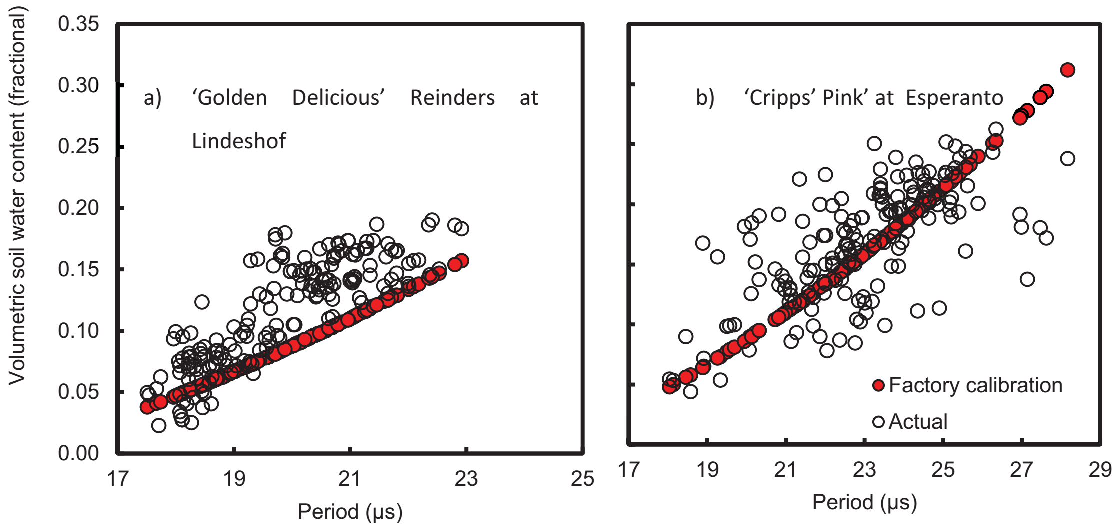


Fig. 4.6 Comparison of CS616 factory calibrated volumetric soil water content and actual volumetric soil water content sampled simultaneously at various CS616 periods at a) Lindeshof) and; b) Esperanto orchards, respectively.

In the 'Golden Delicious Reinders' orchard at Lindeshof, the dynamics of the profile averaged soil water content indicated that soil water status in the irrigated tree row was for the largest part of the season above the -20 kPa refill level (Fig. 4.7). The driest period occurred in April 2017, when only one irrigation could be applied (Table 4.4) as no more water was available due to the Western Cape drought. Soil water dynamics over the season indicated from October to mid-November, in the absence of significant rainfall or irrigation, increased drying of the clean cultivated tree row (Fig. 4.7). Near the end of mid-November the soil water content at all depths monitored exceeded the -20 kPa level (Fig. 4.8a), but remained less than about -40 kPa.

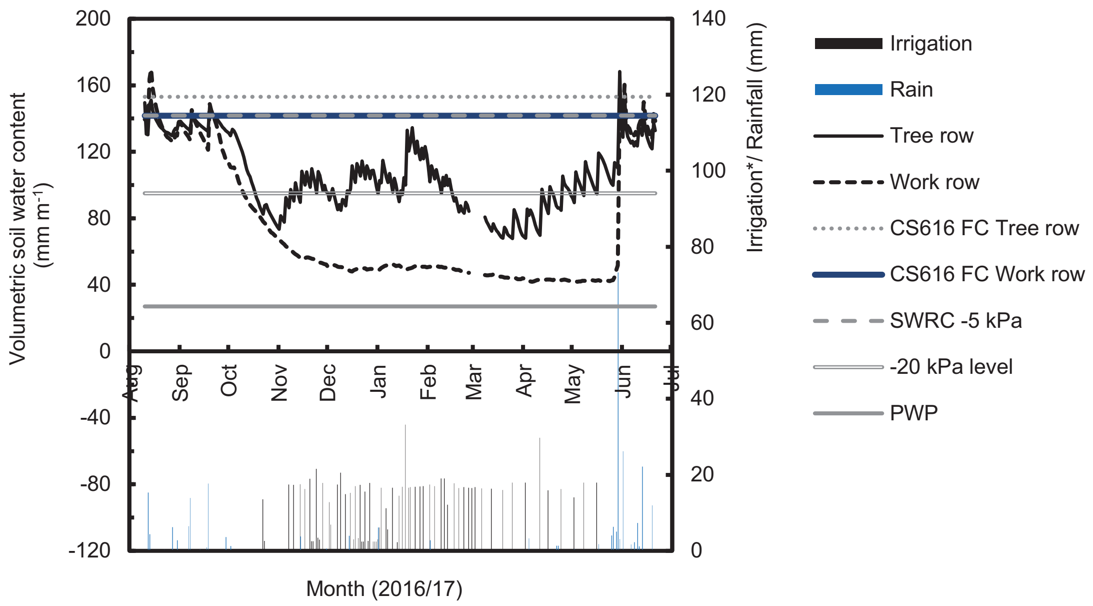


Fig. 4.7 Seasonal changes in volumetric soil water content in the tree row and work row areas of an intermediate bearing 'Golden Delicious Reinders' orchard at Lindeshof in the Koue Bokkeveld during the 2016/17 season. The amount of irrigation applied in the tree row and rainfall received are indicated on the Y-axis.

Table 4.4 Monthly mean amount, number and interval of irrigations applied to intermediate bearing 'Golden Delicious Reinders' and 'Cripps' Pink' orchards at Lindeshof and Esperanto in 2016/17. Irrigation applied on the wetted area is indicated as mm per full surface area.

Month	**Irrigation amount (mm d^{-1})**				**Number (N)**		**Interval (d)**	
	'Golden Delicious Reinders[1]'		**'Cripps' Pink'**		**'Golden Delicious Reinders'**	**'Cripps' Pink'**	**'Golden Delicious Reinders'**	**'Cripps' Pink'**
	Mean	**Stdev**	**Mean**	**Stdev**				
Oct	6.3	4.1	9.3	-	2	1	15.5	31
Nov	9.0	5.0	7.5	3.4	7	11	4.3	2.7
Dec	7.6	5.0	13.1	2.1	16	13	1.9	2.3
Jan	6.9	5.8	15.6	11.8	20	16	1.5	1.9
Feb	10.4	3.8	14.6	1.2	10	4	2.8	7
Mar	9.9	3.7	14.7	1.5	9	13	3.4	2.4
Apr	10.8	-	14.3	1.0	1	2	30	15

[1] Divide by 0.58 to obtain amount applied per wetted area

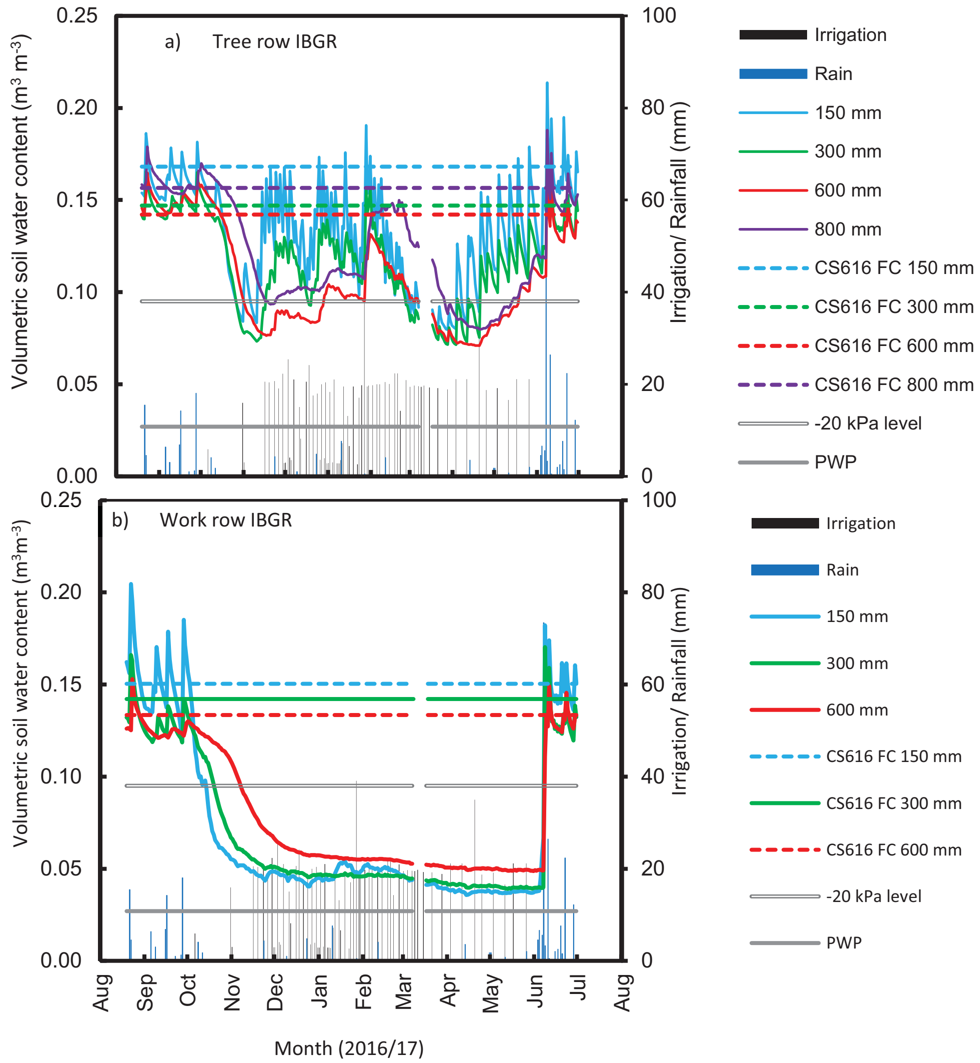


Fig. 4.8 Seasonal changes in volumetric soil water content at selected depths in a) the tree row and b) work row of an intermediate bearing 'Golden Delicious Reinders' orchard at Lindeshof in the Koue Bokkeveld during 2016/17. The amount of irrigation applied in the tree row and rainfall received are indicated on the Y-axis.

Although irrigation amounts applied from mid-November to January (Table 4.4) kept the soil water content at the 150 and 300 mm depths sufficiently wet (Fig. 4.8a), it was not enough to restore the soil water content at the 600 depth or 800 mm depths to field capacity. The 600 and 800 mm depths became drier than the 150 mm and 300 mm depths. The soil water content at the 600 mm depth remained at levels between -20 and -40 kPa until about end December 2016 (Fig. 4.8a). A large irrigation end January (39.1 mm) followed shortly thereafter by irrigations of 19.5 mm and 19.8 mm each increased the soil water content deeper in the soil profile. The amount of c. 20 mm applied per irrigation event thereafter was, however, not enough to replace the evapotranspiration losses as the soil water content at all depths decreased progressively during February to the beginning of April. However, fruit quality was most likely not affected by the soil water status, since the soil water content did not decrease beyond the -20 kPa level at any of the depths before end February. The soil water status in the non-irrigated work row (Fig. 4.8b) decreased from October to mid-November due to evaporation and weed water use and levelled off by December. Soil water content responded mainly in the top soil to rainfall, except in June during which the soil profile was refilled at all depths after significant rainfall (Fig. 4.8b).

Soil water dynamics of the 'Cripps' Pink' at Esperanto indicated that the depth-weighted profile average in the ridge and slopes had an initial upward trend in soil water content followed by continuously wet conditions for almost two and a half months, whereas the cover crop area in general displayed a drying trend (Fig. 4.9).

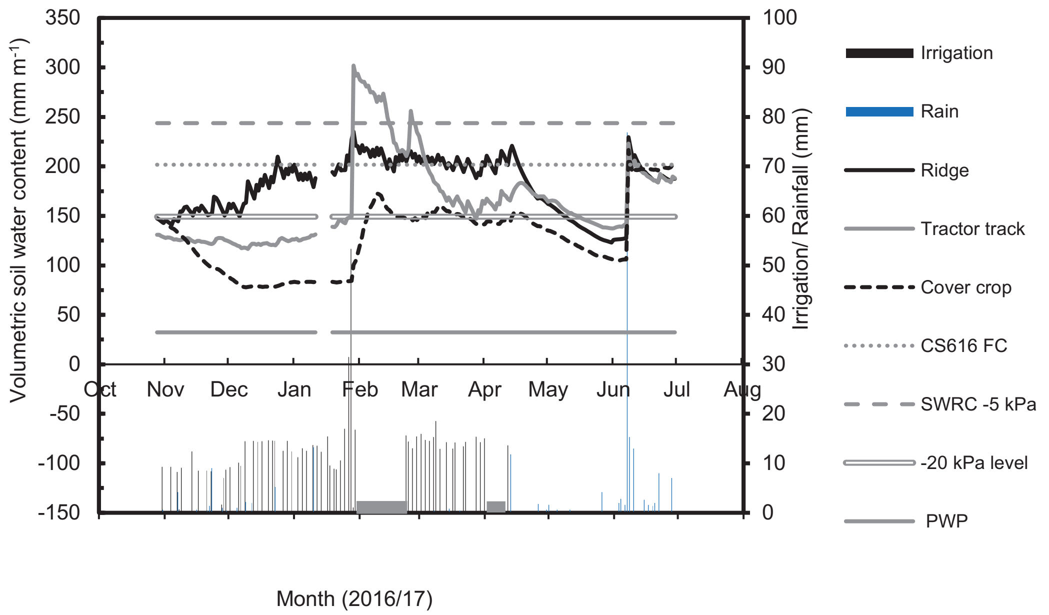


Fig. 4.9 Seasonal changes in volumetric soil water content in the ridge, tractor track ad cover crop areas of the 'Cripps' Pink' orchard at Esperanto in the Koue Bokkeveld during the 2016/17 season. The amount of irrigation applied over the full surface area and rainfall received are indicated on the Y-axis.

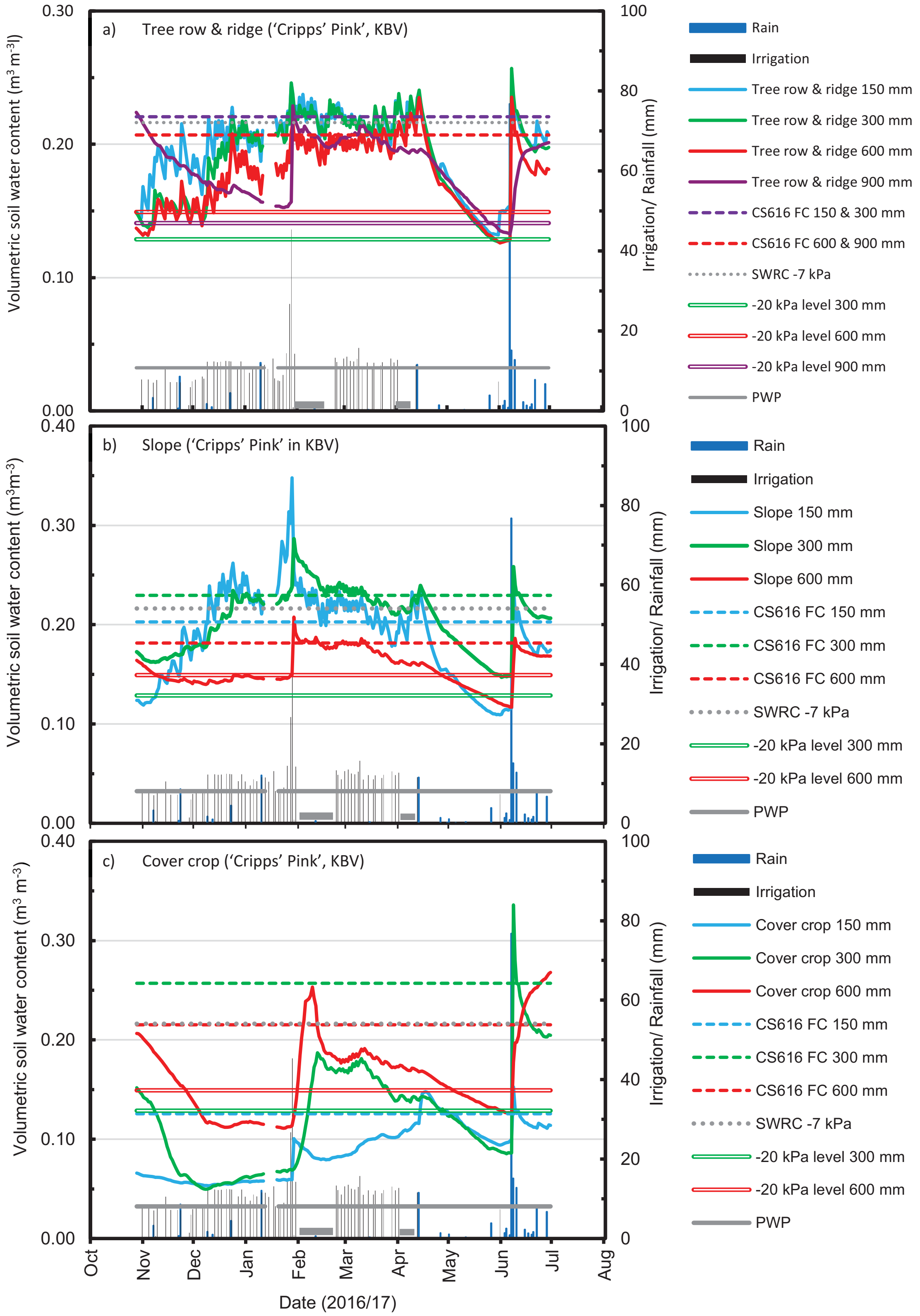


Fig. 4.10 Seasonal changes in volumetric soil water content at selected depths in a) the tree row and ridge, b) slope and c) cover crop of 'Cripps' Pink' orchard at Esperanto in the Koue Bokkeveld during 2015/16. The amount of irrigation applied over the full surface area and rainfall received are indicated on the Y-axis.

Volumetric soil water dynamics in the ridge (average of tree row and western ridge soil water content) from November to end January indicated increased wetness at the 150, 300, and 600 mm depths, whereas the opposite trend occurred at the 900 mm depth (Fig. 4.10a). Between 29 January and 2 February, a series of irrigations (total exceeding 100 mm) increased soil water content at all positions to above field capacity. For the remainder of the season until about mid-April the soil water content at all depths remained wetter than the -11 kPa level and exceeded field capacity several times, resulting in excessive drainage.

At the end of the season after harvest the soil profile was allowed to dry to obtain data for a soil water retention curve. The soil matric potential in the ridge at the end of this drying period was estimated as -19, -21, -34 and -22 kPa at the 150, 300, 600, and 900 mm depths, respectively. The trees were therefore not subjected to significant water deficits during the season. In the eastern slope, soil water content also increased over time in the upper soil depths, but it tended to remain drier at the 600 mm depth compared to in the ridge up until end January and once again from mid-March to mid-April (Fig. 4.10b). The soil matric potential in the slope at the end of the drying period from April onwards was estimated as -35, -14, and -43 kPa at the 150, 300, and 600 mm depths, respectively.

The cover crop area had an initial steeper downward trend in soil water content at all depths, which flattened of towards end January probably due to limited water availability (Fig. 4.10c). Soil water content at the 300 and 600 mm depths in the cover crop improved after the excessive irrigation event at the end of January and followed at similar, but drier trend to the 600 mm depth in the slopes (Fig. 4.10b). The soil water content in the cover crop at the 150 mm depth tended to gradually increase from mid-February to mid-April (Fig. 4.10c). Soil water content in the tractor track did not have a distinct trend but responded to the excessive irrigation and reflected irrigations applied during March (Fig. 4.10). The extreme soil water content estimates for February after the over-irrigation is most likely due to the measured CS616 period being outside the prediction range of the CS616 calibration.

4.3.3 Eco-physiology: gas exchange and stem water potential

The ‘Golden Delicious Reinders’ orchard in KBV was characterised by relatively low photosynthetic (A) and stomatal conductance (g_s) values (Table 4.5). Except for two hotter days, VPD_{leaf} reached up to 2.3 kPa in the morning and up to 3.0 kPa in the afternoon, and the lowest midday Ψ_{stem} was -1.38 MPa. A and g_s were typically reduced and E was increased in the afternoon compared to the morning. The exceptions were 3 December 2016 and 21

June 2017 (measured on active leaves still attached) when conditions became milder in the afternoon and E decreased even though g_s increased slightly. On two hot measurement days (3 December 2016 and 22 March 2017), VPD_{leaf} and E were very high. On 3 December 2016 this did not severely reduce A since the sink strength was high, but A values were low on 22 March 2016 when the fruit had been harvested and sink strength was lower. Midday Ψ_{stem} values did not indicate water stress in this orchard, although the values measured in the early part of the season (December to January) were lower than optimal. The generally high VPD_{leaf} and T_{leaf} values for this season in the KBV region compared to the EGVV region may explain the muted gas exchange capacity. Measurements of seasonal transpiration and irrigation confirm the observation that there was no water stress in this orchard (Section 4.3.4).

The 'Cripps' Pink' orchard at Esperanto had the lowest values of A and g_s of all four orchards (Table 4.6). On all measurement days except June 2017, average VPD_{leaf} was higher than 2.4 kPa and T_{leaf} was higher than 29 °C. Photosynthesis and g_s were lower in the afternoon compared to the morning, and this allowed E to remain relatively constant through the day. Midday Ψ_{stem} was generally lower than optimal, especially in February and March 2017. As for the 'Golden Delicious Reinders at Lindeshof, stressful atmospheric conditions during this season in the KBV region were not optimal for leaf gas exchange and tree water relations. Nevertheless, measurements of seasonal transpiration and irrigation confirm that this orchard was not water stressed, and in fact received high irrigation rates through the season (Section 4.3.4).

Climatic conditions during the first part of the 2016-2017 season were milder in the EGVV region. In the 'Golden Delicious Reinders' orchard at Vyeboom (Table 4.7), leaf temperatures were quite high on several occasions but VPD_{leaf} generally remained lower than in the KBV region. Values of A, g_s and midday Ψ_{stem} was generally high from November to January. In contrast with the KBV region, VPD_{leaf} as measured on the milder days decreased from morning to afternoon. This could be due to afternoon cloud development, and together with the afternoon decline in g_s this led to lower E rates in the afternoon. The exceptions were the afternoons of 6 February and 20 March 2017 when VPD_{leaf} was 3.51 and 5.86 kPa, respectively. On these days, A and g_s declined significantly in the afternoon thus stabilising or reducing E. The response was stronger on 20 March which falls in the Golden Delicious Reinders post-harvest period when sink strength is much lower, and conditions were exceptionally stressful. Very high T_{leaf} on 24 February 2017 also led to low A and g_s values although VPD_{leaf} was only moderately high. On all three days in February and March the midday Ψ_{stem} was low. In June 2017, this orchard (many leaves still attached) was still showing good values of A and g_s, and E was still significant at around 1.9 mmol m^{-2} s^{-1}. Seasonal water use of this orchard was low compared to the ‘Golden Delicious Reinders’ at Lindeshof in KBV, partially because of the lower ET_o in EGVV than KBV (section 4.3.5).

The highest A, E and midday Ψ_{stem} values of the four orchards with medium canopy cover studied during the 2016/17 season were measured in the ‘Cripps’ Pink’ orchard at Dennebos in EGVV (Table 4.8). Climatic conditions were mild except for the afternoon of 10 March 2017. A steep rise in T_{leaf} and VPD_{leaf} from morning to afternoon led to a small reduction in g_s and a larger drop in A, with E rising significantly. On this day the midday Ψ_{stem} was moderate but lower than on the other days. In spite of these trees receiving less irrigation than the other three orchards studied in 2016/2017, with lower seasonal total transpiration (sections 4.3.4 and 4.3.5) – linked to the lower ET_o, they showed no signs of water stress based on gas exchange and water potential values. Trees were still highly active on 2 June 2017, many months after the harvest, with many leaves still attached. The heavy clay soils of this orchard gave a higher water holding capacity compared to the lighter loam soils in the other three orchards, which likely contributed to these results.

Table 4.5 Leaf gas exchange and midday stem water potential of medium canopy cover bearing trees of the 'Golden Delicious Reinders' apple orchard in the KBV production region.

	'Golden Delicious Reinders' at Lindeshof, KBV													
	03/12/2016		27/12/2016		17/01/2017		02/02/2017		25/02/2017		22/03/2017		21/06/2017	
	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
A (μmol m^{-2} s^{-1})	12.35	12.79	17.10	14.62	12.4	10.22	15.24	13.42	11.5	10.5	8.63	7.96	8.49	8.57
g_s (mol m^{-2} s^{-1})	0.12	0.13	0.25	0.20	0.13	0.11	0.21	0.19	-	0.16	0.12	0.10	0.17	0.18
E (mmol m^{-2} s^{-1})	5.63	4.90	4.55	4.85	2.74	3.60	4.69	5.50	1.39	2.37	4.92	5.20	2.25	1.98
VPD_{leaf} (kPa)	4.43	3.44	1.82	2.32	2.00	2.96	2.20	2.75	2.29	1.45	3.91	4.94	1.30	1.09
T_{leaf} (°C)	32.90	34.10	29.30	31.60	33.7	37.70	29.80	32.40	25.3	28.1	36.0	39.0	19.70	18.70
Instantaneous WUEi (mmol CO_2 mol^{-1} H_2O)	2.19	2.61	3.76	3.02	4.53	2.83	3.25	2.44	8.30	4.46	1.76	1.53	3.77	4.34
Intrinsic WUEi (μmol CO_2 mol^{-1} H_2O)	103.5	96.20	69.90	72.50	96.4	89.60	73.70	69.60	-	67.4	73.9	82.7	50.7	48.1
Stem water potential (MPa)	-1.58		-1.38		-1.42		-1.19		-0.86		-1.25		-0.85	

Table 4.6 Leaf gas exchange and midday stem water potential of medium canopy cover bearing trees of the 'Cripps Pink' apple orchard in the KBV production region

	'Cripps' Pink' at Esperanto, KBV													
	02/12/2016		28/12/2016		13/01/2017		03/02/2017		13/03/2017		23/03/2017		20/06/2017	
	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
A (μmol m^{-2} s^{-1})	9.79	9.27	13.29	11.42	-	10.80	12.73	9.41	12.07	10.71	11.12	10.24	5.17	5.33
g_s (mol m^{-2} s^{-1})	0.08	0.09	0.16	0.13	-	0.11	0.16	0.11	0.20	0.14	0.09	0.12	0.16	0.14
E (mmol m^{-2} s^{-1})	3.00	3.41	3.96	3.37	-	3.47	4.41	4.54	5.11	5.07	3.18	3.59	1.42	0.79
VPD_{leaf} (kPa)	3.32	3.62	2.37	2.49	-	2.85	2.52	3.69	2.42	3.34	3.08	2.81	0.88	1.20
T_{leaf} (°C)	32.5	34.7	30.7	31.0	-	31.7	30.6	35.6	28.9	34.4	29.3	30.3	14.4	18.0
Instantaneous WUEi (mmol CO_2 mol^{-1} H_2O)	3.26	2.72	3.36	3.39	-	3.11	2.89	2.08	2.36	2.11	3.50	2.85	3.65	2.98
Intrinsic WUEi (μmol CO_2 mol^{-1} H_2O)	119.3	108.7	83.2	89.1	-	95.5	78.5	85.3	60.5	77.0	118.6	87.9	33.3	37.4
Stem water potential (MPa)	-1.49		-1.54		-1.54		-1.72		-1.71		-1.66		-0.95	

Table 4.7 Leaf gas exchange and midday stem water potential of medium canopy cover bearing trees of the 'Golden Delicious Reinders' apple orchard in the EGVV production region.

	'Golden Delicious Reinders' at Vyeboom, EGVV													
	24/11/2016		21/12/2016		12/01/2017		06/02/2017		24/02/2017		20/03/2017		01/06/2017	
	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
A (μmol m^{-2} s^{-1})	20.6	18.82	16.19	14.28	18.06	17.52	14.70	9.77	7.75	6.48	11.19	2.36	10.18	8.95
g_s (mol m^{-2} s^{-1})	0.39	0.33	0.21	0.19	0.31	0.28	0.21	0.12	0.10	0.08	0.18	0.05	0.15	0.13
E (mmol m^{-2} s^{-1})	5.35	4.58	2.76	2.38	5.03	4.25	4.34	4.10	2.35	1.74	4.11	2.77	1.97	1.84
VPD_{leaf} (kPa)	1.54	1.52	1.35	1.29	1.76	1.61	2.10	3.51	2.50	2.20	2.37	5.86	1.38	1.57
T_{leaf} (°C)	27.9	28.5	28.6	25.4	27.8	27.3	30.6	35.6	37.1	36.2	31.4	42.9	23.4	25.5
Instantaneous WUEi (mmol CO_2 mol^{-1} H_2O)	3.84	4.10	5.86	5.99	3.59	4.12	3.38	2.38	3.30	3.73	2.72	0.85	5.16	4.86
Intrinsic WUEi (μmol CO_2 mol^{-1} H_2O)	54.4	57.7	76.9	75.2	59.2	62.4	69.1	81.3	77.0	85.7	61.1	48.8	67.5	71.6
Stem water potential (MPa)	-0.91		-0.96		-1.07		-1.69		-2.03		-1.74		-1.09	

Table 4.8 Leaf gas exchange and midday stem water potential of medium canopy cover bearing trees of the 'Cripps Pink' apple orchard in the EGVV production region.

	'Cripps' Pink' at Dennebos, EGVV													
	01/12/2017		22/12/2017		16/01/2017		07/02/2017		10/03/2017		24/03/2017		02/06/2017	
	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
A (μmol m^{-2} s^{-1})	22.26	18.41	20.24	17.90	20.96	19.38	19.41	17.87	17.40	14.57	17.93	17.60	16.13	11.72
g_s (mol m^{-2} s^{-1})	0.46	0.34	0.42	0.36	0.467	0.40	0.49	0.40	0.30	0.25	0.38	0.41	0.38	0.17
E (mmol m^{-2} s^{-1})	5.95	5.87	4.64	5.18	4.14	5.06	3.21	5.50	4.66	7.87	4.38	4.00	5.68	4.84
VPD_{leaf} (kPa)	1.43	1.90	1.20	1.56	0.99	1.41	0.76	1.51	1.64	3.23	1.28	1.08	1.64	2.88
T_{leaf} (°C)	27.6	29.5	26.7	28.8	23.3	26.4	27.5	34.7	29.0	37.1	23.6	21.6	27.5	32.3
Instantaneous WUEi (mmol CO_2 mol^{-1} H_2O)	3.74	3.14	4.36	3.46	5.07	3.83	6.05	3.25	3.74	1.85	4.09	4.40	2.84	2.42
Intrinsic WUEi (μmol CO_2 mol^{-1} H_2O)	48.3	55.0	48.0	49.9	44.9	48.8	39.9	44.8	57.9	58.6	47.6	42.5	43.1	68.7
Stem water potential (MPa)	-0.96		-0.91		-0.92		-0.93		-1.31		-0.96		-1.18	

4.3.3.1 Canopy and stem growth: KBV orchards

Trees at Esperanto were larger than those in the other three orchards. Average height of 20 randomly selected trees at Esperanto was approx. 4.0 m with a standard error in the mean of ±0.09 m while the mean row to row canopy diameter was about 1.86 m. Average stem diameter was 8.6 cm with a standard error in the mean of ±0.2 cm. At Lindeshof, average tree height was 3.36 ± 0.06 m. Tree canopy diameter was about 1.35 m while the average stem thickness was 6.10 ± 0.13 cm. The leaf area index varied from close to zero early in the season to peaks around 1.5 for the 'Golden Delicious Reinders' at Lindeshof and ~ 2.0 for the 'Cripps' Pink' at Esperanto (Fig. 4.11).

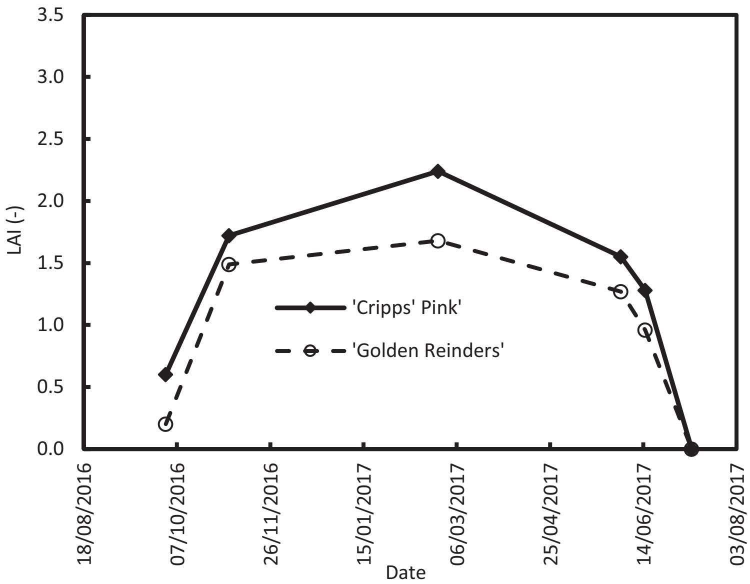


Fig. 4.11 Seasonal changes in the leaf area index of the trees in the 'Cripps' Pink' and 'Golden Delicious Reinders' orchards in KBV during the 2016/17 growing season.

Stem growth was measured at hourly intervals on one tree per orchard using electronic dendrometers (model DEX 70: Dynamax Inc., Houston, USA). Diurnal fluctuations were evident in all the orchards with stem expansion during the night and shrinkage during the day time. Over the course of the entire season, stem growth of the 'Cripps' Pink' trees (Fig. 4.12a) at Esperanto was very small (< 2 mm). This was probably because the trees had reached or were closer to their maximum stem size. The 'Golden Reinders' trees at Lindeshof grew by close to 4 mm (Fig. 4.12b) between October 2016 and March 2017. Stem growth ceased after March likely as the allocation of carbon reserves shifted from supporting growth of the above ground biomass to storage in the roots.

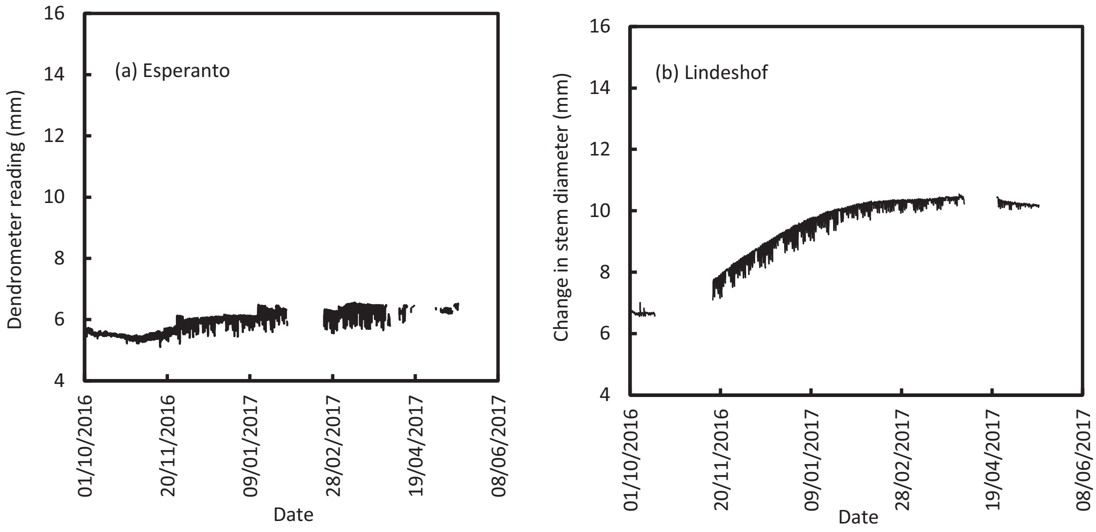


Fig. 4.12 Changes in stem size above the graft union of the bearing: (a) 'Cripps' Pink' at Esperanto, and (b) 'Golden Delicious Reinders' at Lindeshof during the 2016/17 growing season.

4.3.3.2 Canopy and stem growth: EGVV orchards

The 'Cripps' Pink' trees at Dennebos had an average height of 3.97 ± 0.07 m while the average row to row canopy width was about 2.20 m. Stems, measured just above the graft union, were fairly thick with a mean diameter of 9.9 ± 0.2 cm.

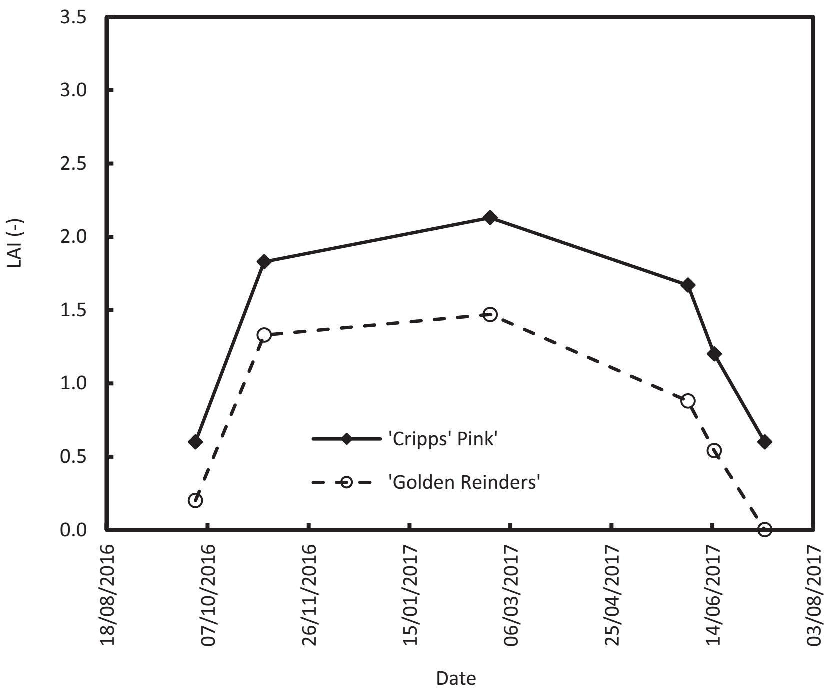


Fig. 4.13 Seasonal changes in the leaf area index of the apple orchards in EGVV during the 2016/17 growing season.

The 'Golden Delicious Reinders' trees at Vyeboom were smaller with an average height less than 3.0 m and the average canopy diameter ranged from 1.5 to 2.7 m. The average stem diameter was about 5.33 ± 0.08 cm. The seasonal dynamics of the LAI are as shown in Fig. 4.13. The LAI peaked at 1.8 for the 'Cripps' Pink' trees at Dennebos and at around 1.3 for the 'Golden Delicious Reinders' at Vyeboom. The 'Cripps' Pink' at Dennebos had a longer growing season than the 'Golden Delicious Reinders' with spring flush occurring in mid to late September 2016 and some leaves (though few) were still on the trees as late as mid-July 2017.

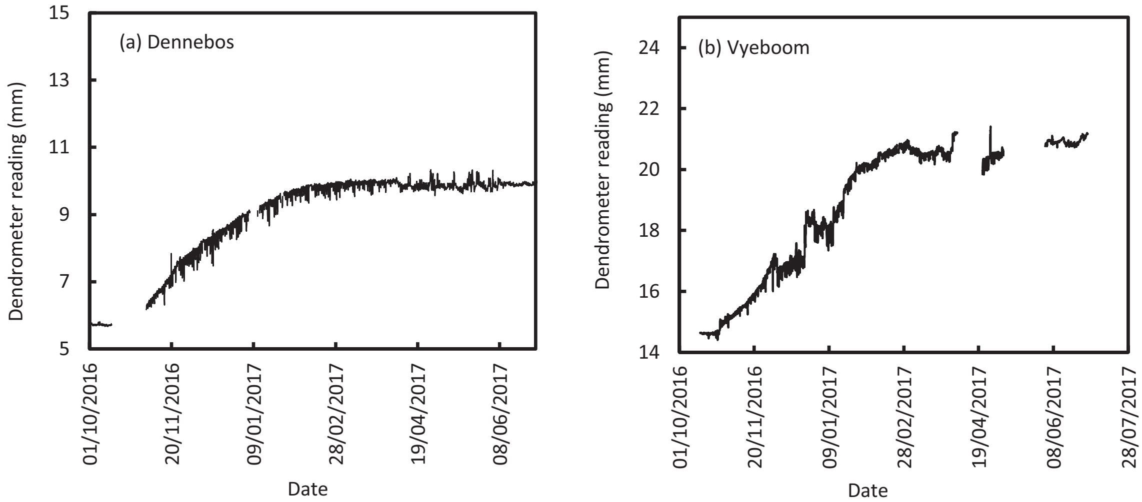


Fig. 4.14. Changes in stem size above the graft union of the (a) 'Cripps' Pink' at Dennebos, and (b) 'Golden Delicious Reinders' at Vyeboom during the 2016/17 growing season.

There was substantial stem growth in the 'Cripps' Pink' Block at Dennebos (Fig. 4.14a). Stem growth for the season exceeded 4.5 mm. The growth rate was most rapid between October and March where the monthly stem growth rate was just over 1.0 mm month^{-1}. Substantial stem growth also occurred in the 'Golden Delicious Reinders' orchard although the dendrometer signal was less well defined for unclear reasons (Fig 4.14b).

4.3.4 Transpiration and irrigation dynamics: KBV

Average wound size due to the implantation of the HPV sap flow sensors was about 3.79 ± 0.04 mm for the 'Golden Delicious Reinders' trees at Lindeshof and 2.98 ± 0.07 mm for the 'Cripps' Pink' trees at Esperanto. The sapwood depth was up to 94% of the stem radius and the heartwood radius was negligible. Maximum daily water uses by a typical 'Golden Delicious Reinders' tree at Lindeshof was just under 20 L d^{-1} in summer (data not shown). A single tree transpired approximately 2 520 L between 01 October 2016 and 30 June 2017 (Fig. 4.15a) compared to an average of 3 360 L of irrigation. So the difference between actual tree water consumption and irrigation applied was small at Lindeshof.

Transpiration by a single ‘Cripps’ Pink’ tree at Esperanto was substantially higher than the ‘Golden Delicious Reinders’ at Lindeshof, with peak transpiration just above 30 L d^{-1}. The high transpiration rate at Esperanto was because the trees were also larger. A typical tree at Esperanto transpired approximately 5 430 litres of water from 01 October 2016 to 30 June 2017 (Fig. 4.15b). Irrigation applied over the same period was around 8 130 L d^{-1} $tree^{-1}$ which translates to approx. 9 000 m^3 ha^{-1}.

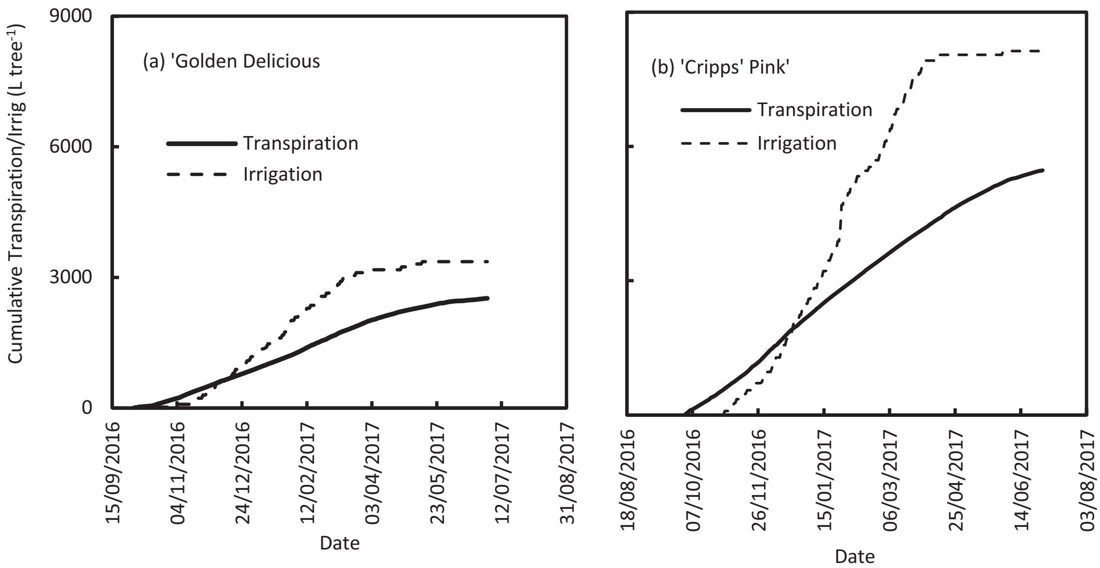


Fig. 4.15 Seasonal total transpiration and irrigation applied to a single bearing; (a) ‘Golden Delicious Reinders’ and; (b) ‘Cripps’ Pink’ tree in the KBV during the 2016/17 season.

Transpiration by individual trees at Esperanto was higher than that observed for full-bearing ‘Cripps’ Pink’ trees measured in earlier studies in other orchards. For example, Gush and Taylor (2014) measured a single tree transpiration of ~ 3 994 L at the neighbouring Nooitgedacht Farm in 2012/13. Scaling up the transpiration at Esperanto from single tree to orchard level (Fig. 4.16a) led to a seasonal transpiration of 547.4 mm (Table 4.9) which was lower than the full-bearing ‘Cripps’ Pink’ at Nooitgedacht which transpired 687 mm in 2012/13 (Gush and Taylor, 2014). Changes in soil water content at Esperanto correlated with irrigation events (Fig. 4.16). Seasonal total transpiration by the bearing ‘Golden Delicious Reinders’ orchard at Lindeshof was 419.8 mm.

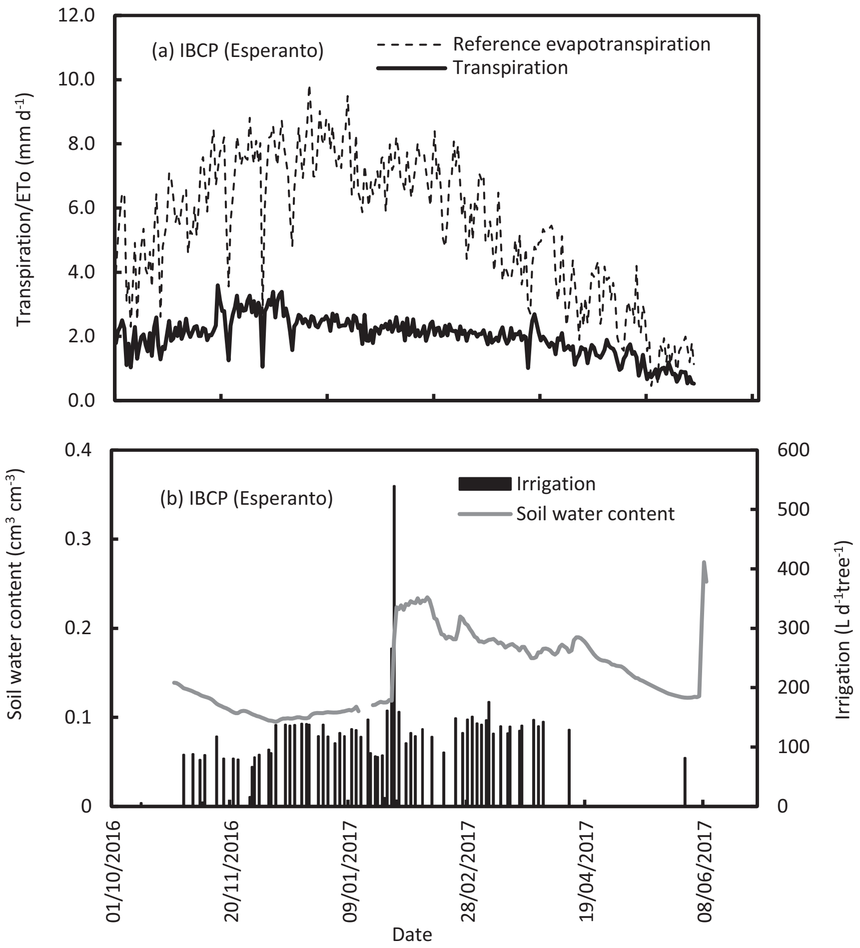


Fig. 4.16 (a) Effect of ETo on transpiration by intermediate bearing "Cripps' Pink' trees at Esperanto, and; (b) effect of irrigation events on soil water content during the 2016/17 season.

There was a non-linear relationship between the daily transpiration and the reference evapotranspiration (Fig. 4.17). This curvilinear relationship is thought to be related to the sensitivity of apple trees to high vapour pressure deficits which causes stomata to close as a result of a high hydraulic resistance somewhere in the transpiration stream which causes water supply to the evaporating sites not to match water loss via transpiration. Under these conditions, the trees have to close their stomata to prevent a catastrophic decline in tree water status. As expected, transpirational losses were greatest during summer for both cultivars (Table 4.9). The basal crop coefficients (transpiration/ET_o) varied from 0.31 to 0.53 for the 'Cripps' Pink' and were much lower for the 'Golden Delicious Reinders' at Lindeshof which varied from 0.22 to 0.35 (Table 4.9).

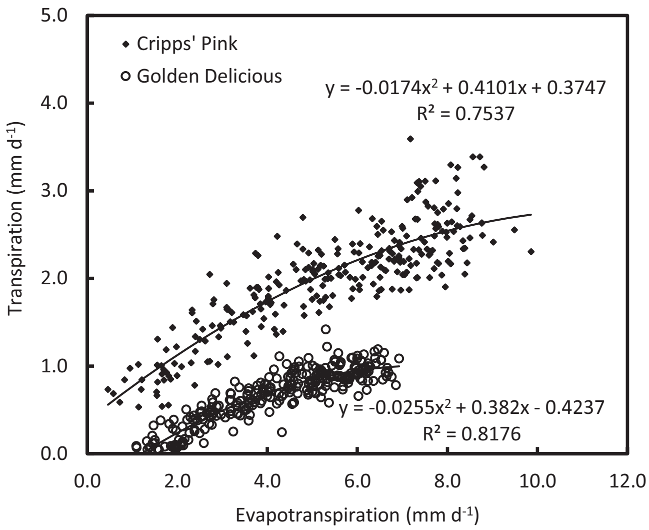


Fig. 4.17 Effects of the reference evapotranspiration on the daily transpiration rate of orchards with medium canopy cover in KBV during the 2016/17 growing season.

Table 4.9. Summary of seasonal transpiration of intermediate bearing orchards in the Koue Bokkeveld.

Month	ETo (mm)	'Cripps' Pink' Transpiration (mm)	'Golden Delicious Reinders' Transpiration (mm)	'Cripps' Pink' K_{cb} (-)	'Golden Delicious Reinders' K_{cb} (-)
Oct-16	150.8	59.1	32.9	0.39	0.22
Nov-16	199.2	71.7	55.2	0.36	0.28
Dec-16	231.8	83.8	56.8	0.36	0.25
Jan-17	234.3	73.3	59.3	0.31	0.25
Feb-17	202.3	62.6	64.6	0.31	0.32
Mar-17	187.1	64.5	64.8	0.34	0.35
Apr-17	131.2	58.8	41.5	0.45	0.32
May-17	94.3	46.3	30.6	0.49	0.32
Jun-17	52.0	27.3	14.1	0.53	0.27
Total	**1482.9**	**547.4**	**419.8**		

4.3.5 Transpiration and irrigation dynamics: EGVV

Transpiration by a typical bearing 'Cripps' Pink' tree at Dennebos varied from zero at the beginning of the season to a peak around 25 L d^{-1} (data not shown). On average each tree transpired 3 765 L from 01 October 2016 to 30 June 2017 based on the sap flow measurements (Fig. 4.18). However, the trees received less irrigation than all the other orchards studied during 2016/17 with a single tree receiving only 1 820 L for the whole season. Reasons for the low irrigation amounts are unclear. But the heavy clay soils with a high water holding capacity and the water logging conditions in parts of the orchard were contributory factors. In addition, there was no evidence of water stress in the orchard as confirmed by the plant water status measurements in section 4.4.3. Our water flow meter also worked well besides a few instances when the battery ran down (less than 2 weeks down time for the whole season).

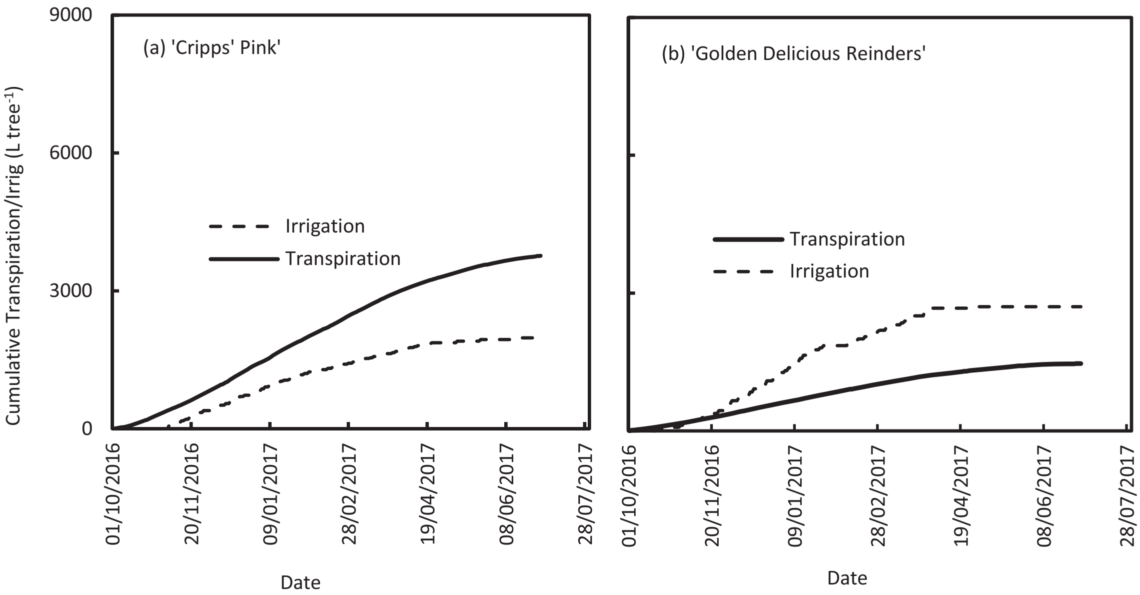


Fig. 4.18 Seasonal total transpiration and irrigation applied per tree for a: (a) 'Cripps' Pink' and (b) 'Golden Delicious Reinders' tree in EGVV during the 2016/17 season.

The 'Golden Delicious Reinders' trees had lower daily transpiration rates. Peak transpiration was around 16 L $d^{-1}tree^{-1}$ since the trees had a relatively small canopy cover. The seasonal total transpiration was about 1 460 L $tree^{-1}$ while irrigation amounted to 2 700 L $tree^{-1}$ (Fig. 4.18b). Orchard level transpiration closely followed the course of the reference evapotranspiration (Fig. 4.19a & Fig. 4.20a) for both orchards in EGVV. Peak transpiration for the 'Cripps' Pink' orchard was lower than 3.0 mm d^{-1} while that of the 'Golden Delicious Reinders' was around 1.5 mm d^{-1}.

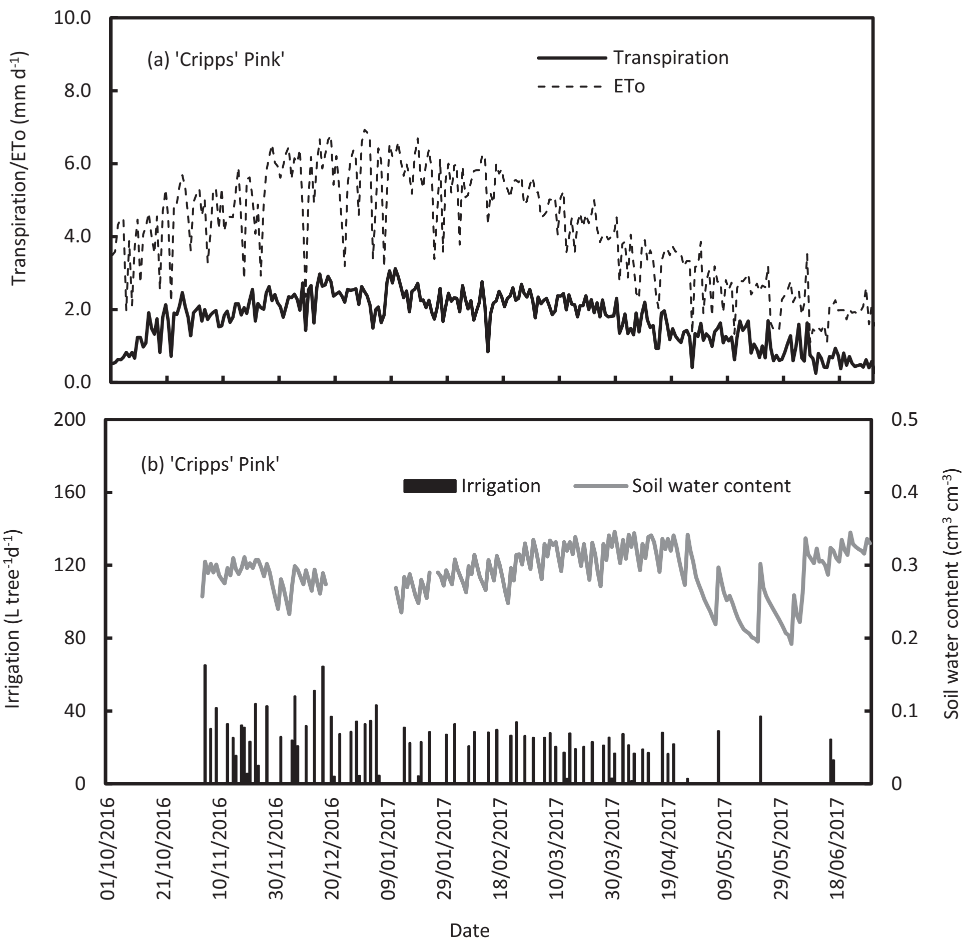


Fig. 4.19 Seasonal dynamics of; (a) the daily transpiration and reference evapotranspiration, and (b) soil water content and irrigation for the 'Cripps' Pink' orchard at Dennebos.

Seasonal orchard transpiration for the 'Cripps' Pink at Dennebos was about 471 mm compared to approx. 249 mm at Vyeboom (Table 4.10). December 2016 and January 2017 had the highest transpiration rates for both orchards and the transpiration coefficient ranged from 0.32 to 0.47 for the 'Cripps' Pink' and from 0.1 to 0.25 for the 'Golden Delicious Reinders. The seasonal total transpiration by the 'Cripps' Pink' orchard at Dennebos was lower than that at Esperanto likely because of the higher atmospheric evaporative demand in KBV than in EGVV (Tables 4.8). The 'Golden Delicious Reinders' at Lindeshof also used more water than that at Vyeboom not only because of the high ETo in KBV but also because of the larger plant density since the orchards are not yet fully established and the trees are still growing.

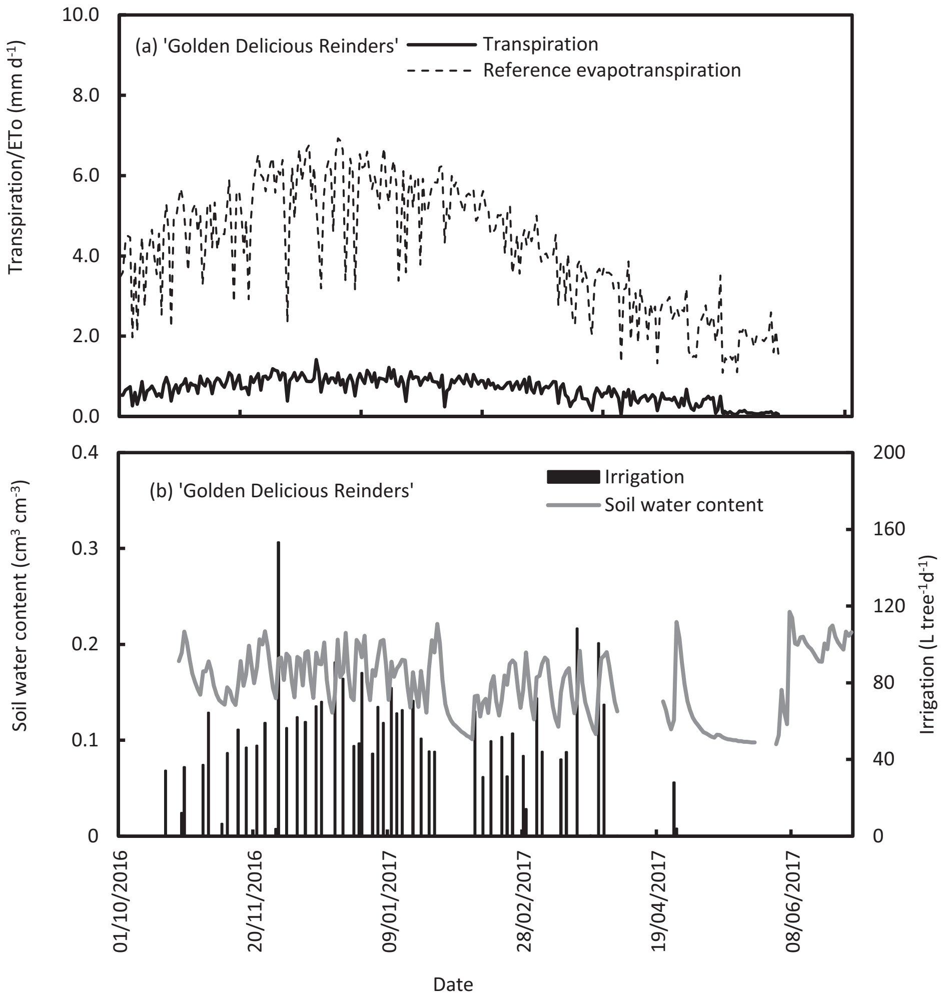


Fig. 4.20 Seasonal dynamics of: (a) the daily transpiration and reference evapotranspiration, and (b) soil water content and irrigation for the 'Golden Delicious Reinders' orchard at Vyeboom.

Table 4.10 Summary of monthly transpiration of bearing orchards in the EGVV production region.

Month	ET_o (mm)	'Cripps' Pink' Transpiration (mm)	'Golden Delicious Reinders' Transpiration (mm)	'Cripps' Pink' K_{cb} (-)	'Golden Delicious Reinders' K_{cb} (-)
Oct-16	128.0	41.5	26.8	0.32	0.21
Nov-16	147.5	60.3	36.6	0.41	0.25
Dec-16	177.6	74.4	41.2	0.42	0.23
Jan-17	172.4	70.7	38.3	0.41	0.22
Feb-17	152.2	62.3	32.8	0.41	0.22
Mar-17	136.5	64.3	32.3	0.47	0.24
Apr-17	96.8	43.1	19.4	0.44	0.20
May-17	76.3	34.5	17.2	0.45	0.23
Jun-17	57.9	19.6	4.8	0.34	0.10
Total	**1148.2**	**470.7**	**249.3**		

4.3.6 Orchard evapotranspiration

4.3.6.1 Eddy covariance method

Actual orchard evapotranspiration was measured using the eddy covariance system for 8 days at Esperanto, 25 days at Dennebos, 6 days at Vyeboom, and 16 days at Lindeshof. The orchard ET was linearly related to the reference evapotranspiration (Fig. 4.21). However, the slopes of the graphs differed, as a result of differences in the crop coefficients of the orchards and also reflecting seasonal variations of the coefficients.

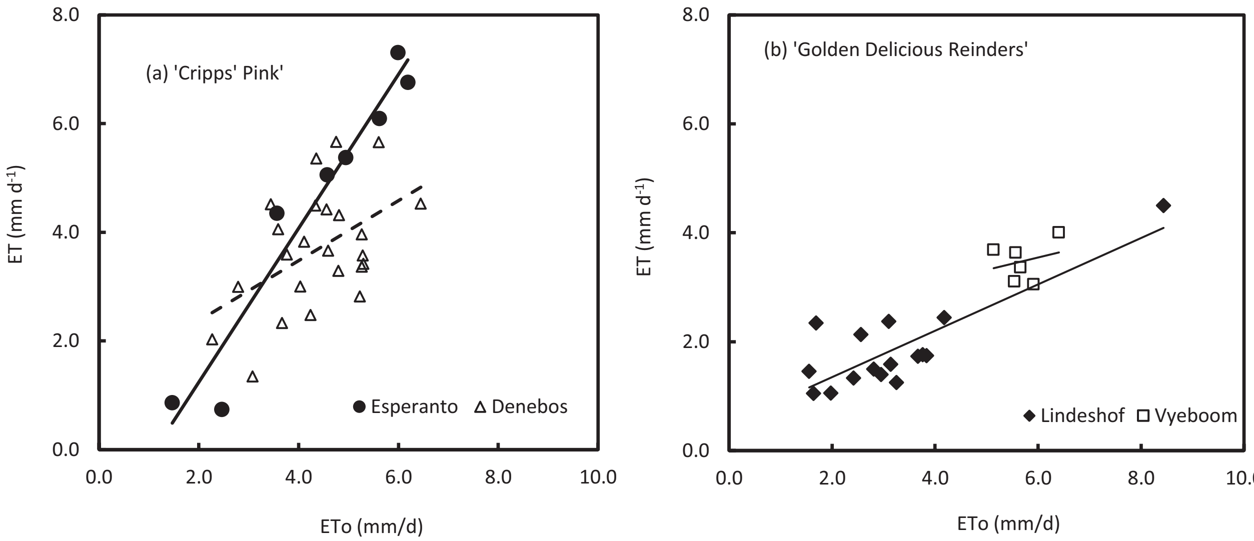


Fig. 4.21 Actual measured evapotranspiration of (a) 'Cripps' Pink' and (b) 'Golden Delicious Reinders' orchards during the 2016/17 season.

Evapotranspiration derived from the remote sensing FruitLook tool for the period August 2016 to May 2017 are shown in Fig. 4.22. The 'Cripps' Pink' orchards had the highest total ET of 897 mm at Esperanto followed by 827 mm at Dennebos. Evapotranspiration from the 'Golden Delicious Reinders' orchard at Lindeshof was 726 mm while the 'Golden Delicious Reinders' at Vyeboom's ET was 734 mm. These ET trends are consistent with the sap flow derived transpiration that showed the two 'Cripps' Pink' orchards having higher water use rates than the 'Golden Delicious Reinders' orchards.

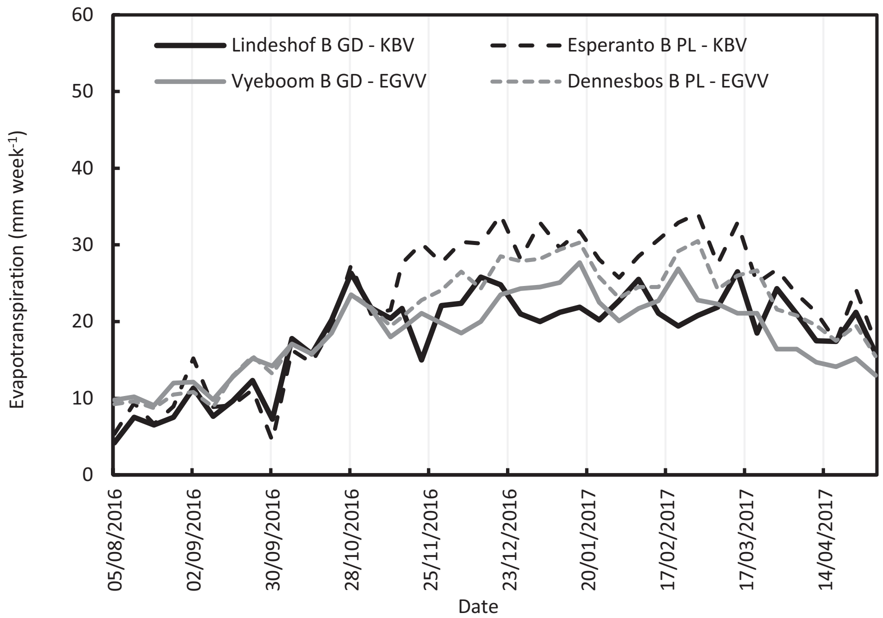


Fig. 4.22 FruitLook evapotranspiration trends for the four orchards during the 2016/17 season.

4.3.6.2 Evapotranspiration determined with the soil water balance method

At the Lindeshof orchard, the ET in general followed the trend of ET_o over the season, except for periods when trees were subjected to water deficits (Fig. 4.23a). Decreased ET from the tree row during October/November and February to April may have been due to the lower soil water status during these periods. The ET tended to increase until December and reached in general during December and January a maximum of c. 5.3 mm. The ET values in excess of 6.8 mm d^{-1} occurred on days having ET_o of between 7 to 8.7 mm d^{-1} in combination with irrigation of 20 mm or more per day. During February the ET declined steeply as soil water content deeper in the soil profile decreased beyond the -20 kPa refill level (Fig. 4.23a) and irrigation management applied resulted in a continuous deficit irrigation scenario since the soil did not refill to field capacity after irrigation. After application of c. 30 mm of irrigation on 20

April 2017 ET increased from c. 1.5 mm d^{-1} to 2.7 mm d^{-1} and thereafter decreased gradually to 1.5 mm d^{-1} in June. Work row ET was in general associated with rainfall events and reached a maximum of 2.7 mm on 10 January 2016 (Fig. 4.23b) when 6 mm rainfall occurred. A tree and work row weighted ET for the orchard reached a maximum of 8.7 mm d^{-1} for the season (Fig. 4.23c). Transpiration exceeded the soil water balance determined ET and these cases should be investigated further.

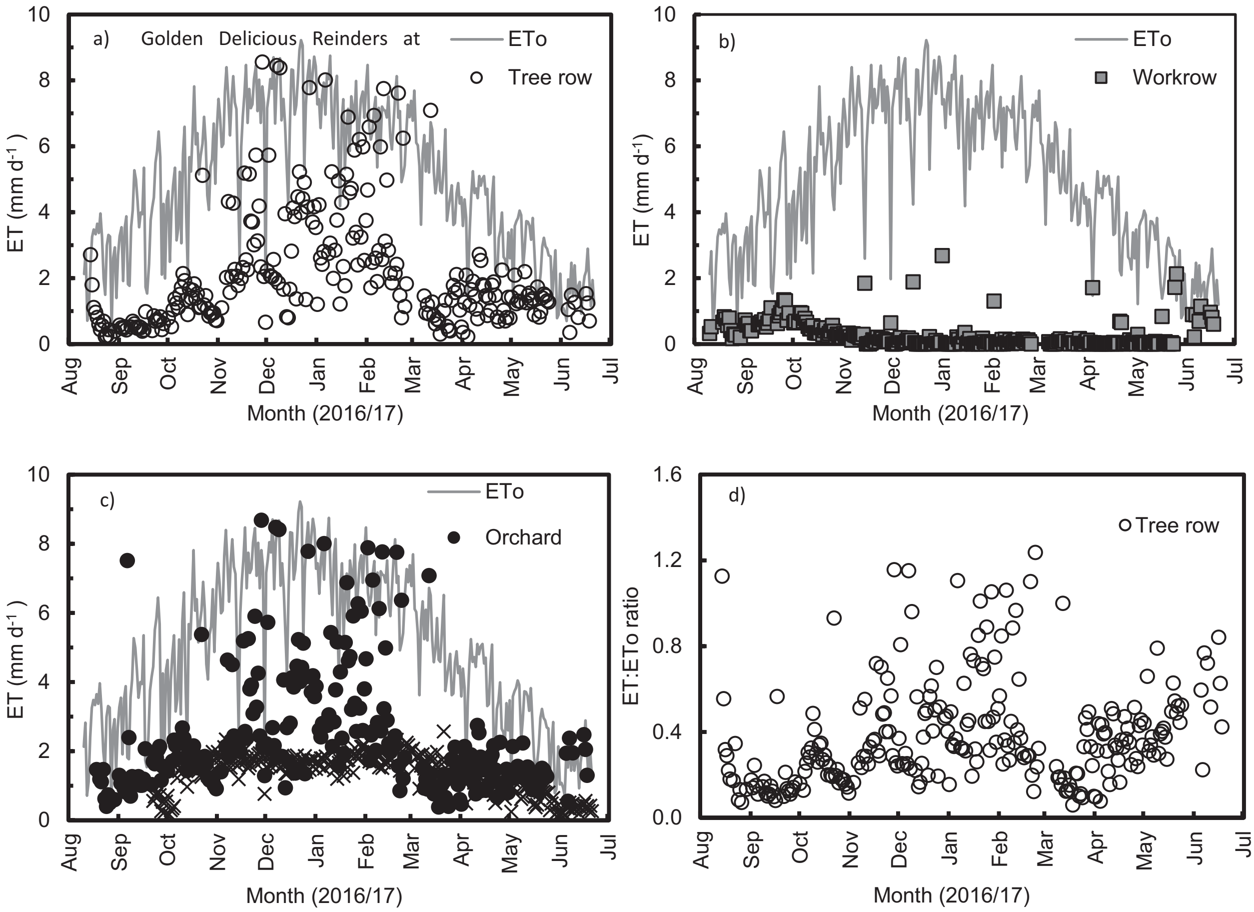


Fig. 4.23 Seasonal changes in reference evapotranspiration (ETo) and evapotranspiration (ET) of the: a) tree row, b) work row and c) orchard of a non-bearing 'Golden Delicious Reinders' at Lindeshof in the Koue Bokkeveld during the 2014/15 season. The amount of tree transpiration (T) relative to orchard ET and the ET: ET$_o$ ratio for the irrigated tree row area is indicated in c) and d), respectively.

The ET: ETo ratio was about 0.3 in August and increased to a maximum of c. 1.15 during December to February if the extremely high ET$_o$ days are taken into account (Fig. 4.23d).

Based on the monthly average though, the tree row had during midseason in January an ET of 4 mm/d and an ET:ET$_o$ ratio of 0.5 (Table 4.11).

Table 4.11 Monthly averaged orchard component and total orchard evapotranspiration (ET) and ET to Penman-Monteith reference evapotranspiration (ET$_o$) ratios for the 'Golden Delicious Reinders' at Lindeshof in the Koue Bokkeveld in 2016/17. The number of days with reliable data are indicated (N).

Month	ET (mm d^{-1})			ET:ET$_o$ ratio			N
	Tree row	Work row	Orchard	Tree row	Work row	Orchard	
Sep	0.5	0.5	1.4	0.15	0.17	0.31	23
Oct	1.3	0.7	2.0	0.27	0.14	0.41	27
Nov	2.1	0.3	2.4	0.31	0.05	0.34	25
Dec	3.4	0.1	3.6	0.45	0.03	0.48	30
Jan	3.8	0.1	4.0	0.50	0.02	0.54	28
Feb	3.8	0.1	3.9	0.52	0.01	0.54	27
Mar	1.9	0.1	2.0	0.31	0.01	0.32	20
Apr	1.4	0.1	1.5	0.32	0.03	0.35	30
May	1.3	0.1	1.3	0.42	0.04	0.44	26
Jun	1.1	0.8	1.7	0.57	0.35	0.89	9

At the full surface irrigated 'Cripps' Pink' orchard at Esperanto, ET was calculated separately for the ridge (tree row, western ridge and eastern slope), the tractor track and cover crop (Fig. 4.24a-c). The ET from the ridged area increased from about 0.7 mm d^{-1} near end October to 2.9 mm d^{-1} in January and decreased to its original value at the beginning of May (Fig. 4.24a). Increased ET to a value of 1.7 mm d^{-1} during mid-June can only be attributed to evaporative losses and weed water use after a significant rainfall event (>80 mm) occurred on 7 and 8 June 2017. The maximum ET that occurred from the tractor track and cover crop during December was 3.2 mm d^{-1} and 3.1 mm d^{-1}, respectively, and is most likely due to excessive weed growth observed in the orchard at the time (Fig. 4.24b & c). The latter contributed significantly to the maximum orchard ET, which weighted for the different components, amounted to 8.3 mm (Fig. 4.24d). Transpiration as determined by sap flow exceeded, as previously, ET determined by the soil water balance during drying periods. This should be investigated further.

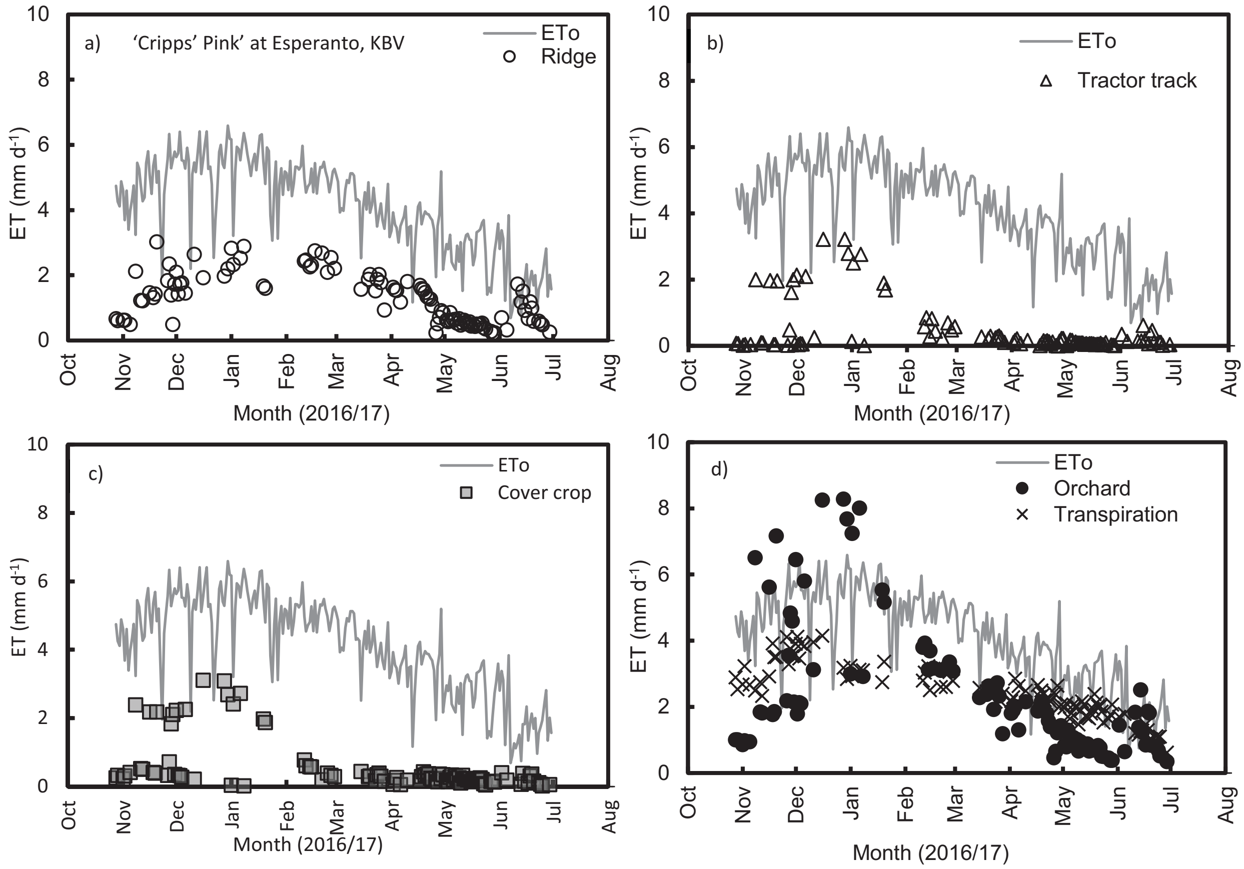


Fig. 4.24 Seasonal changes in reference evapotranspiration (ET_o) and evapotranspiration (ET) of the a) ridge, b) tractor track, c) cover crop and d) orchard of intermediate bearing 'Cripps' Pink' at Esperanto in the Koue Bokkeveld during the 2016/17 season. The amount of tree transpiration (T) relative to orchard ET is indicated in (d).

The ET: ET_o ratio for the ridge was about 0.15 by end October and increased to a maximum of between 0.58 and 0.6 during the period between December and February, after which it levelled off at c. 0.5 until mid-April (Fig. 4.25a). The ET: ET_o ratio decreased thereafter gradually linearly to an average of 0.15 at the beginning of June. The high values in June were, as explained for the ET above, associated with a significant rainfall event. The ET:ET_o ratios of the work row reached a value of 1.1 during November to January (Fig. 4.25 b) and was considerably higher than that of the ridge (Fig. 4.25a). The water losses from the work row area contributed significantly to the orchard losses which resulted in the maximum possible orchard ET:ET_o ratio of 1.4 (Fig. 4.25c). Based on monthly averages, the work row used more water than the ridge during November to January (Table 4.12) and it can most likely be attributed to excessive weed water use. However, it should be noted that these observations are based on a very limited dataset.

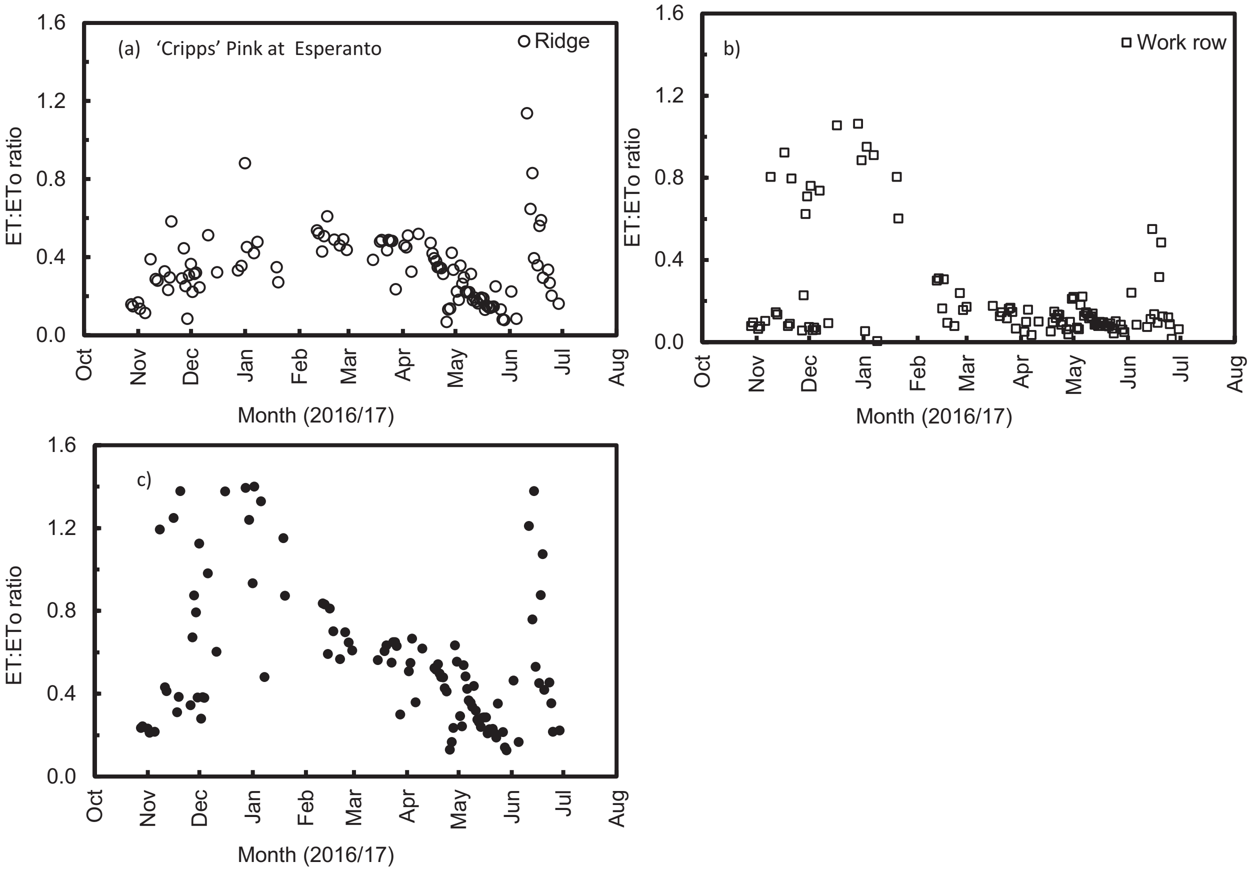


Fig. 4.25 Seasonal changes in the evapotranspiration (ET) to reference evapotranspiration (ET_o) ratios of a) the ridge b) work row (i.e. tractor track and cover crop) and c) orchard of intermediate bearing 'Cripps' Pink' at Esperanto in the Koue Bokkeveld during the 2016/17 season.

Table 4.12 Monthly averaged orchard component and total orchard evapotranspiration (ET) and ET to Penman-Monteith reference evapotranspiration (ET_o) ratios for the intermediate bearing 'Cripp's Pink' at Esperanto in the Koue Bokkeveld in 2016/17. The number of days with reliable data are indicated (n).

Month	**ET** (mm d^{-1})			**ET:ET$_o$ ratio**			**n**
	Ridge	**Work row**	**Orchard**	**Tree row**	**Work row**	**Orchard**	
Nov	1.4	1.8	3.2	0.28	0.34	0.62	14
Dec	1.9	2.9	4.8	0.33	0.48	0.81	10
Jan	2.3	3.0	5.3	0.47	0.55	1.03	6
Feb	2.4	1.0	3.4	0.51	0.20	0.71	8
Mar	1.8	0.6	2.3	0.44	0.14	0.58	9
Apr	1.3	0.4	1.6	0.36	0.10	0.46	17
May	0.5	0.3	0.8	0.20	0.10	0.30	27
Jun	0.8	0.4	1.2	0.43	0.18	0.61	14

4.4 Conclusions

‘Cripps’ Pink’ orchards with medium canopy cover used more water than the ‘Golden Delicious Reinders’ because they tended to have larger canopies. Transpiration rates of the trees at Esperanto were highest due to large irrigation levels during parts of the season as a result of faulty irrigation equipment. However, an extended period of excess irrigation from end of January to mid- February 2017 resulted in a transpiration reduction, presumably in response to water logging. Estimates of the ratio of ET: ET_o were derived and these covered a wide range of values depending on the ET levels. The seasonal total ET under these orchards will be presented in Chapter 6. Although tree density differed considerably between orchards, this did not appear to influence the orchard transpiration levels as was the case in young orchards. This was because the trees in most of the medium canopy orchards had filled their allocated space.

CHAPTER 5

WATER USE AND ITS DRIVERS IN MATURE HIGH PERFORMING APPLE ORCHARDS

5.1 Introduction

Irrigation is the single most repetitive operation in fruit production, especially in arid and semi-arid regions (Fernández and Cuevas, 2010, Liu et al., 2014). In key deciduous fruit exporting countries such as Spain, Italy and South Africa, most of the fruit is produced under irrigation (Gush and Taylor, 2014; Volschenk, 2017). The average yield of apple orchards varies considerably between countries. In South Africa, for example, it is approximately 60 t ha^{-1} (Hortgro, 2016). However, in recent years, exceptionally high yielding orchards that consistently produce more than 100 t ha^{-1} have become common due to improved plant material and orchard management practices (W. Steyn, pers. com.). This raises questions on the sustainability of these orchards given the increasingly limited water resources and most growers are now "pushing" their orchards to yield at least 100 t ha^{-1}. The impact of these production practices on the water requirements of the orchards is currently not known.

Some studies have shown that high crop loads increase the demand for assimilates (Steduto et al., 2012, Naor et al., 1997). Low photosynthesis rates for trees carrying a lot of fruit lead to small fruit size and fruit of low quality as a result of the high competition for the limited assimilates. This can also trigger alternate bearing in subsequent years (Girona et al., 2011). However, with improved orchard management practices, mainly irrigation, nutrition, and pest control, it is now possible to consistently produce high yields of good quality fruit in successive years.

To meet the increased demand for assimilates under high crop loads, it is hypothesized that trees have to maximize photosynthesis (Naor et al., 1997, Naschitz and Naor, 2005, Steduto et al., 2012). This can be achieved through more sustained stomatal opening leading to a higher stomatal conductance than under normal crop loads. This inevitably leads to higher transpiration rates, as seen in trials where crop loads were adjusted on potted apple trees (Wünsche et al., 2005) and field grown trees (Fereres et al., 2012).

Another trial with apple trees grown on a lysimeter at the Agri-Food Research and Technology Institute (IRTA), in Spain showed that transpiration rates decreased immediately after de-fruiting the trees during the course of the season (Jaume Casadesus, pers. com.). However, the leaf area index (LAI) increased at a faster rate after de-fruiting compared to trees that still had fruit on them. Consequently, there was no significant difference in transpiration between the two treatments at the end of the season. The Spain study provided two vital pieces of information. Firstly, it supports the observation that high crop loads result in high transpiration rates. Secondly, it suggests that low crop loads appear to promote excessive vegetative growth, consistent with the observations of Bacon (2009). This leads to a large transpiring leaf area possibly negating the benefits of a low crop load on water use.

The aim of this study was to quantify the maximum unstressed water use of the country's most productive orchards. We also investigate the driving variables for water use and productivity through detailed eco-physiological measurements and orchard water balance assessments. This information can be used to improve management of these orchards and to improve economic returns to the growers.

5.2 Materials and methods

5.2.1 Study sites and plant material

5.2.1.1 Full-bearing orchards in the Koue Bokkeveld

The two orchards in KBV comprised a full-bearing 'Golden Delicious' (22 years old) in Block KP07 at Kromfontein farm. The orchard area was 11.1 ha and tree spacing was 4.0 m x 1.5 m giving a plant density of 1 667 trees per hectare. Canopy cover was high at around 52% in summer. The 'Cripps' Pink' orchard was 9 years old in Block KP06 also at Kromfontein (Fig. 5.1). The block was approximately 6.0 ha with trees spaced at 4.0 m x 1.5 m. Both orchards were on the industry standard M793 rootstock. Canopy cover was slightly lower than the 'Golden Delicious' at about 45%.

The yield history showed that the 'Golden Delicious' orchard consistently produced more than 100 t ha^{-1} since the 2010/11 season. The 'Cripps' Pink' orchard, on the hand, was relatively young and the yield had gradually increased over the years and exceeded 100 t ha^{-1} in the last two seasons (2012-2014). Soil types were deep sandy soils of the Cartref form. Irrigation was via a micro-sprinkler system with one sprinkler per tree delivering about 32 L h^{-1}. The trees were irrigated two to three times per week for one to two hours early in the season.

Fig. 5.1 A typical high yielding apple orchard in KBV.

The irrigation frequency increased to daily during summer. There was evidence of under irrigation in the 'Golden Delicious' orchard which led to substantial stress and yield reduction for the current season as reported in section 5.4. Irrigation in the 'Cripps' Pink' orchard appeared excessive during January-February which may have caused stress as well. But there was no yield reduction. Both orchards had a dense cover crop of tall fescue covering about 1.4 m of row width.

5.2.1.2 Full-bearing orchards in EGVV

This 'Golden Delicious' orchard (Block B4 at Southfield farm) was 29 years old (planted in 1987) on the M793 rootstock. The trees were planted with a north-south row orientation. Orchard size was approximately 5.5 ha and the trees were planted with a 4 m x 2 m spacing giving 1 250 trees per hectare. Average tree height was approx. 4.5 m while the mean canopy diameter was about 2.5 m. Maximum fractional canopy cover was approx. 51%. One in every ten trees was a 'Granny Smith' pollinator. The water table in some parts of the orchard was relatively shallow although the tree roots were in the unsaturated zone. Cover crop was a mixture of Kentucky fescue grass (*Festuca arundinacea*) and indigenous species in a narrow strip about 1.5 m wide. Yield in this orchard, dubbed as the "Local Flagship", was consistently above 100 t ha^{-1} in the past four seasons.

The full-bearing ‘Cripps’ Pink’ orchard was Block B6 at Radyn farm situated next to Southfield. The orchard was 12 years old (planted in 2004) on an east facing moderately sloping terrain. The trees were grafted on the M793 rootstock. Orchard size was 5.2 ha with the trees planted in a northwest-southeast row orientation. Tree density was higher than in the ‘Golden Delicious’ orchard being 4.0 m x 1.5 m giving 1 667 trees per hectare. Average height of the trees was approx. 4.3 m while the mean canopy diameter was about 2.2 m with a canopy cover of about 46%. One in every ten trees was a ‘Granny Smith’ pollinator and the cover crop was predominantly the fescue. Yield in this orchard was 96.9 t ha^{-1} in 2011, 79.0 t ha^{-1} in 2012, 118.8 t ha^{-1} in 2013 and 105.3 t ha^{-1} in 2014. Both EGVV orchards were under micro-sprinkler irrigation scheduled in the same way as in KBV.

5.2.2 Soil properties, water content dynamics, and irrigation

5.2.2.1 Soil physical properties

Soil samples for chemical and five fraction particle size analyses (PSA) were taken in KBV and EGVV in November 2014 and October 2015, respectively, following the procedure described in section 3.2.3.1. At the KBV ‘Golden Delicious’ orchards for soil water balance and Eddy covariance measurements (Kromfontein), sampling depth increments were 0-50, 50-300, 300-600, and 600-900 mm and 900-1100 mm and at the ‘Cripps’ Pink orchard (Kromfontein), 0-450, 450-700, and 750-1050 mm. At the EGVV ‘Golden Delicious’ orchard (Southfield) sampling depth increments were 0-300 mm, 300-600 mm and 600-900 mm and at the ‘Cripps’ Pink orchard (Radyn), 0-450, 450-700, and 700-900 mm.

To determine soil water retention properties at the ‘Golden Delicious’ orchards (Kromfontein and Southfield), tensiometers were installed at 150, 450, and 750 mm depths. There were no suitable tensiometers available to install at the 1.05 m or 1.1 m depths. At the ‘Cripps’ Pink’ orchards (Kromfontein and Radyn) tensiometers were installed at 300, 600, and 900 mm depths. Soil bulk density (P_b) for the EGVV ‘Golden Delicious’ orchard (Southfield) was determined according to the core method (Blake and Hartge, 1986) at the 150, 450, 750 and 1 100 mm depths in the clean cultivated tree row area and in the middle of the work row.

5.2.2.2 Soil water content and irrigation

In 2014/15 and 2015/16, the 'Golden Delicious' orchards at Kromfontein in the KBV and at Southfield in EGVV, respectively, were selected for detailed soil water balance measurements. Soil water content measurements in the 'Cripps' Pink' orchards at Kromfontein (2014/15) and Radyn (2015/16) were done only in the upper soil horizon using CS616 sensors attached to HPV systems.

In October 2014, soil water content equipment was installed at Kromfontein in the 'Golden Delicious' orchard according to a procedure similar to that described for Lindeshof in section 4.2.3.2 (Appendix A: Fig. 3; Table 3). The equipment was installed in the root zone at 150 mm, 450 mm and 750 mm soil depths and below the root zone at 1.05 m from the soil surface (Fig. 5.2). The soil was not homogeneous and contained distinctly different layers having increasing gravel and stone content. Roots were proliferous at the face of the soil profile especially in the 300 to 750 mm depth increment where gravel and stone prevailed. Roots deeper in the soil profile were more sparsely distributed but observed up to a depth of 1.0 m.

Fig. 5.1 Installation of CS616 sensors in the high canopy cover 'Golden Delicious' orchard at Kromfontein in 2014/15 in sandy loam soil at 150, 450, 750 and 1 050 mm depths. The measuring tape indicates centimetres.

In August 2015, soil water content equipment was installed in the 'Golden Delicious' orchard at Southfield according to an installation procedure similar to that described for the Kromfontein orchard above. Eight soil profiles per tree included two in the tree row with sensors orientated perpendicular to the tree trunk (East and West), four on the clean-cultivated strip with sensors oriented 45° from the tree row and perpendicular to the tree trunk (North West, South West, North East and South East) and two were located in the work row (North and South) (Appendix A: Fig. 3, Table 4). The work row soil profile was perpendicular to the tree row and sensors orientated parallel to the tree row. In the soil profiles thermocouples were installed c. 200 mm away from the CS616 sensors to minimise the possibility of electronic interference during measurement. Cable length limitations in some cases required alternative placement of thermocouples.

The root system of the full-bearing 'Golden Delicious' trees was extensive and well developed up to 1.2 m depth in uniform dark coloured sandy soil in the whole area allocated to the tree. The equipment was installed in the root zone at 150 mm, 450 mm, 750 mm and 1.1 m soil depths (Fig. 5.3), but only to a depth of 750 mm in the work rows. Soil water content could, due to limited equipment availability not be measured below the root zone. Also, in some cases restricted thermocouple cable length or CS616 sensor positioning required adjustment of thermocouple placement.

Fig. 5.2 Installation of CS616 sensors in 2015/16 in the high canopy cover 'Golden Delicious' orchard at Southfield (EGVV) in loamy sand to sandy loam soil at 150, 450, 750 and 1 1 00 mm depths.

Large roots in some cases necessitated that sensors at deeper levels be installed in an alternate position at similar depth. Beyond 1.2 m depth the roots tended to turn and grow upward, which indicates some restriction to normal growth e.g.an impermeable soil layer or a water table. However, no free water was observed at the time the profile holes were inspected. This was most likely due to the dry winter foregoing the current season. Gravimetric soil sampling for the purpose of soil water content equipment calibration and monitoring of irrigation applied in these orchards is similar to that described in section 3.2.3.2.

5.2.3 Eco-physiology

5.2.3.1 Leaf gas exchange and stem water potential

Stem water potential and gas exchange measurements were taken monthly from November until March, using methods described in Chapter 3.

5.2.3.2 Diurnal stem diameter fluctuations

Water relations were continuously measured in the two full-bearing apple orchards studied in 2015-2016 in the EGVV region: FBGD and FBCP. DEX 70 Dynamax dendrometers were used to measure hourly trunk and fruit diameter, and potential water stress was identified using daily growth (DG), maximum daily trunk growth (MXDTG) and maximum daily shrinkage (MDS) of the tree trunk and fruit, as described in Chapter 3.

5.2.3.3 Drivers of leaf level water use across all orchards

In this chapter, we also present an overarching analysis of all spot measurements of gas exchange and stem water potential measurements collected over the course of the three production seasons (Chapters 4 and 5) to investigate the underlying physiological drivers and regulation of water loss at the leaf and xylem level. Analysis of possible relationships between the various parameters was conducted according to the following factors:

- By canopy cover: low (non-bearing), medium (intermediate-bearing) and high (full-bearing)
- By cultivar: 'Golden Delicious'/'Golden Delicious Reinders'), and 'Cripps' Pink'-type (including 'Rosy Glow' and 'Cripps' Red')
- By production region: Koue Bokkeveld (KBV) and Elgin/Grabouw/Vyeboom/Villiersdorp (EGVV)
- By time of day: morning and afternoon

Where possible relationships of significance were identified, best fit regression was applied.

5.2.4 Tree transpiration rates

Transpiration in each of the full-bearing orchards was measured on six trees of different stem sizes using the heat ratio method of the heat pulse velocity (HPV) sap flow technique (Burgess et al., 2001). Four sets of heater probes and T-type thermocouple pairs were inserted into the sap wood of the stems at depths ranging from 10 to 50 mm under the bark in the bigger 'Golden Delicious' trees and at shallow depths for the smaller 'Cripps' Pink' trees. The HPV data was corrected for wounding, moisture fraction and wood density at the end of the experiment according to the approach by Swanson and Whitfield (1981). The wound widths were measured at five positions across the length of the wound created by sensor implantation using Vernier callipers. Mean values of the wound sizes were 4.14 mm with a standard error in the mean (SEM) of ±0.50 mm for the mature 'Golden Delicious' trees. For the 'Cripps' Pink', the mean wound size was 3.78 mm with an SEM of ±0.18 mm. The size of the conducting sapwood area was determined by injecting a weak solution of methylene blue dye into the stems towards the end of the experiment as described in Chapter 4.

5.2.5 Evapotranspiration of the mature apple orchards

5.2.5.1 Eddy covariance measurements

Orchard microclimate was measured using automatic weather stations. Detailed information is provided in Chapter 3 for KBV in 2014/15 and EGVV in 2015/16. Evapotranspiration was quantified using two open path eddy covariance systems (Fig 5.4). So, evapotranspiration of two orchards were measured concurrently when the equipment was available. The systems comprised sonic anemometers (model: CSAT3, Campbell Sci. Inc., Utah, USA) which measured the wind speed in 3 dimensions (*u, v, w*). The concentration of atmospheric water vapour and carbon dioxide were measured using infrared gas analysers (IRGA) (model: LI-7500A, LI-COR Inc., Nebraska, USA). One eddy covariance system was connected to a CR3000 data logger while the other used the CR5000 data logger, both manufactured by Campbell Scientific. The high frequency data, collected at 10 Hz, was stored on 2 GB memory cards. Additional sensors included a net radiometer (model: CNR1, Kipp & Zonen, The Netherlands) on the CR5000 station and a four component net radiometer (model: CNR 4, Kipp & Zonen, The Netherlands) on the CR3000 station.

Fig. 5.3 Open path eddy covariance system monitoring evapotranspiration in a full-bearing 'Golden Delicious' orchard at Southfield farm in Villiersdorp.

Two clusters of soil heat flux plates (model: HFP01, Hukseflux, The Netherlands) were installed at 8 cm depth below the surface to measure the soil heat fluxes under the canopies and between the rows in each station. Soil averaging thermocouples (model: TCAV, Campbell Sci. Inc., Utah, USA) were installed above the soil heat flux plates at 2 and 6 cm depths from the surface to correct the measured fluxes for the energy stored by the soil above the plates. Soil water content was measured using time domain reflectometer probes (model: CS616, Campbell Sci. Inc., Utah, USA). The IRGA and sonic anemometers were installed at heights around 2.0 m above the mean canopy height. These heights ensured that the sensors were above the surface roughness sublayer and the fetch was roughly 200 m around the tower. The eddy covariance ET data was collected during short window periods in spring, summer and autumn seasons due to the high demand on the equipment from other projects according to the schedule in Table 5.1. The orchard LAI was measured using an LAI-2000 leaf area meter (LI-COR Inc., Nebraska, USA) either at sunset or on overcast days when the assumption that leaves act like black bodies was most realistic.

Table 5.1. Attributes of the orchards monitored in KBV during the 2014/15 and in EGVV during the 2015/16 growing season. LAI = leaf area index; FC = volumetric soil water content at field capacity; PWP = volumetric soil water content at the permanent wilting point; f_c = fractional vegetation cover.

Season	Cultivar	Orchard age	ET duration	Sap flow duration	Soil water		f_c (-)	LAI (-)	Yield (t ha^{-1})
					FC (cm^3 cm^{-3})	PWP (cm^3/cm^3)			
2014/15	'Cripps' Pink'	Full-bearing (9 yr.)	18 to 28 Sept '14 11 to 31 Mar '15 01 to 15 Apr '15 01 to 07 Mar '15	Whole season	0.174	0.049	0.45	2.6	110
	'Golden Delicious'	Full-bearing (22 yr.)	07 to 20 Nov '14 01 to 24 Feb '15 01 to 07 Mar '15 24 to 27 Apr '15	Whole season	0.171	0.027	0.52	3.6	74
2015/16	'Cripps' ink'	Full-bearing (12 yr.)	18 to 23 Oct '15 04 Nov to18 Dec'15 01 to 18 Mar' 16 08 to 16 Apr' 16	Whole season	0.230	0.050	0.46	2.8	109
	'Golden Delicious'	Full-bearing (29 yr.)	09 to 28 Oct '15 18 to 28 Nov '15 11 to 16 Dec '15	Whole season	0.189	0.055	0.51	3.3	102

*5.2.5.2 S*oil water balance

Evapotranspiration was calculated for the full-bearing ‘Golden Delicious’ orchards (FBGD) in the KBV (Kromfontein) and EGVV (Southfield) according to the universal soil water balance as described in section 3.2.6.2. At the FBGD at Kromfontein the sensors at 150, 450, 750, and 1 050 mm depths respectively represent soil depth increments for 0 to 300 mm, 300 to 600 mm, 600 to 900 mm and 900 to1 050 mm in the soil profile. The soil water balance was calculated for the 0-900 mm depth increment for both the tree and work row. At Southfield soil water content was weighted to represent the 0-300 mm, 300-600 mm, 600-925 mm and 925-1 200 mm depth increments to obtain the average soil profile water content during the season. The soil water balance was calculated for the 0-1 200 mm depth increment in the tree row and 0-925 depth increment in the work row. In both orchards irrigation wetted the full surface area. For calculation of ET volumes per orchard component the total tree row and work row width, respectively, was at Kromfontein 2.7 and 1.3 m, and at Southfield 3.3 and 0.7 m.

5.3 Results and discussion

5.3.1 Soil properties, soil water content and irrigation

5.3.1.1 Soil physical properties

According to the particle size distribution most of the high canopy cover orchard soils had a sandy loam texture (Table 5.2). The KP07 eddy covariance site at Kromfontein had loamy sand and Radyn clay loam with more than 27% stone in the upper 700 mm of soil (Appendix B: Table 5). Kromfontein KP06 tended to have less stone in the upper soil layers compared to KP07 (Soil water balance site), but also contained c. 20% stone deeper in the soil profile. The KP07 (Eddy covariance site) had surprisingly lower stone content compared to the other orchards at Kromfontein. However, the sampling methods excluded large stones (i.e. > 50 mm in diameter), which were prevalent in the KP07-Eddy covariance orchard. The deep, well drained, uniform black soil at Southfield had no coarse fragments and texture changed from loamy sand in the top soil to sandy loam deeper in the profile.

Table 5.2 Profile averaged soil texture classes and particle size analysis for the soils at the high canopy cover orchards.

Orchard	Profile depth (mm)	Texture class	Clay	Silt %	Sand	Stone (v/v)
Kromfontein KP07	900	Sandy loam	13.6	2.9	83.5	16.3
Kromfontein KP07	900	Loamy sand	8.6	4.1	87.4	9.6
Kromfontein KP06	800	Sandy loam	13.3	4.0	82.7	13.9
Southfield	900	Sandy loam	10.3	8.7	80.8	0.0
Radyn	900	Clay loam	37.6	28.4	33.8	25.9

Chemical analysis of soils sampled at Kromfontein in the KBV confirmed that - based on fertilization norms for deciduous fruit trees - growth and therefore water use of trees would not be adversely affected by any soil related nutrient deficiencies/ imbalances or salinity (Appendix B: Table 6). Chemical analysis of the soil at Southfield ('Golden Delicious') indicated no apparent salinity or sodicity related problems. The pH and levels of potassium and calcium in the soil were low at the time of sampling and the other elements analysed were at acceptable levels (Appendix B: Table 6). Low pH could affect uptake of certain nutrients and thereby affect tree growth and/or fruit quality. At Radyn ('Cripps' Pink') the pH in the upper soil levels was acceptable, whereas the phosphate and potassium levels appeared to be low and magnesium exceptionally high. However, since tree nutrient status should also be taken into account before soil chemical adjustments are made, the information was made available to farm management to consider in their soil amendment and fertilisation actions.

The *in-situ* soil water retention curves for the high canopy cover orchards are displayed in Fig. 5.5, except for the 'Cripps' Pink' orchard at Radyn. Here, severe problems were experienced with gravimetric soil water content sampling in extremely stony shale soils and a mathematical relationship between soil water content and soil matric potential could therefore not be determined for this orchard.

A single soil water retention curve for the FBGD orchard at Kromfontein (Fig. 5.5a) was not possible, since the trends at the different depths differed too much (Refer Appendix C: Table 3). The retention curve for the 'Cripps' Pink' orchard at Kromfontein (KP06) represented only a limited range of soil matric potentials (Fig. 5.5b) even though gravimetric soil samples for establishment of the soil water retention curves were taken on ten occasions.

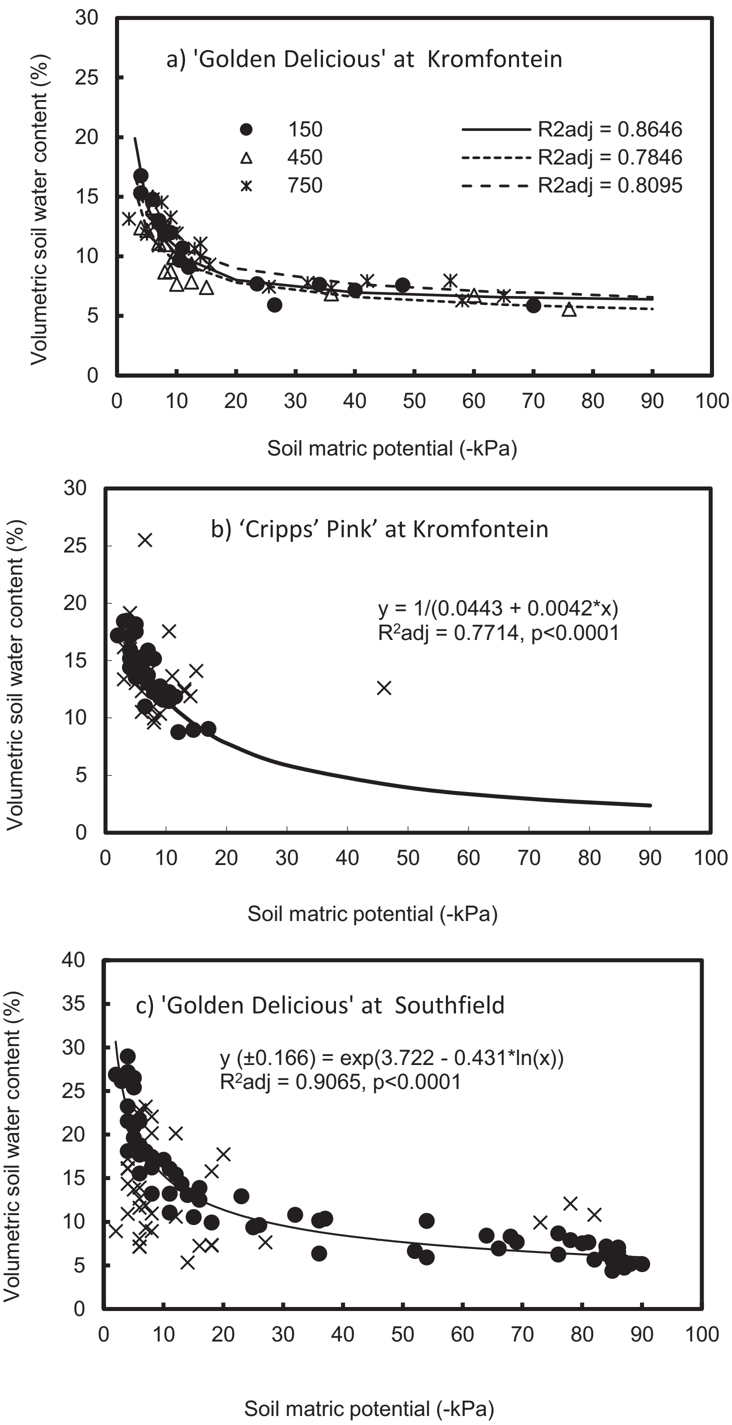


Fig. 5.4 Soil water retention curves of sandy loam soils in the a) 'Golden Delicious' and b) 'Cripps' Pink' orchards at Kromfontein in the KBV and in the FBGD orchard at Southfield in EGVV. Outliers are indicated as crosses.

Refer to Table 3 in Appendix C for statistics of the *in situ* determined soil water retention curves for various depths of each orchard.

According to estimates from the *in situ* determined soil water retention curves (Fig. 5.5) the FBGD at Kromfontein (Fig. 5.6a) had 87 mm m^{-1} total available soil water (TAW between -5 kPa and -1 500 kPa) compared to 152 and 189 mm m^{-1} of the soils in the 'Cripps' Pink' at Kromfontein and the FBGD at Southfield, respectively.

For the respective orchards c. 59%, c. 50% and c. 49% of the TAW is available to a soil matric potential of -20 kPa. To refill the soil to field capacity to a 600 mm root depth in the respective orchards one would have to apply 31, 46 and 56 mm of irrigation.

Soil bulk density (P_b) values as determined for the KP07 orchard in a previous research project amounted to 1 554±52 kg m^{-3}; 1 565±39 kg m^{-3} and 1 606±22 kg m^{-3} at 300 mm, 600 mm and 900 mm soil depths (T. Volschenk, unpublished data). These values were taken to be representative of the bulk density of the soil in KP06 and KP07, which had, compared to the other sites, similar stone fraction. The P_b values for Southfield at the 150, 450, 750, and 1 100 mm depths amounted to 1 500, 1 420, 1 390 and 1 370 kg m^{-3} respectively in the clean cultivated tree row area, and to 1 510, 1 450, 1 330 and 1 410 kg m^{-3} in the middle of the work row. At Radyn, stony and dry soil conditions made *in situ* determination of the bulk density according to the core method of Blake & Hartge (1986) impossible.

5.3.1.2 Soil water content and irrigation

The CS616 *in situ* calibration statistics for the 30 sensors each at the FBGD orchards at Kromfontein and Southfield are listed in Appendix D: Tables 5 and 6, respectively. Similar to the other orchards, individual calibration per sensor normally resulted in the best accuracy (Appendix D: Tables 5 & 6). The CS616 manufacturer's calibration again underestimated the actual (i.e. gravimetically sampled) volumetric soil water content at similar CS616 periods sampled in both the full bearing orchards (Fig. 5.6a & b).

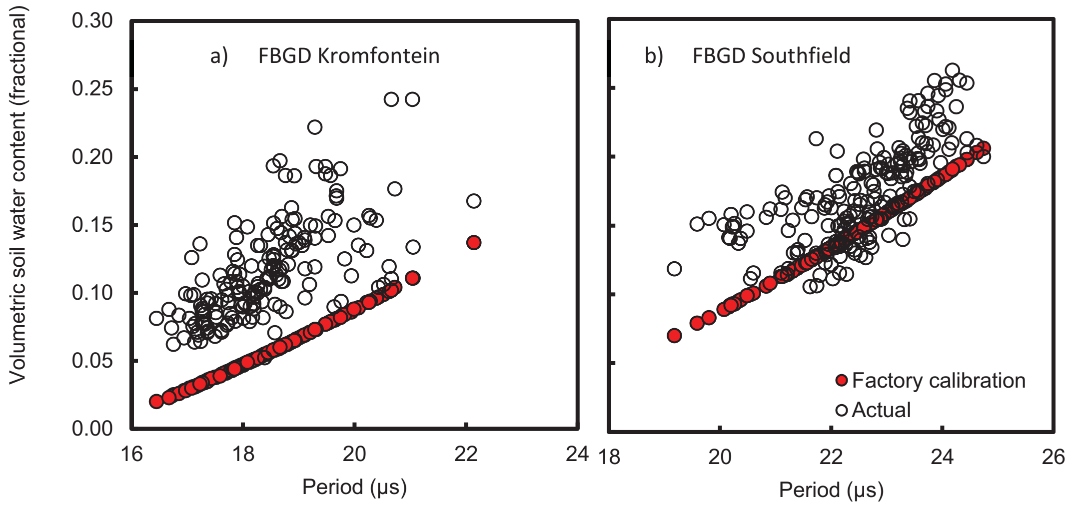


Fig. 5.5 Comparison of CS616 factory calibrated volumetric soil water content and actual volumetric soil water content sampled simultaneously at various CS616 periods at the FBGD orchards at a) Kromfontein and b) Southfield.

According to the manufacturer, the CS616 sensors are sensitive to soil organic matter and clay content, bulk density, temperature and electric conductivity and i*n situ* calibration of sensors are recommended to obtain the accuracy needed for ET calculations.

Soil water dynamics at the full surface irrigated FBGD orchard at Kromfontein indicated that the volumetric soil water content in the tree row to a 900 mm depth was between 20 November and 24 March 2015 for extended periods just below the -20 kPa refill target and substantially less compared to that in the work row area (Fig. 5.7). The work row area furthermore reflected irrigation and rainfall events much clearer than the tree row. The apparent lack of response of soil water content in the tree row to irrigation and rainfall may indicate higher water use by the tree from this area or absorption of a fraction of the irrigation applied by the barley mulch on the tree row. The daily amount of irrigation applied until March was not sufficient to restore the soil water content in the tree row to the levels measured at the beginning (Table 5.3, Fig. 5.7).

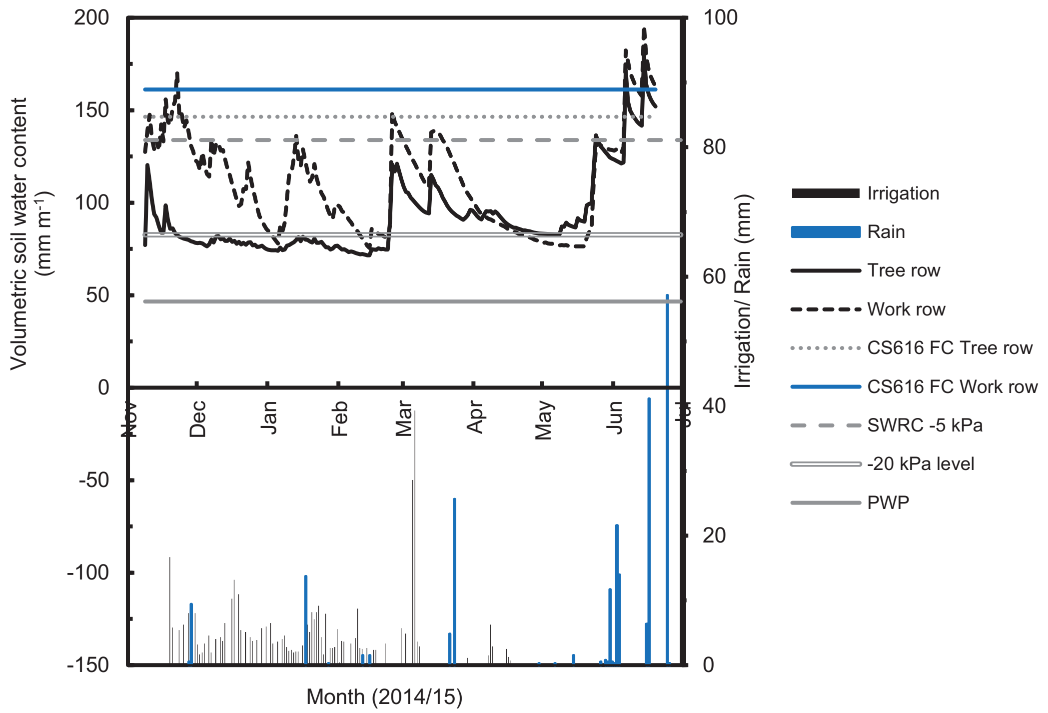


Fig. 5.6 Seasonal changes in volumetric soil water content in the tree row and work row areas of a full-bearing 'Golden Delicious' orchard at Kromfontein in the Koue Bokkeveld during the 2014/15 season. The amount of irrigation applied over the full surface area and rainfall received are indicated on the Y-axis.

Table 5.3 Monthly mean amount, number and interval of irrigations applied to full-bearing 'Golden Delicious' orchards at Kromfontein in the Koue Bokkeveld (KBV) in 2014/15 and Southfield in EGVV in 2015/16. Irrigation is applied on the full surface area.

Month	Irrigation amount (mm d^{-1})				Number (N)		Interval (d)	
	KBV		EGVV		KBV	EGVV	KBV	EGVV
	Mean	Stdev	Mean	Stdev				
Oct	-	-	10.3	5.2	-	6	-	5.2
Nov	5.6	4.0	13.7	0.3	13	2	2.3	15
Dec	5.2	3.0	7.3	3.7	20	16	1.5	1.9
Jan	4.4	2.3	7.5	2.9	25	25	1.2	1.2
Feb	3.5	2.0	6.6	2.2	13	21	2.2	1.4
Mar	11.5	15.7	7.4	3.4	7	11	4.4	2.8
Apr	2.2	1.9	4.8	2.2	8	12	3.8	2.5
May	2.2	0.5	9.8	2.4	3	7	10.3	4.4

Depletion of soil water occurred progressively from the work row region in between significant rainfall and irrigation events during December to March. From the 24th of March, after harvest and during the leaf fall stage, the volumetric soil water content in the tree and work row profiles and its response to irrigation and rainfall events became more comparable. From the 10th of April the work row tended to be drier than the tree row until substantial rainfall (>40 mm) occurred in June. From November to March, soil water content in the tree and work row responded at the different depths monitored to irrigation and rainfall events, but in the work row there were much greater oscillations between wet and dry conditions at all depths (Fig. 5.8 a & b).

In the tree row, the soil water content at the 750 and 1 050 mm depth decreased gradually and responded mostly to rainfall or single or consecutive irrigation events exceeding c. 10 mm (Fig. 5.8a). In general, the estimated soil matric potential for the driest periods at the 150, 450 and 750 mm depths in the tree row appeared to be about -20, -100, and -40 kPa, respectively. In the work row, the soil water content at the 150 mm depth at times approached PWP, whereas it remained above the -20 kPa level for the 300 mm and 600 mm depths (Fig. 5.8b). Although the soil water content in the tree row at 450 mm depth approached the lower end of easily available plant water (-100 kPa), there were still water available in the rest of the soil profile to supply the 900 mm deep root system in the tree and work row area.

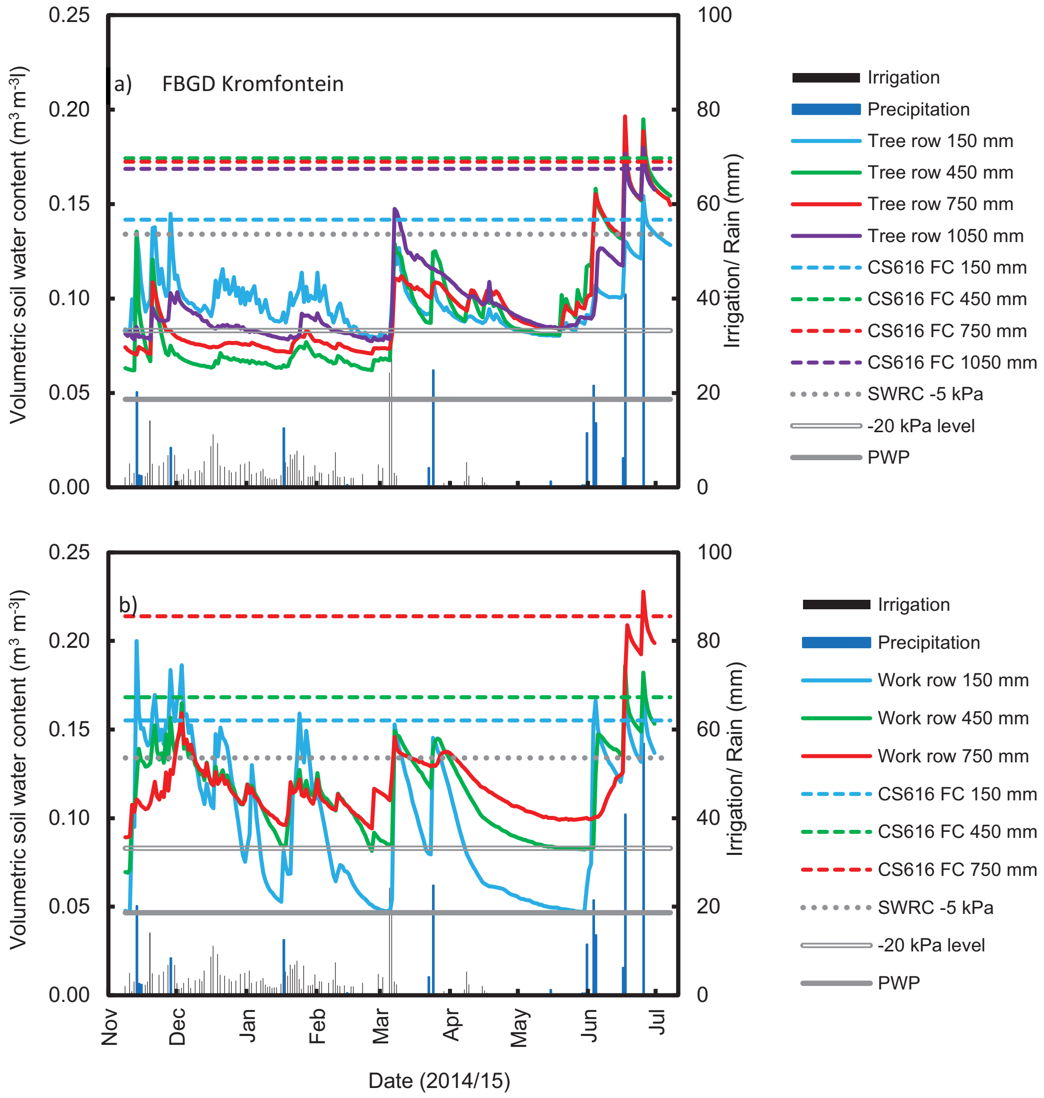


Fig. 5.7 Seasonal changes in volumetric soil water content at selected depths in a) the tree row and b) work row of a full-bearing 'Golden Delicious' orchard at Kromfontein during 2014/15. The amount of irrigation applied over the full surface area and rainfall received are indicated on the Y-axis.

At Southfield the profile averaged soil water content of the FBGD orchard indicated that irrigation was managed relatively well except for over-irrigation that occurred in the clean cultivated tree row during February (Fig. 5.9). Trees received on average 7.1 (±2.9) mm of irrigation every 1.5 days during summer (Table 5.3).

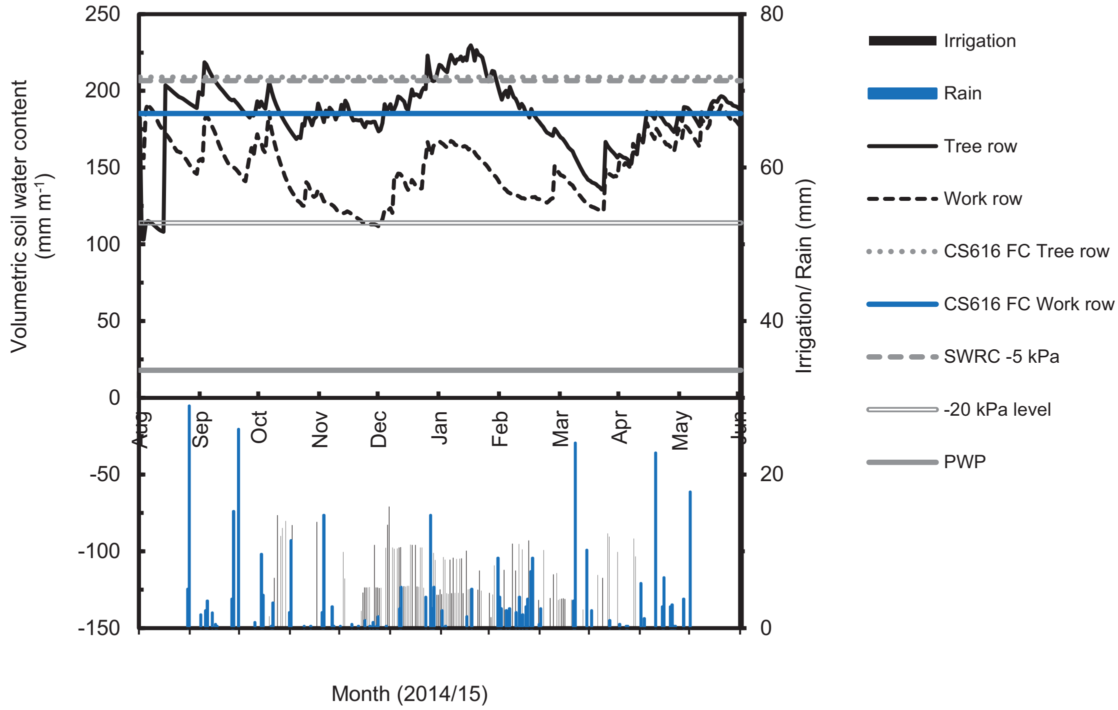


Fig. 5.8 Seasonal changes in volumetric soil water content in the tree row and work row areas of a full-bearing 'Golden Delicious' orchard at Southfield in EGVV during the 2015/16 season. The amount of irrigation applied over the full surface area and rainfall received are indicated on the Y-axis.

Soil water dynamics over the season indicated that soil water content in the clean cultivated tree row did not exceed the -20 kPa level at any depth monitored and the tree was irrigated frequently enough to avoid drought stress (Fig. 5.10a). The 450 mm and 750 mm depths became drier than the 150 mm and 1 100 mm depths. The soil tended to dry out gradually at all depths from mid-February to near end April, most likely due to an adjustment in the irrigation interval (Table 5.3). In the work row soil water content at the 150 mm depth reflect a combination of evaporation and cover crop water use (Fig. 5.10b). The soil water content in the work row in general remained below or at the targeted -20 kPa level. Lower soil water content at the 450 and 750 mm depths may be attributed to tree water use as roots were prevalent in the whole area allotted per tree up to a depth of 1.2 m.

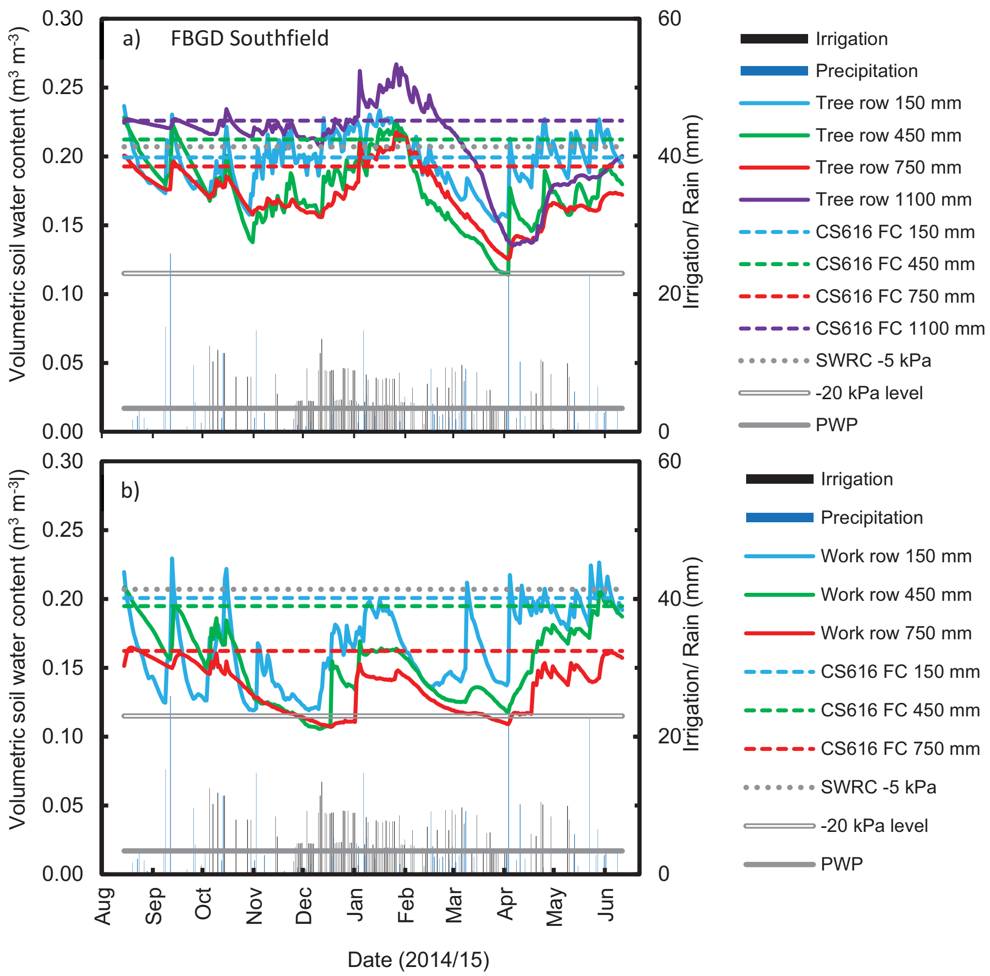


Fig. 5.9 Seasonal changes in volumetric soil water content at selected depths in a) the tree row and b) work row of a full-bearing 'Golden Delicious' orchard at Southfield during 2015/16. The amount of irrigation applied over the full surface area and rainfall received are indicated on the Y-axis.

5.3.2 Leaf area index of the mature orchards

The climatic conditions in KBV during the 2014/15 season and in EGVV during the 2015/16 season were discussed in detail in Chapter 3. So, they will not be repeated here. The full-bearing 'Cripps' Pink' orchard blossomed earliest in late August to early September in KBV during 2014/15. By mid-September, substantial numbers of flowers and new shoots were clearly visible. Bud-break occurred two to three weeks later in the full-bearing 'Golden Delicious' orchard. However, growth of the new shoots was more rapid in the 'Golden Delicious' than the 'Cripps' Pink' trees such that full-bloom dates for the two cultivars were not far apart. When the water use measurements began on 19 September 2014, the LAI were 0.61 and 1.21 for the 'Golden Delicious' and 'Cripps' Pink' orchards, respectively in KBV (Fig.

5.11a). The ‘Golden Delicious’ trees had bigger canopies and thicker stems with an average diameter of ~11.2 cm at the sap flow gauge installation positions. The ‘Cripps’ Pink’ trees had relatively smaller and more open canopies. The average stem diameter at the sap flow gauge installation position was ~ 9.4 cm. Maximum LAI were 3.6 for the ‘Golden Delicious’ and 2.6 for the ‘Cripps’ Pink’ orchards in KBV.

The LAI was measured nine times during the course of the 2015/16 season in EGVV (Fig. 5.11b). As in the KBV, bud break also occurred first in the ‘Cripps’ Pink’ trees in EGVV, around mid-September, followed by the ‘Golden Delicious’ end of September to early October. Leaf growth was more rapid at the beginning of the season in the ‘Golden Delicious’ than the ‘Cripps’ Pink’ such that peak LAI was reached at about the same time in both orchards in early to mid-November.

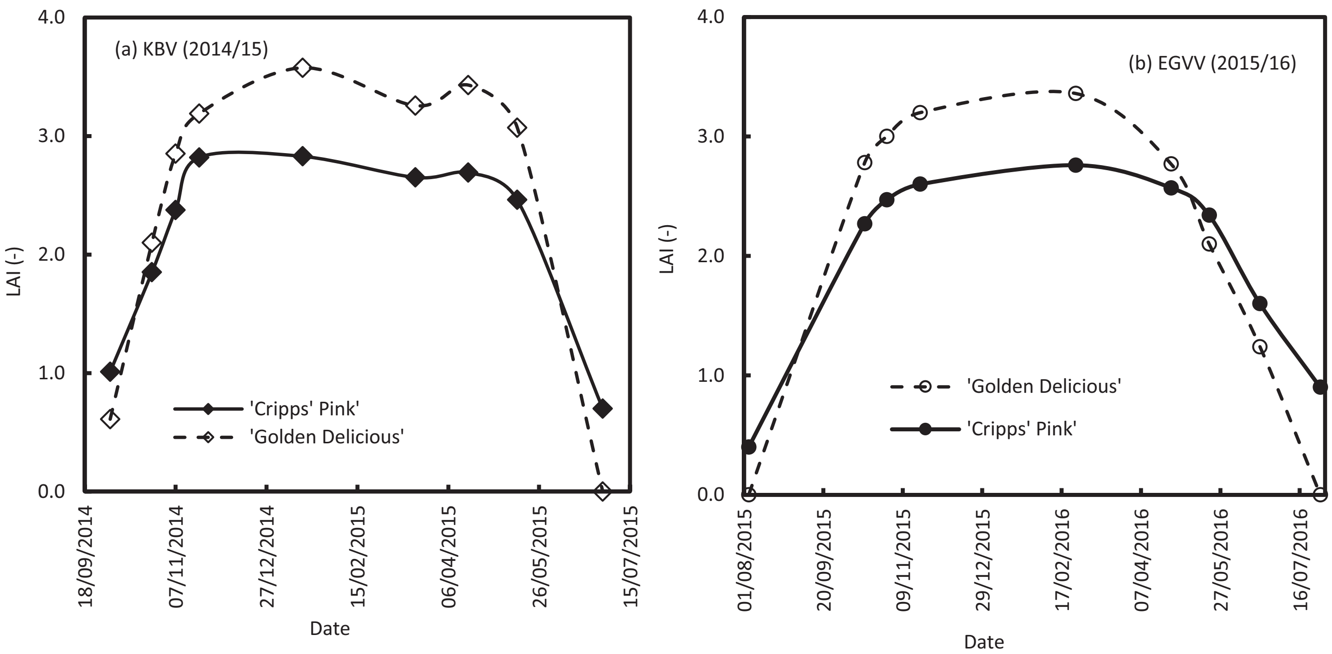


Fig. 5.10 Seasonal evolution of the leaf area index of the mature high yielding orchards in: (a) KBV during 2014/15, and; (b) EGVV during 2015/16.

The ‘Golden Delicious’ orchard in EGVV had a peak LAI of about 3.3 compared to about 2.8 for the ‘Cripps’ Pink’. These values are of the same order of magnitude as those for the full-bearing orchards in KBV. Towards the end of the growing season from April onwards senescence and leaf drop occurred quicker in the full-bearing ‘Golden Delicious’ than the ‘Cripps’ Pink’ in EGVV. Overall the orchards in EGVV retained their leaves for longer in (end of June for ‘Golden Delicious’ stretching into August for ‘Cripps’ Pink’) than in KBV. In KBV both orchards had shed most of their leaves by mid-June 2015. Management practices such as the late application of N fertilizer and the late cessation of irrigation after harvest in the 'Cripps' Pink' block in EGVV was likely a contributory factor to the long season. Physiological and climatic differences may also have played a part.

5.3.3 Eco-physiological responses of the mature apple orchards

5.3.3.1 Leaf gas exchange and stem water potential

In full-bearing apple trees of both cultivars in KBV (Table 5.4), gas exchange capacity was muted although clearly sufficient for the development of a large crop. A and g_s generally declined in the afternoon in response to rising VPD_{leaf}. This either stabilised E or led to a small increase in E in the afternoon. However, in mid-season (15 January 2015), when carbon assimilate demand was high in FBGD in KBV, g_s increased in the afternoon and this led to a steep rise in E. The lowest values for A and g_s were recorded on 17 February 2015 in the afternoon for FBGD in KBV, under exceptionally hot conditions and high evaporative demand, but partial stomatal closure prevented an excessive increase in E. This prevented the midday stem water potential from falling below -1.5 MPa. Measurements of tree level transpiration, soil water content and irrigation showed that the FBGD in KBV orchard was under-irrigated (see section 5.3.3.1). Cumulative transpiration exceeded irrigation and led to some periods of water stress (see section 5.3.3.3). This did not have a noticeable impact on gas exchange and stem water potential on the days of measurement. It is possible that the smaller than expected yield (74 t ha^{-1}) and small fruit size problem in this block can be partially ascribed to persistent water stress as a result of under irrigation.

In the FBGD in EGVV orchard, microclimatic conditions were generally mild, with VPD_{leaf} only rising above 2.2 kPa on two measurement days in the afternoon. On these days, 9 February 2016 and 4 March 2016, T_{leaf} was also very high, and there were strong reductions in A and g_s between morning and afternoon, with a moderate Ψ_{stem} of around -1.4 MPa. On mild days in January and February 2016, A decreased slightly (26 January) or increased (26 February) in the afternoon, whereas A decreased noticeably on 15 December 2015. This could relate to high rates of fruit growth and a strong carbon sink in January/February compared to December.

Table 5.4 Leaf gas exchange and midday stem water potential of high canopy cover full-bearing trees of 'Golden Delicious' and 'Cripps Pink' apple orchards in the KBV production region.

Parameter	FBCP KBV				FBGD KBV					
	25/11/2014		15/01/2015		25/11/2014		15/01/2015		17/02/2015	
	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
A (µmol m^{-2} s^{-1})	14.88	-	15.54	13.49	13.36	11.42	14.18	13.87	12.92	10.0
g_s (mol m^{-2} s^{-1})	0.26	-	0.37	0.35	0.23	0.18	0.29	0.31	0.23	0.13
E (mmol m^{-2} s^{-1})	5.89	-	5.69	6.66	6.92	6.86	4.96	7.08	6.46	6.43
VPD_{leaf} (kPa)	2.17	-	1.54	1.87	2.91	3.58	1.72	2.33	2.71	4.51
T_{leaf} (°C)	27.66	-	24.2	27.3	32.4	34.8	25.8	29.6	29.6	36.7
Instantaneous WUEi (mmol CO_2 mol^{-1} H_2O)	2.53	-	2.73	2.03	1.93	1.66	2.86	1.96	2.00	1.56
Intrinsic WUEi (µmol CO_2 mol^{-1} H_2O)	57.3	-	41.9	38.1	58.4	62.0	49.4	45.5	55.3	74.9
Stem water potential (MPa)	-1.06		-0.77		-1.03		-1.29		-1.46	

Table 5.5 Leaf gas exchange and midday stem water potential of high canopy cover full-bearing trees of the 'Golden Delicious' apple orchard in the EGVV production region.

Parameter	'Golden Delicious' at Southfield, EGVV									
	15/12/2015		26/01/2016		09/02/2016		26/02/2016		04/03/2016	
	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
A (µmol m^{-2} s^{-1})	17.71	14.16	17.46	16.56	13.95	9.242	15.27	17.09	13.74	9.62
g_s (mol m^{-2} s^{-1})	0.22	0.17	0.26	0.33	0.25	0.19	0.33	0.33	0.25	0.11
E (mmol m^{-2} s^{-1})	4.72	3.21	2.50	3.06	5.02	6.71	3.37	3.80	3.79	3.59
VPD_{leaf} (kPa)	2.24	1.95	1.01	1.00	2.12	3.82	1.08	1.23	1.60	3.45
T_{leaf} (°C)	28.1	27.9	28.2	28.2	32.9	38.7	23.8	26.6	25.4	34.8
Instantaneous WUEi (mmol CO_2 mol^{-1} H_2O)	3.75	4.41	6.98	5.42	2.78	1.38	4.53	4.50	3.63	2.68
Intrinsic WUEi (µmol CO_2 mol^{-1} H_2O)	79.8	84.8	67.6	50.7	55.7	49.3	45.7	51.7	55.8	90.5
Stem water potential (MPa)	-1.52		-1.22		-1.39		-0.75		-1.46	

Table 5.6 Leaf gas exchange and midday stem water potential of high canopy cover full-bearing trees of the 'Cripps Pink' apple orchard in the EGVV production region.

Parameter	'Cripps' Pink' at Radyn, EGVV							
	15/12/2015		26/01/2016		09/02/2016		04/03/2016	
	AM	PM	AM	PM	AM	PM	AM	PM
A (µmol m^{-2} s^{-1})	17.99	13.60	16.97	18.73	13.64	12.14	16.17	15.89
g_s (mol m^{-2} s^{-1})	0.25	0.22	0.27	0.24	0.25	0.26	0.30	0.31
E (mmol m^{-2} s^{-1})	4.94	4.25	2.44	2.29	4.50	9.24	5.21	8.72
VPD_{leaf} (kPa)	2.02	2.06	0.93	1.04	1.95	3.74	1.82	2.93
T_{leaf} (°C)	29.6	28.14	27.9	30.3	32.0	39.8	31.0	37.0
Instantaneous WUEi (mmol CO_2 mol^{-1} H_2O)	3.64	3.20	6.95	8.18	3.03	1.31	3.10	1.82
Intrinsic WUEi (µmol CO_2 mol^{-1} H_2O)	71.1	63.2	62.2	77.3	55.6	47.1	54.3	52.0
Stem water potential (MPa)	-1.38		-1.26		-1.68		-1.26	

The sap flow (transpiration) and soil water content measurements did not indicate any stress in this orchard in the 2015-2016 season (sections 5.3.3.2 and 5.3.3.3). In the EGVV region in 2015-2016, leaves on 'Cripps' Pink' trees had higher A, E and g_s than the 'Golden Delicious' trees, especially in the afternoon and in March. Leaf gas exchange and tree water status in 'Cripps' Pink' was less sensitive to very high VPD_{leaf} and T_{leaf} (9 February and 4 March). The higher values in March for 'Cripps' Pink' could relate to this cultivar's later harvest (in April) compared to the end-February harvest in 'Golden Delicious', thus experiencing a high sink strength in the maturing fruit and need for strong supply of assimilates. This was a well-watered orchard with no signs of water stress (sections 5.3.3.2 and 5.3.3.3).

5.3.3.2 Diurnal stem diameter fluctuations

A strong negative (R^2 = 0.863) relationship was established between MDS and midday Ψ_{stem} (Fig. 5.12a). As Ψ_{stem} increased, the MDS decreased, and vice versa. An attempt was made to predict Ψ_{stem} values using MDS and there was a close association between measured and predicted Ψ_{stem} values (R^2 = 0.858, Fig. 5.12b). This demonstrates that MDS can potentially be used to estimate the water status of apple trees effectively.

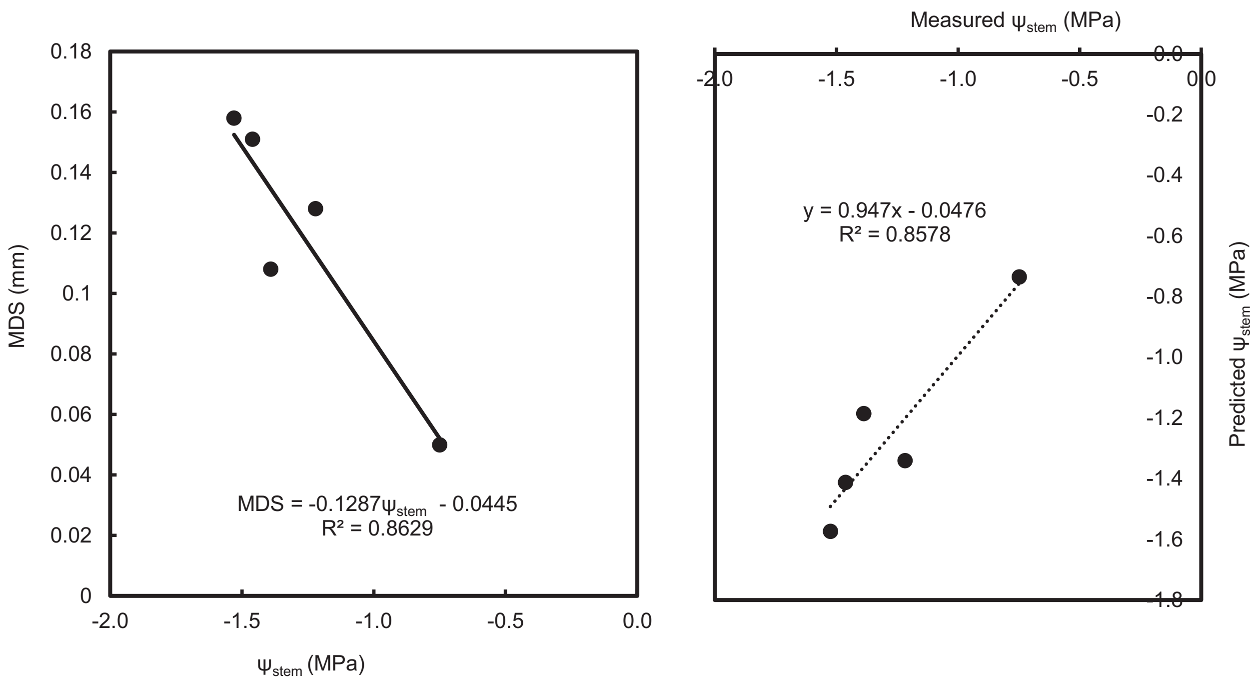


Fig. 5.11 Relationship between a) MDS and Ψ_{stem} for the FBGD EGVV orchard, and b) measured and predicted Ψ_{stem} values for this orchard.

5.3.4 Transpiration and irrigation of the full-bearing orchards

5.3.4.1 Koue Bokkeveld orchards

The seasonal trends in transpiration by the full-bearing 'Golden Delicious' trees in KBV were strongly related to the course of the driving climatic variables mainly the solar radiation (R_s) as shown in Fig. 5.13. A mature 22 yr. old 'Golden Delicious' tree had a peak transpiration of approx. 29 L d^{-1} during warm and dry weather in summer (January 2015) (Fig. 5.13a). Total transpiration for the entire season amounted to approx. 4 720 L tree^{-1}. These values are higher than those reported in a previous Water Research Commission funded project (Volschenk et al., 2003) on the same rootstock-scion combination, but in a different growing region.

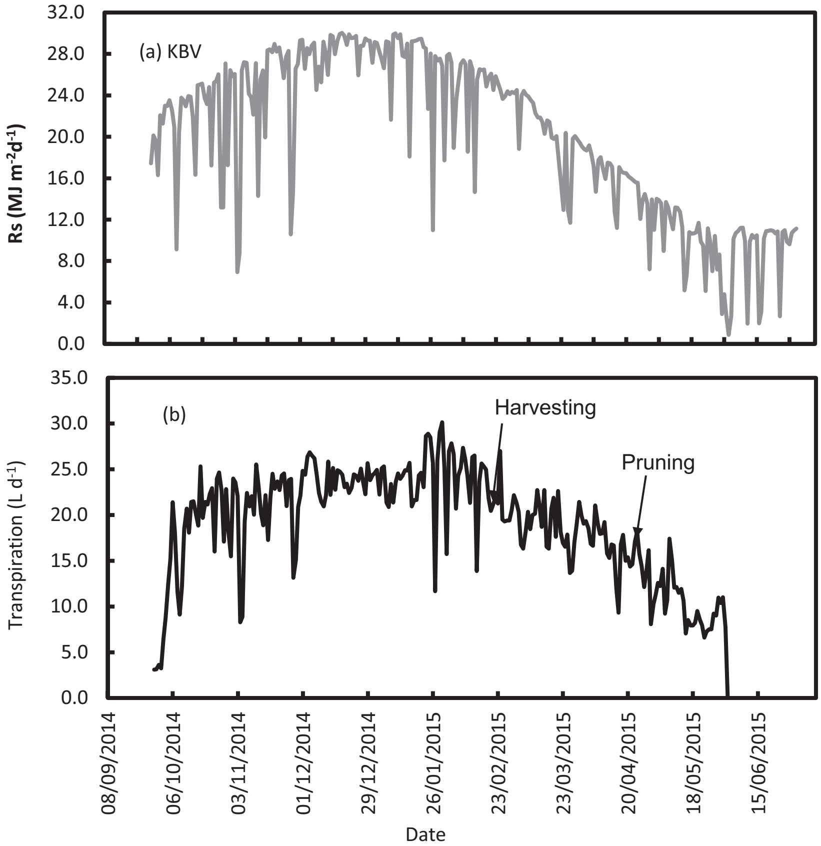


Fig. 5.12 Comparison of the seasonal dynamics of: (a) the daily solar irradiance with (b) the average transpiration by a full-bearing 'Golden Delicious' apple tree.

In Volschenk's study, 8 yr. old full-bearing 'Golden Delicious' trees at Grabouw Farms had a maximum daily transpiration of only 14 L d^{-1}tree^{-1} during the 2000-2001 growing season while a 10-yr. old tree at Oak Valley transpired up to 21 L d^{-1}. Both sites were in EGVV and the orchards were not exceptionally high yielding. Lower transpiration of these trees may partially be attributed to smaller and less dense canopies and lower evaporative demand compared to the full-bearing ‘Golden Delicious’ site in Koue Bokkeveld. The effect of harvesting, done on 19 February 2015, on tree transpiration dynamics were not readily apparent. Post-harvest pruning was done on 17 April 2015 in the ‘Golden Delicious’ orchard. The effects of this on transpiration were immediate as evidenced by the sharp decline in daily transpiration in Fig. 5.13b. Tree LAI changed from a peak of approx. 3.6 to around 2.9 after pruning.

The seasonal trend in daily transpiration by a typical full-bearing 9 yr. old ‘Cripps’ Pink’ tree is shown in Fig. 5.14. The maximum transpiration was 21 L $d^{-1}tree^{-1}$ reached in February 2015. This was clearly lower than the maximum rate for the ‘Golden Delicious’ trees. The seasonal total transpiration by an average ‘Cripps’ Pink’ tree was approx. 3 565 L $tree^{-1}$. The lower transpiration rates by the ‘Cripps’ Pink’ were a result of the relatively smaller transpiring leaf area than that of the ‘Golden Delicious’ trees.

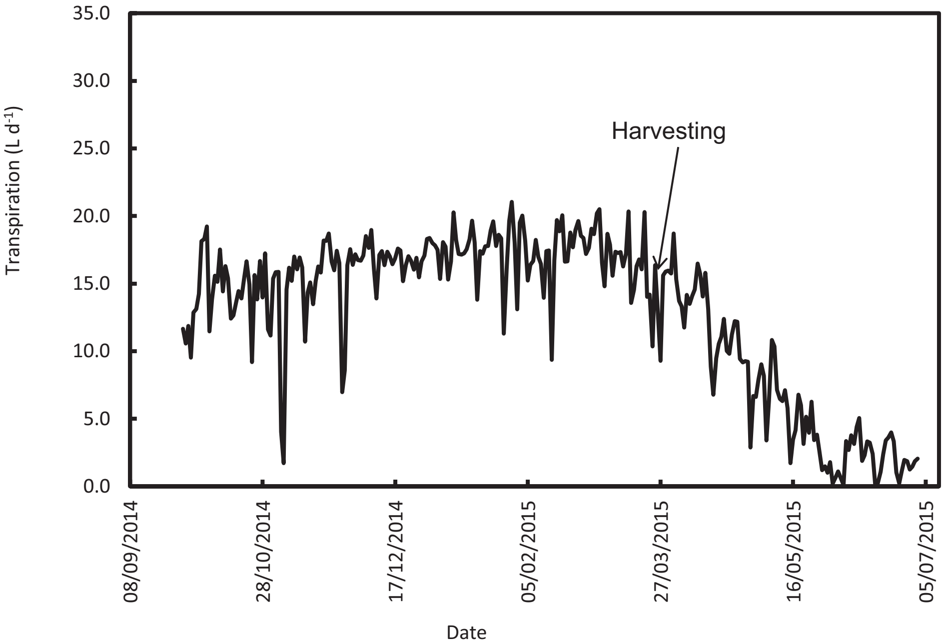


Fig. 5.13 Seasonal dynamics of the transpiration by a full-bearing ‘Cripps’ Pink’ tree in KBV.

Being a long season cultivar, it is apparent in Fig. 5.14 that the ‘Cripps’ Pink’ trees were already transpiring when sap flow measurements commenced on 19 September 2014. The delay in the start of measurements was a result of administrative challenges in the first year of the study. In an earlier study done over two seasons by Gush and Taylor (2014) in the same production area, 13 yr. old ‘Cripps’ Pink’ trees transpired between 3 980 and 3 994 L per season. However, these trees were larger than those in the current study with a peak LAI of 3.4 compared to only 2.8 in the current study. Unlike the ‘Golden Delicious’ trees, it is also clear that the ‘Cripps’ Pink’ trees continued to use, albeit small amounts of water, well into the winter season beyond 30 June 2015 as a result of some leaves left on the trees. Harvesting of the trees (clean stripping) was in April and changes in the transpiration rates were also not readily apparent.

The measured seasonal total transpiration by a full-bearing 'Golden Delicious' orchard in KBV was 787 mm while the full-bearing 'Cripps' Pink' transpired 589 mm. This translates to 7 870 m^3 ha^{-1} per season for the 'Golden Delicious' and 5 890 m^3 ha^{-1} per season for the full-bearing 'Cripps' Pink'. In contrast, Volschenk et al (2003) measured seasonal total transpiration of between 3 556 and 4 224 m^3 ha^{-1} per season for 8-10 yr. full-bearing 'Golden Delicious' orchards described earlier. Gush and Taylor (2014) in 'Cripps' Pink' orchards obtained a total transpiration of 6 870 m^3 ha^{-1} per season (average for two seasons).

5.3.4.2 Full-bearing orchards in EGVV

An average sized full-bearing 'Cripps' Pink' tree at Radyn farm in EGVV transpired between 2.0 and 3.0 litres of water per day early in the season in September 2015 gradually rising to a maximum between 23 and 25 L d^{-1} in December and January (Fig. 5.15). The order of magnitude of the transpiration in EGVV was similar to that in KBV. The seasonal course of transpiration (Fig. 5.15a) closely mirrored the reference evapotranspiration (Fig. 5.15b) suggesting that atmospheric factors were the main drivers of tree water use. Total transpiration by an individual 'Cripps' Pink' tree from 01 October 2015 to 30 June 2016 was about 3 785 L. Total transpiration during the winter months from 01 May to 30 June was 450 L $tree^{-1}$ which was about 12% of the seasonal water use.

Transpiration of a single 'Golden Delicious' tree ranged from less than 2 L d^{-1} in early September sharply rising to high values by end of October. Daily peak transpiration per tree was around 38 L in late December to early January 2016 (Fig. 5.16) which was substantially higher than that of trees in KBV. Total transpiration by an average 'Golden Delicious' tree from 01 October 2015 to 30 June 2016 was around 6 054 L which is more than 1 000 L more than in KBV. The differences in the water use rates between the 'Golden Delicious' trees in the two production regions were likely a result of the water stress experienced by the KBV orchard as seen from the soil water content data. The EGVV transpiration data for the 'Golden Delicious' orchard is also higher than the values reported by Volschenk et al (2003) presented earlier. This could be a result of the smaller canopies of the trees they studied while the low crop load may also have played a part. Winter time transpiration (May-June) of the EGVV 'Golden

Delicious' was about 13% of the seasonal total and this was a result of the longer growing season in EGVV during the study.

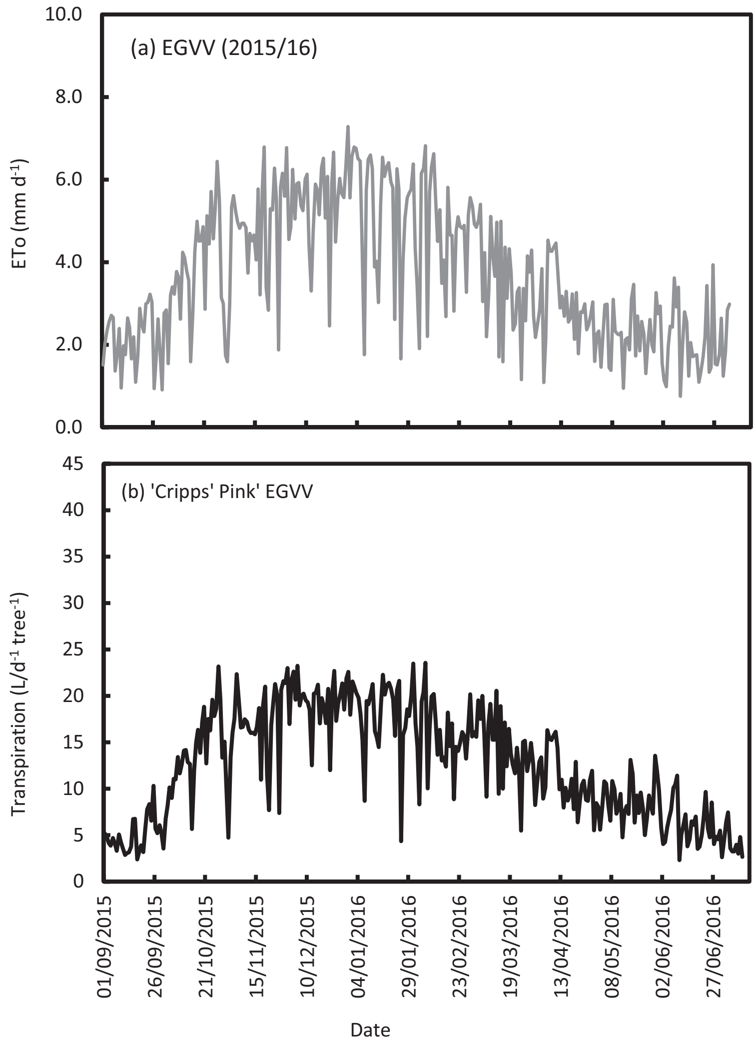


Fig. 5.14 The seasonal course of the reference evapotranspiration (a) and transpiration of mature 'Cripps' Pink' trees (b) at Radyn farm in Villiersdorp.

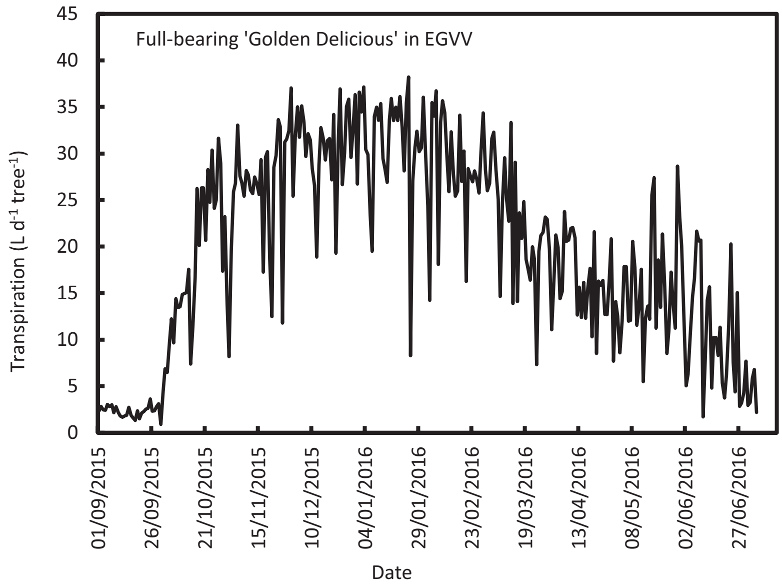


Fig. 5.15 Transpiration dynamics of an individual full-bearing 'Golden Delicious' tree at Southfield farm in Villiersdorp.

Maximum transpiration by the 'Golden Delicious' orchard in EGVV was around 4.8 mm d^{-1}. The seasonal total transpiration was 757 mm translating to 7 570 m^3 ha^{-1}. Transpiration in the 'Cripps' Pink' orchard peaked at 3.9 mm d^{-1} with the seasonal total being 631 mm (or 6 310 m^3 ha^{-1}).

5.3.4.3 Tree water use and irrigation

A full-bearing 'Cripps' Pink' tree in KBV received approx. 7 210 L of irrigation during the 2014/15 season while it transpired only 3 565 L (Fig. 5.17). The water flow meters were only installed mid to late October 2014. So, earlier irrigation events were missed suggesting that the applied irrigation was even higher than what was recorded. Comparison of irrigation to orchard evapotranspiration is presented in Chapter 8. The situation in the full-bearing 'Golden Delicious' orchard in KBV was the opposite of that in the 'Cripps' Pink' block (Fig. 5.17b). Cumulative transpiration by a 'Golden Delicious' tree ~4 720 L exceeded the irrigation ~2 998 L, which was rather unexpected. There was under-irrigation in this orchard and there is independent evidence from the soil water content and plant water status measurements. It is highly possible that the low yield obtained in the 'Golden Delicious' orchard in KBV ~ 74 t ha^{-1} was partly due to water stress as a result of under irrigation.

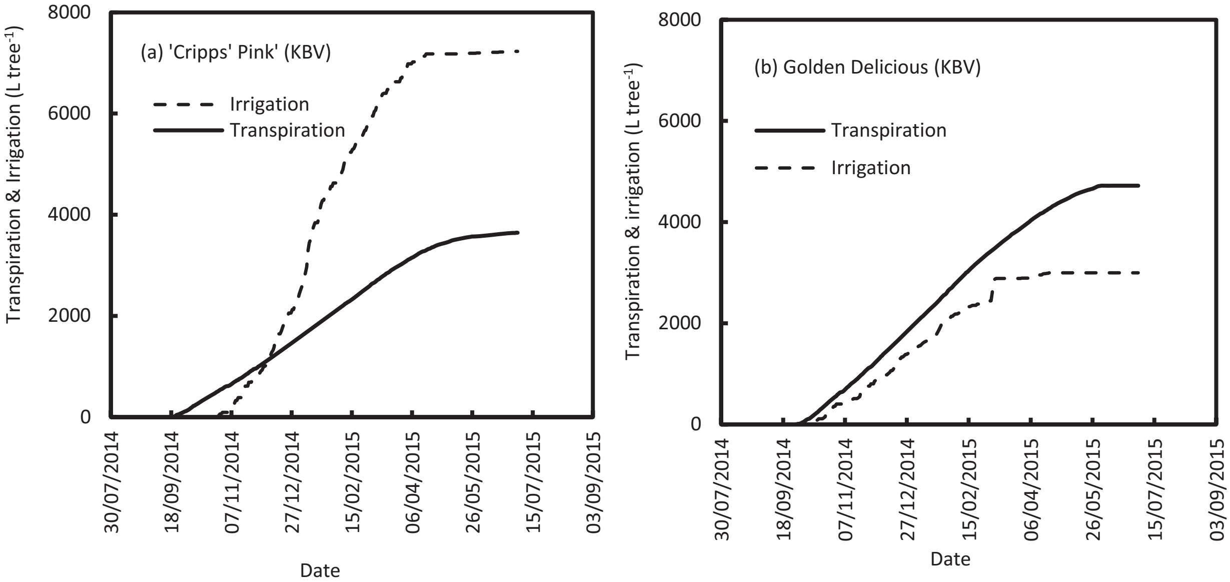


Fig. 5.16 Comparison of the cumulative irrigation with transpiration rates per tree in (a) full-bearing 'Cripps' Pink', and; (b) full-bearing 'Golden Delicious.

In EGVV, irrigation of the full-bearing 'Golden Delicious' orchard started on 19 October 2015 and some irrigation was recorded as late as May 2016.

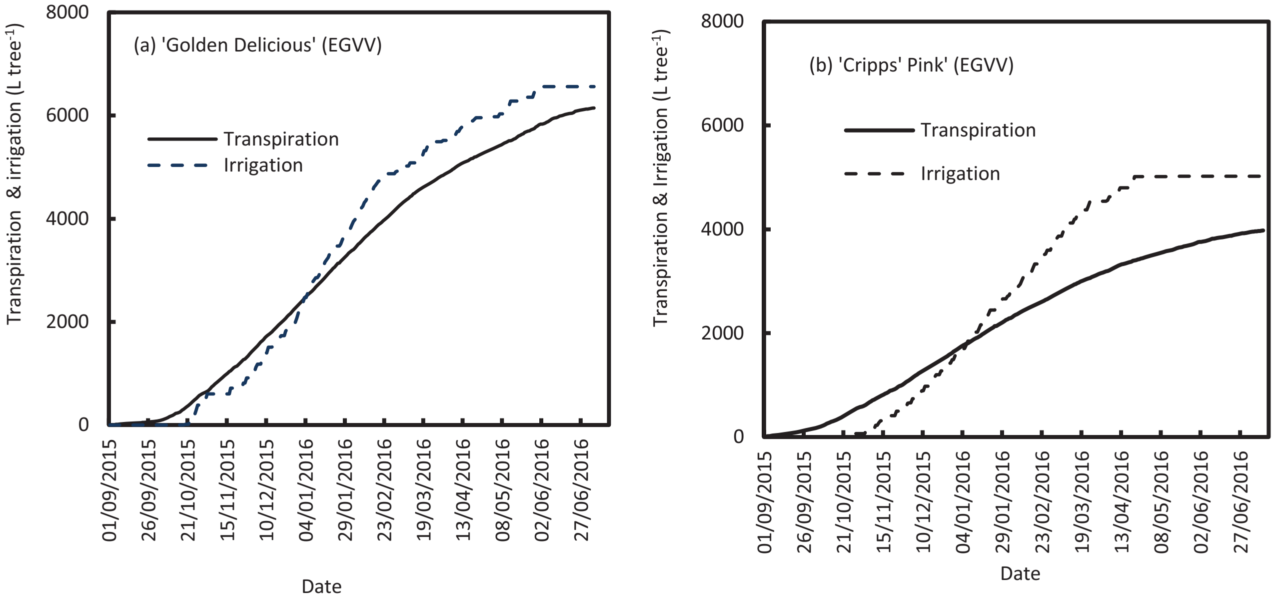


Fig. 5.17 Comparison of cumulative transpiration and irrigation of a single; (a) full-bearing 'Golden Delicious' and, (b) full-bearing 'Cripps' Pink' tree at Southfield and Radyn farms, respectively in Villiersdorp.

Total irrigation applied to a single 'Golden Delicious' tree in EGVV was 6 560 L compared to 6 054 L of transpiration (Fig. 5.18a). An individual 'Cripps' Pink' tree on the other hand received 5 020 L of irrigation of which about 3 977 litres was used as transpiration (Fig. 5.18b). Since the aim of this study was to derive the unstressed water use by the orchards, we identified and corrected the data for incidences of water stress in the 'Golden Delicious' orchard in KBV using a Crop Water Stress Index (CWSI) defined as:

$$\mathrm{CWSI} = 1 - \frac{\mathrm{T}}{\mathrm{ETo}} \qquad (5.1)$$

where T is the transpiration rate (in mm d^{-1}). The 'Golden Delicious' trees in the two production regions had a similar canopy cover and so we could directly compare their CWSI. In EGVV, the CWSI rarely exceeded ~0.4 (see dotted line in Fig. 5.19). In addition, the soil water content and plant water status measurements in EGVV (data not shown) did not indicate any stress. So we used the following criterion to identify periods of water stress in the KBV 'Golden Delicious' orchard:

CWSI $\geq$ 0.4, and;
Average root zone soil water content ≤ 0.037 cm^3 cm^{-3}.

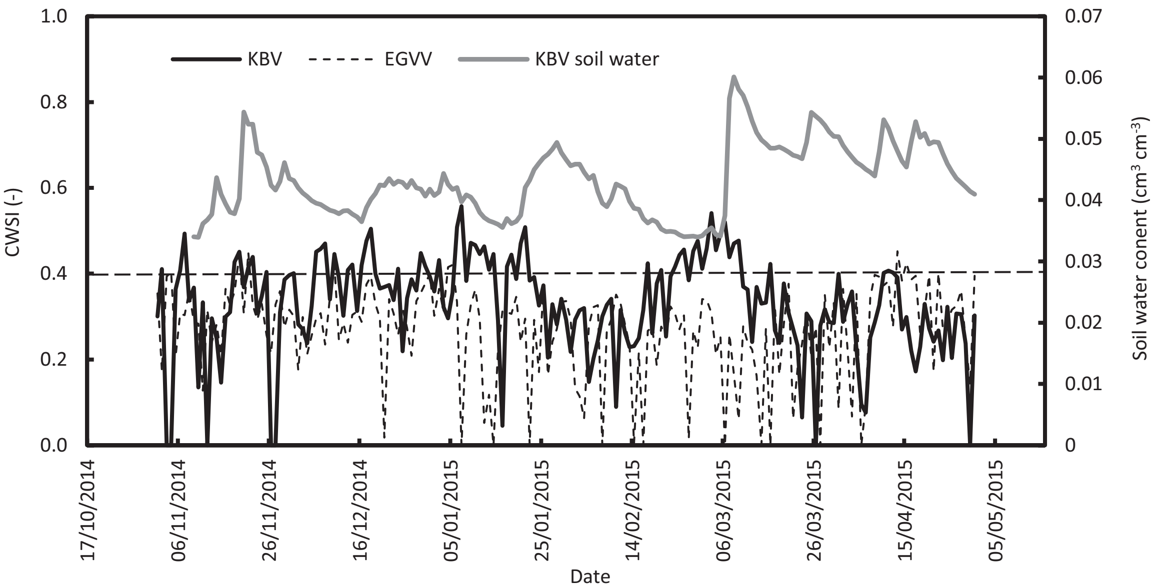


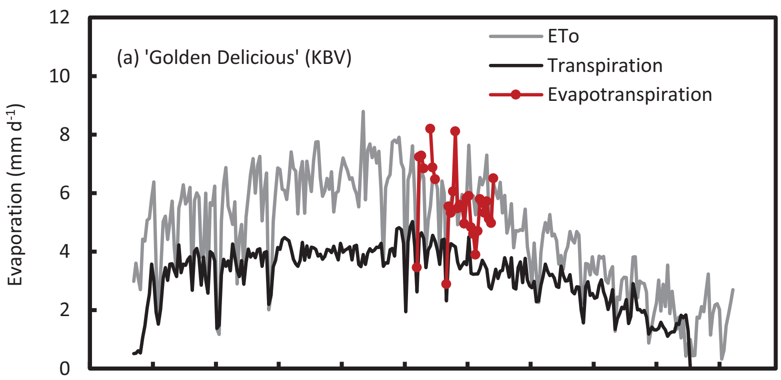
Fig. 5.18 Comparison of the Crop Water Stress Index in the full-bearing Golden Delicious orchards in KBV (continuous line) and EGVV (dotted line) and the corresponding root zone soil water content in the EGVV orchard. The KBV data was collected from 01 November 2014 to 30 April 2015 while the EGVV data was from 01 November 2015 to 30 April 2016.

Using soil water content data in addition to the CWSI was important to exclude days when ET_o was very high and transpiration could not keep up with the atmospheric evaporative demand. The CWSI was a direct measure of the tree response to water supply limitation. Using this method we identified the following periods of severe water stress in KBV: 16-19 December 2014, 06-13 January 2015, 18-22 January 2015 and 23 February to 10 March 2015. Correction for water stress was subsequently done by deriving a transpiration coefficient on clear well-watered days before the stress ensued and using the Allen et al (1998) approach to calculate the unstressed transpiration rates. Implementing this correction yielded a revised seasonal transpiration for the full-bearing 'Golden Delicious' orchard in KBV of 813 mm.

5.3.5 Evapotranspiration of full-bearing orchards

5.3.5.1 Eddy covariance

A comparison of the ET measured using the eddy covariance system with transpiration and seasonal ET_o is shown in Fig. 5.20 for the two orchards. The measured ET was comparable with ET_o in both orchards indicating higher water use compared to the young orchards reported in Chapter 3. High ET rates early in the growing season were a result of transpiration by the dense cover crop in the orchards. The maximum measured ET were 8.2 mm/d in the 'Golden Delicious' and 6.7 mm d^{-1} in the 'Cripps' Pink orchards. In EGVV on the other hand, the actual ET measured using the eddy covariance system ranged from 1.4 to around 5.50 mm d^{-1} in the full-bearing 'Cripps' Pink' (Fig. 5.21a). The highest value of measured ET was 8.8 mm d^{-1} recorded in the full-bearing 'Golden Delicious' orchard (Fig. 5.21b). The slope of the ET vs ET_o graphs for measurements taken during selected periods in the season gives an estimate of the crop factor (K_c) for the orchard. For the EGVV orchards, this was approx. 0.90 for the full-bearing 'Cripps' Pink', and 1.10 for full-bearing 'Golden Delicious' (Fig. 5.20).



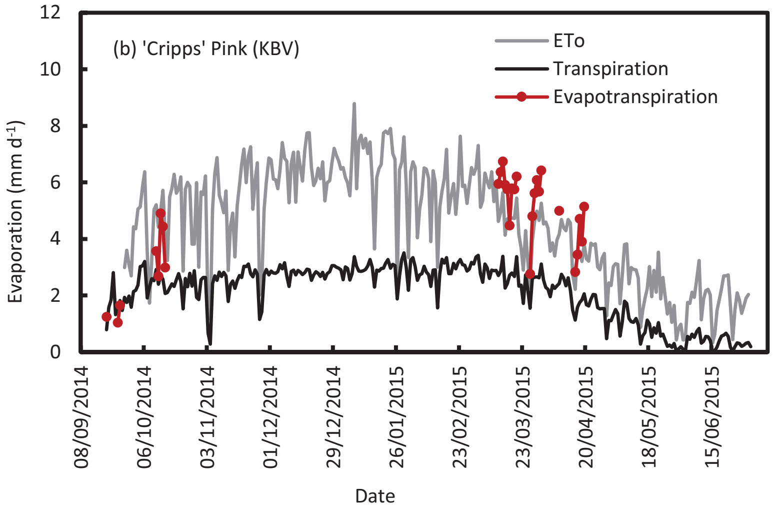


Fig. 5.19 Comparison of measured transpiration, actual evapotranspiration and the reference evapotranspiration for: (a) full-bearing 'Golden Delicious'; and; (b) full-bearing 'Cripps' Pink' in KBV.

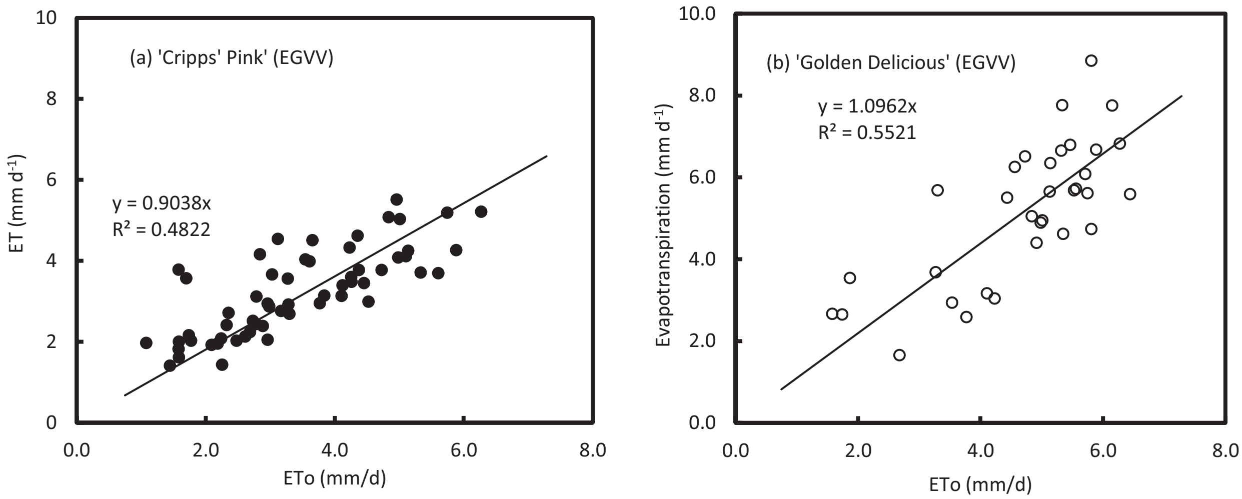


Fig. 5.20 Comparison of the actual evapotranspiration measured using the eddy covariance system with the reference evapotranspiration in: (a) a full-bearing 'Cripps' Pink', and (b) a full-bearing 'Golden Delicious' orchard during the 2015/16 fruit growing season.

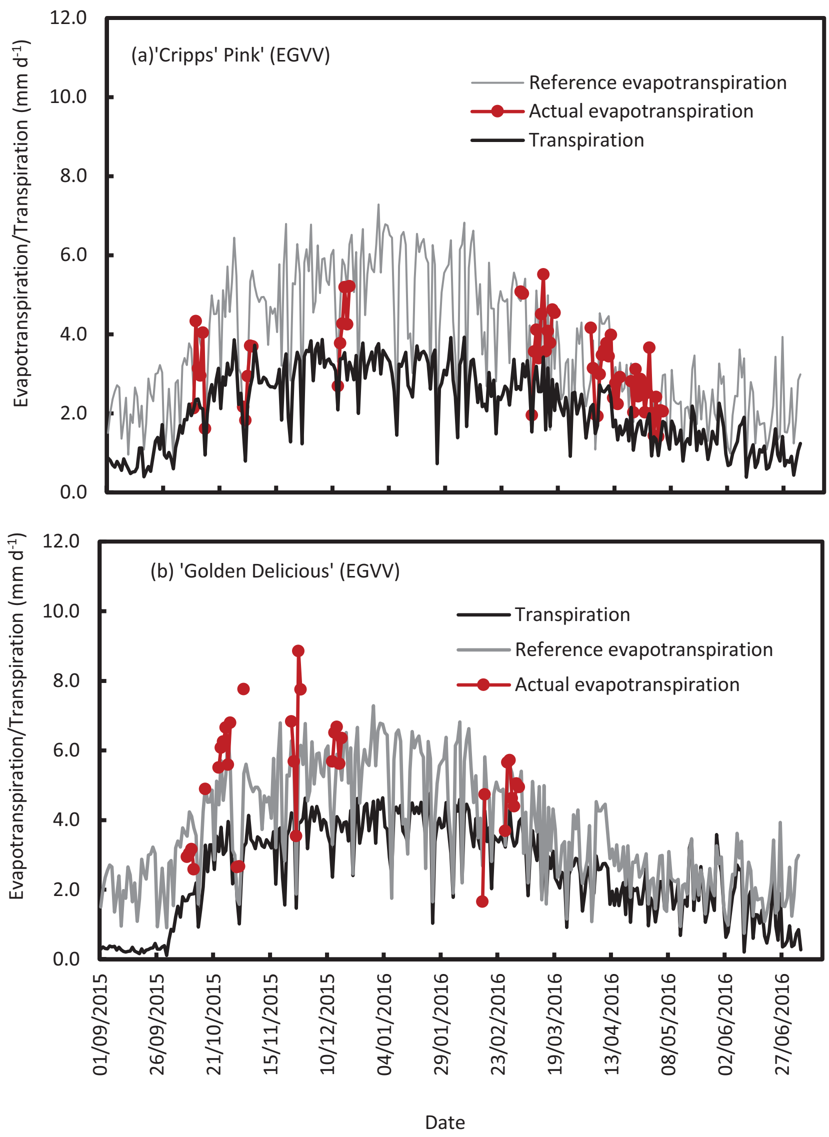


Fig. 5.21 Comparison of the measured transpiration, reference evapotranspiration and actual evapotranspiration in: (a) full-bearing 'Cripps' Pink', and; b) 'Golden Delicious' orchards in EGVV.

5.3.5.2 Estimating ET using the soil water balance approach in mature orchards

In the FBGD orchard at Kromfontein the maximum ET from the tree row between 21 November and 9 February was about 5 mm d^{-1}, after which it decreased to 3.7 mm d^{-1} in March and rather steeply thereafter to c. 1 mm at the beginning of April (Fig. 23a). Increased ET of about 1.3 mm in June and July were attributed to increased evaporation and weed growth in the tree row after significant rainfall occurred.

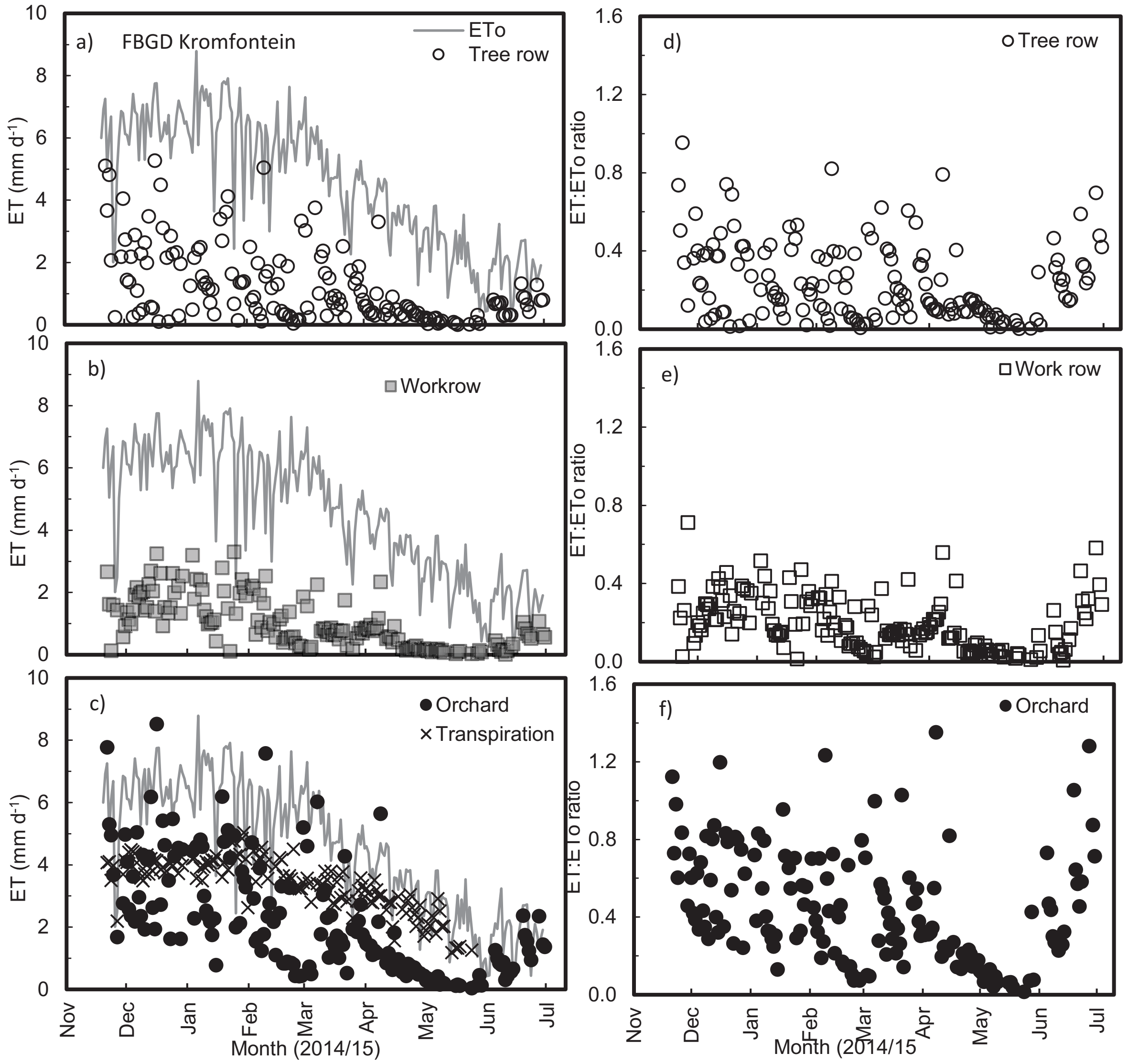


Fig. 5.22 Seasonal changes in reference evapotranspiration (ETo) and evapotranspiration (ET) of the a) tree row, b) work row and c) orchard of a full-bearing 'Golden Delicious' orchard at Kromfontein in the Koue Bokkeveld during the 2014/15 season. The amount of tree transpiration (T) relative to orchard ET is indicated in c). The ET:ET$_o$ ratio for the irrigated tree row, work row and orchard is indicated in d), e) and f), respectively.

Evapotranspiration in the tree row on average per month tended to decrease from 2.9 mm/d in November 2014 to between 1.2 and 1.3 mm d^{-1} in February and March 2015, respectively (Table 5.7). This decrease in tree row ET was associated with lower soil water levels in the tree row. The ET from the irrigated work row containing tree roots, cover crops and some weeds was 2.7 mm d^{-1} in November and c. 3.2 in December and January after which it gradually decreased to less than 1 mm d^{-1} in mid-April until end May (Fig. 5.24b).

Table 5.7 Monthly averaged orchard component and total orchard evapotranspiration (ET) and ET to Penman-Monteith reference evapotranspiration (ET_o) ratios for the full-bearing 'Golden Delicious' at Kromfontein in the Koue Bokkeveld in 2014/15. The number of days with reliable data are indicated (N).

Month	**ET** (mm d^{-1})			**$ET:ET_o$ ratio**			**N**
	Tree row	**Work row**	**Orchard**	**Tree row**	**Work row**	**Orchard**	
Nov	2.9	1.1	3.9	0.51	0.21	0.72	12
Dec	1.9	1.8	3.7	0.30	0.29	0.58	26
Jan	1.7	1.8	3.4	0.24	0.26	0.50	22
Feb	1.2	1.1	2.2	0.21	0.19	0.39	24
Mar	1.3	0.8	2.1	0.27	0.15	0.42	24
Apr	0.6	0.6	1.2	0.16	0.16	0.32	24
May	0.1	0.1	0.2	0.06	0.05	0.10	14
Jun	0.7	0.5	1.2	0.33	0.22	0.56	16

The maximum orchard ET was in November 7.8 mm d^{-1} and increased in December to 8.5 mm d^{-1}, following a downward trend towards February (7.6 mm d^{-1}) and April (5.6 mm d^{-1}) (Fig. 5.24c). In comparison, the monthly average orchard ET for these respective months was 50, 56, 71, and 79% lower than these maximum values (Table 5.7). Orchard ET during June 2015 increased up to 2.3 mm d^{-1}. Transpiration tended to exceed the orchard ET during the latter part of March until May 2015. The reason for this discrepancy is not clear and should be investigated further. The tree row $ET:ET_o$ ratio in general followed the declining trend in ET (Fig. 5.24a, Table 5.7), decreasing from 0.95 in November 2014 to 0.39 near end February 2015 (Fig. 5.24d). However, the $ET:ET_o$ ratio became intermittently high until 8 April 2018, after which it dropped to a value of c. 0.15. The work row $ET:ET_o$ ratio increased from 0.39 in November to a maximum of 0.52 in December, decreasing gradually and flattening off to about 0.41 for February to mid-April, after which it also dropped to a value of c., 015 or less (Fig. 5.24e). The maximum orchard $ET:ET_o$ ratios are comparable to a crop coefficient of 1.2 reported by Allen et al. (1998) for apple with an active ground cover, but even exceeded it during April and June (Fig. 5.24f). The monthly averaged ratio of $ET:ET_o$ for the orchard was 0.5 for January (Table 5.7), which is considerably less than that expected for a well-irrigated full bearing orchard. In this full surface irrigated orchard, the tree row and work row area had for the greatest part of the season comparable ET.

At the FBGD at Southfield the maximum ET closely followed the trend of ET_o over the season (Fig. 5.24). The maximum ET in the tree row increased from c. 0.9 mm d^{-1} on 7 September to 6.7 mm/d by mid-January, after which it decreased gradually and levelled off in April at c. 2.4

mm d^{-1} until near end June 2016. Unfortunately, there was a paucity of data for February as excessive drainage prevented ET calculation according to the soil water balance.

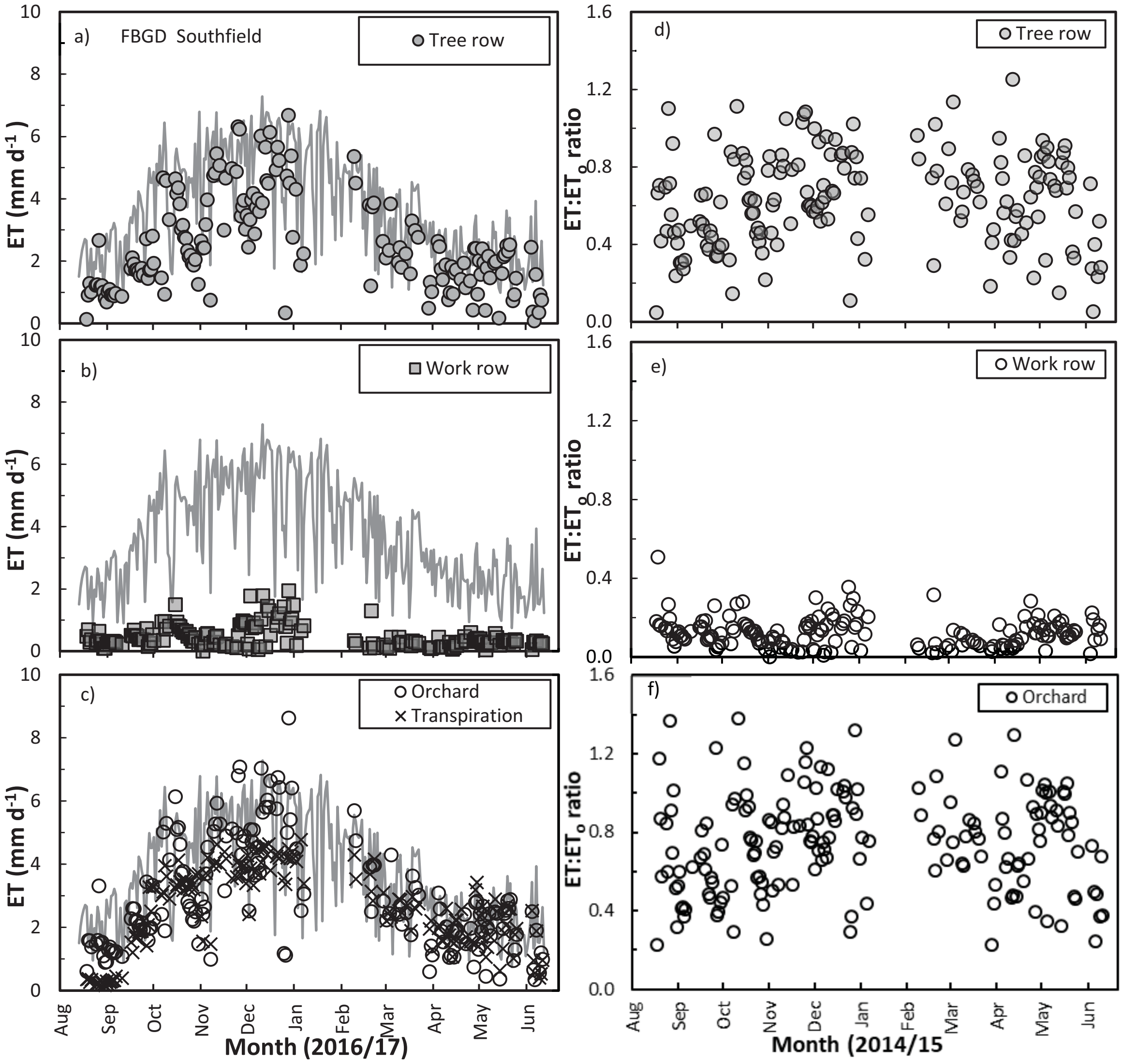


Fig. 5.23 Seasonal changes in reference evapotranspiration (ETo) and evapotranspiration (ET) of the a) tree row, b) work row and c) orchard of a full-bearing 'Golden Delicious' orchard at Southfield in EGVV during the 2015/16 season. The amount of tree transpiration (T) relative to orchard ET is indicated in c). The ET:ET$_o$ ratio for the irrigated tree row, work row and orchard is indicated in d), e) and f), respectively.

Maximum ET in the work row increased from 0.7 mm d^{-1} in September to 1.9 mm d^{-1} in December, decreased to 1.3 mm d^{-1} near the beginning of March and levelled off at 0.5 mm d^{-1} by the end of March 2015 (Fig. 5.24b). A tree and work row weighted ET for the orchard was 1.6 mm d^{-1} on 7 September 2015 and reached a maximum of 8.6 mm for the season. The orchard ET decreased to c. 2.7 mm d^{-1} in April until June 2016 (Fig. 5.24c). Although the tree row ET: ET_o ratio was 0.66 on 7 September 2015 there was not a clear trend and maximum values from later in September to end March exceeded 1 (Fig. 5.24d). The ratio fluctuated from near end April to 6 June 2016 between 0.95 and 0.9, decreasing by end June to 0.52. The work row maximum ET:ET_o ratio was c. 0.17 at the beginning of September 2015 (excludes outlying value), increased to 0.35 by mid-January 2016 and decreased to 0.22 by June 2016 (Fig. 5.24e). The orchard ET: ET_o ratios did not have a clear seasonal trend and maximum values varied between 1.27 and 1.38, which approaches the perceived maximum ratio possible for orchards (Fig. 5.24f). In this orchard the tree row contributed between 79 and 94% of the total water use (Table 5.8).

Table 5.8 Monthly averaged orchard component and total orchard evapotranspiration (ET) and ET to Penman-Monteith reference evapotranspiration (ET_o) ratios for the full-bearing 'Golden Delicious' at Southfield in EGVV in 2015/16. The number of days with reliable data are indicated (N).

Month	**ET (mm d^{-1})**			**ET:ET_o ratio**			**N**
	Tree row	**Work row**	**Orchard**	**Tree row**	**Work row**	**Orchard**	
Sep	1.1	0.3	1.4	0.50	0.15	0.66	19
Oct	2.2	0.5	2.7	0.54	0.13	0.67	20
Nov	3.0	0.5	3.6	0.62	0.11	0.72	24
Dec	4.1	0.6	4.8	0.75	0.11	0.86	22
Jan	4.1	0.9	5.0	0.66	0.17	0.83	17
Feb	4.9	0.3	5.2	0.90	0.05	0.96	2
Mar	2.7	0.3	3.0	0.72	0.09	0.81	11
Apr	1.9	0.2	2.1	0.62	0.07	0.69	14
May	1.6	0.3	1.9	0.67	0.13	0.80	23
Jun	1.4	0.3	1.6	0.51	0.13	0.64	17

5.4 Conclusions

The maximum transpiration of the high yielding apple orchards studied here was in the range 6 000 to 8 000 m^3 ha^{-1} per season. The 'Golden Delicious' orchards had the highest transpiration rates because they had a larger canopy cover. These were a result of differences in canopy management practices rather than physiological differences between the two cultivars. For example, growers maintain small canopy cover for 'Cripps' Pink' trees e.g. by heavy pruning and spraying shoot growth retardants such as Regalis®. This is done to expose the fruit to solar radiation for anthocyanin synthesis to occur and to promote the development of the red fruit colour. Mature 'Golden Delicious' trees, on the other hand, had larger canopy cover since the fruit is susceptible to sunburn and there is no need for red colour development.

So, careful canopy management is critical in apple orchards to balance fruit quality and orchard water requirements. For example, small canopy cover for the 'Golden Delicious' orchard under shade nets may help reduce the orchard water use, but accurate quantitative information is required on the water saving benefits of shade nets. Alternatively, the 'Golden Delicious' trees could also be grafted on dwarfing rootstocks to control canopy cover and hence orchard water use.

CHAPTER 6

MODELLING WATER USE OF APPLE ORCHARDS WITH VARYING CANOPY COVER

6.1 Introduction

Effective management of irrigation requires knowledge of key components of the hydrological cycle such as the evapotranspiration (ET). Accurate tools are required to quantify ET which is the second largest component of the water cycle after rainfall. Evapotranspiration accounts for more than 90% of annual precipitation in arid and semi-arid environments (Fisher et al., 2008, Kool et al., 2014, García et al., 2013). So, irrigation is critical for fruit production to replace the water lost by ET, especially in areas where most of the rain falls outside the fruit growing period e.g. in the Western Cape Province. In fruit production, accurate ET information is required for: 1) designing irrigation systems, 2) refining irrigation schedules, and; 3) for water allocation purposes, among others.

Evapotranspiration is a difficult and complicated component to measure and predict accurately because of the heterogeneity in the orchard environments and the large number of controlling factors which include climate, plant biophysics, soil properties, topography and orchard management practices such as mulching, ridging, cover crops, type of irrigation etc. (Yuan et al., 2010, Fisher et al., 2005). Use of state-of-the-art eco-hydrological and micrometeorological instruments to measure tree and orchard scale water use has provided useful information on the water requirements of apple orchards (Dzikiti et al., 2017, Volschenk, 2017, Volschenk et al., 2003, Gush and Taylor, 2014, Dragoni et al., 2005, Heinemann et al., 2000). However, these techniques cannot be used to measure the water use of every orchard due to the complexity of the methods, the high costs involved, and other practical considerations. For this reason, the development of simple but robust models of orchard water use is important in order to facilitate the scaling up of results of site specific studies to other fruit growing regions.

Several models have been developed and applied to estimate ET in orchards. Examples include soil based models such as the Soil Water Balance (SWB) model (Annandale et al., 2003, Volschenk et al., 2003), the big leaf Penman-Monteith type models (e.g. Dragoni and Lakso, 2011; Rana et al., 2005) and dual source models (e.g. (Ortega-Farías and López-Olivari, 2012, Li et al., 2010, Allen et al., 1998)). Dual source models partition ET into the transpiration (T) and the orchard floor evaporation (E_s) components. Given the heterogeneity that characterises orchard environments comprising trees in rows, bare ground, cover crops and at times mulches, dual source models are considered to give more accurate ET information for row crops (Kool et al., 2014).

Examples of some of the dual source models that have been evaluated on agricultural crops including orchards are listed in Table 6.1.

Table 6.1 Summary of selected models that partition ET into transpiration and evaporation components that have been applied in crop production systems (after Kool et al., 2014)

	Full name	Acronym	Reference
1.	Shuttle-Wallace	S-W	Shuttleworth and Wallace (1985)
2.	Energy and Water Balance	ENWATBAL	Lascano et al. (1987)
3.	Plant – Environment Energy Balance combined with the Water Droplet Evaporation Trajectory	Cupid-DPEVAP	Thompson et al. (1993)
4.	Soil, Water, Energy and Transpiration	SWEAT	Daamen and Simmonds (1994)
5.	Two Source Energy Balance	TSEB	Norman et al. (1995)
6.	FAO dual-Kc	FAO dual-Kc	Allen et al. (1998)

Of the suite of models described in Table 6.1, the Shuttleworth and Wallace (S-W) model is considered to be one of the most accurate models. It requires readily available input data although it is considerably difficult to parameterize. The goal of this Chapter is to provide estimates of the seasonal dynamics of ET and its components from 12 orchards studied in this project.

6.2 Materials and methods

6.2.1 Data collection

Detailed descriptions of the study sites and data collection methods were given in Chapters 3, 4 and 5. But briefly the data included orchard transpiration and evapotranspiration rates, orchard leaf area index, soil moisture regimes, eco-physiological data, and the orchard microclimates, among others. The data were collected from the 2014/15 to the 2016/17 season in KBV and EGVV, respectively.

6.2.2 Model Description

In the S-W scheme (Fig. 6.1), a relationship similar to the Penman-Monteith equation is applied to the tree canopies and on the orchard floor. These two surfaces are treated as separate sources of water. Orchard evapotranspiration (λE, in W/m^2) is calculated as the algebraic sum of the fluxes from the tree canopies and from the orchard floor:

$$\lambda E = \lambda E_c + \lambda E_s \qquad (6.1)$$

where λE_c is the latent heat flux from tree canopies (transpiration) and λE_s is evaporation from the orchard floor. The fluxes are calculated at a reference height x above the orchard (Fig. 6.1) and the transpiration (T) and soil evaporation (E_s) components are given by:

$$\lambda E_c = C_c \frac{\Delta A + \left\{ \dfrac{\rho c_p D - \Delta r_a^c A_s}{r_a^a + r_a^c} \right\}}{\Delta + \gamma \left\{ 1 + r_s^c / (r_a^a + r_a^c) \right\}} \qquad (6.2)$$

and;

$$\lambda E_s = C_s \frac{\Delta A + \dfrac{\left\{ \rho c_p D - \Delta r_a^s (A - A_s) \right\}}{r_a^a + r_a^s}}{\Delta + \gamma \left\{ 1 + r_s^s / (r_a^a + r_a^c) \right\}} \qquad (6.3)$$

where C_c is a dimensionless canopy resistance coefficient; C_s is the substrate resistance coefficient, also dimensionless; Δ is the slope of the saturation vapour pressure-temperature curve (kPa K^{-1}), c_p is the specific heat at constant pressure (J kg^{-1} K^{-1}), ρ is the density of air (kg m^{-3}); λ is the latent heat of vaporization (J kg^{-1}), D is the vapour pressure deficit of the air at the reference height (kPa) and it is presented as VPD elsewhere in this report, r_a^a (s m^{-1}) is the aerodynamic resistance between canopy source height and reference level, r_a^c (s m^{-1}) is the boundary layer resistance of the canopy, r_s^c (s m^{-1}) is the canopy resistance, r_s^s (s m^{-1}) is the surface resistance of the substrate, r_a^s (s m^{-1}) is the aerodynamic resistance between the substrate and the canopy source height and γ is the psychrometric constant (kPa K^{-1}). A is the available energy (W m^{-2}) absorbed by the orchard calculated as the difference between the net radiation and the soil heat flux, and A_s (W m^{-2}) is the available energy at the orchard floor calculated from A using Beer's law.

Orchard floor management practices varied among the orchards used in this study. So we do not differentiate between evaporation from bare ground, mulches, or transpiration from the cover crop at this stage. Rather we combine total evaporation from all these sources into soil evaporation (E_s). The total available energy (A, in W m^{-2}) was calculated as:

$$A = R_n - G \tag{6.4}$$

where (R_n, W m^{-2}) is the net radiation which was calculated as:

$$R_n = (1-\alpha)S_d + (\varepsilon_a - \varepsilon_s)\delta(T_a + 273.15)^4 \tag{6.5}$$

where α is the surface albedo of the orchard. Albedo values were measured using the four component net radiometer (model: CNR4, Kipp & Zonen, The Netherlands). S_d is the downward solar radiation (W m^{-2}) which was measured by a pyranometer at the weather station located outside the orchards, and T_a is the air temperature (in °C).

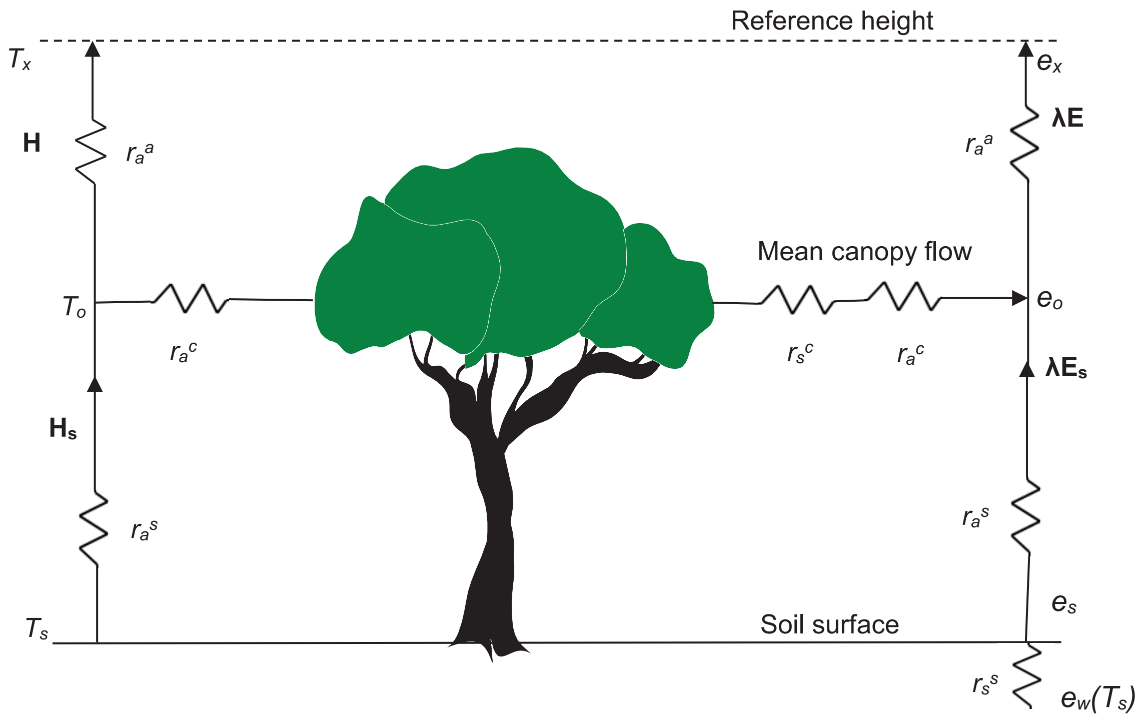


Fig. 6.1 Schematic diagram of the S-W model for evaporation from a sparse crop (Shuttleworth & Wallace, 1985).

Sigma (δ) is the Stefan-Boltzmann constant while ε_a and ε_s represents the emissivity of the atmosphere and the orchard surface, respectively. These were calculated according to Mu et al (2011) and Bastiaansen et al (2002) as:

$$\varepsilon_a = 1 - 0.26e^{(-7.77x10^4 xT_a^2)} \quad (6.6)$$

and;

$$\varepsilon_s = 0.95 + 0.01xLAI \quad (6.7)$$

where LAI is the orchard level leaf area index. The soil heat flux, G (in W m^{-2}) in equation 6.5 was estimated as 20% of the net radiation incident on the orchard floor ($R_{ns,}$ in W m^{-2}) in the full-bearing orchards and 30% in the non-bearing orchards which had more exposed soil surfaces. According to Shuttleworth and Wallace (1985) and also Li et al (2010), R_{ns} was calculated using Beer's law as:

$$R_{ns} = R_n \bullet e^{-kLAI_o} \quad (6.8)$$

The available energy at the soil surface (A_s, W m^{-2}) was then given by:

$$A_s = R_{ns} - G \quad (6.9)$$

The extinction coefficient (k) in equation 6.8 was taken as a constant at 0.6 according to Impens and Lemeur (1972). According to Shuttleworth and Wallace (1985), the dimensionless constants C_c and C_s in equations 6.2 and 6.3 are given by the expressions

$$C_c = \{1 + R_c R_a / R_s (R_c + R_a)\}^{-1} \quad (6.10)$$

$$C_s = \{1 + R_s R_a / R_c (R_s + R_a)\}^{-1} \quad (6.11)$$

where

$$R_a = (\Delta + \gamma) r_a^{\ a} \quad (6.12)$$

$$R_s = (\Delta + \gamma) r_a^{\ s} + \gamma r_s^{\ s} \quad (6.13)$$

$$R_c = (\Delta + \gamma) r_a^{\ c} + \gamma r_s^{\ c} \quad (6.14)$$

The mean boundary layer resistance of the canopy r_a^c and the bulk stomatal resistance of the canopy r_s^c are both surface resistances influenced by the surface area of the vegetation present and were given by:

$$r_s^{\ c} = \frac{r_{ST}}{2LAI} \quad (6.15)$$

$$r_a^{\ c} = \frac{r_b}{2LAI} \quad (6.16)$$

where r_{ST} is the mean stomatal resistance and r_b the mean boundary layer resistance. The original equations are given in Shuttleworth and Wallace (1985) and these used a constant stomatal resistance (r_{sT}) of 400 s m^{-1}, while the soil surface resistances ($r^s{}_s$) were fixed at 0, 500, and 2000 s m^{-1} for wet, moderately wet, and dry soils. In this study, as in others, a variable stomatal conductance ($g_{sT} = 1/r_{ST}$) was employed following Jarvis (1976). According to this method, if $g_{s\ \max}$ is the maximum stomatal conductance for apples, then the stomatal conductance at any given time (in m s^{-1}) is moderated by environmental stress factors according to:

$$g_{ST} = g_{s\max} \times f(R) \times f(T) \times f(VPD) \times f(\theta) \quad (6.17)$$

where $f(R)$, $f(T)$, $f(VPD)$ and $f(\theta)$ are the: solar radiation (R), air temperature (T), vapour pressure deficit of the air (VPD) and soil water content (θ) stress factors with values between 0 and 1. The stress factor expressions took the following forms:

$$f(R) = \frac{R}{R + k_r} \quad (6.18)$$

$$f(T) = \left(\frac{T - T_{\min}}{T_{opt} - T_{\min}}\right) \times \left(\frac{T_{\max} - T}{T_{\max} - T_{opt}}\right)^{\left((T_{\max} - T_{opt})/(T_{opt} - T)\right)} \quad (6.19)$$

$$f(VPD) = e^{-k_{vpd} * VPD} \quad (6.20)$$

$$f(\theta)=\begin{cases}1 & \theta \geq \theta_{FC} \\ \left(\dfrac{\theta-\theta_{WP}}{\theta_{FC}-\theta_{WP}}\right)^{\beta} & \theta_{WP}<\theta<\theta_{FC} \\ 0 & \theta \leq \theta_{WP}\end{cases} \qquad (6.21)$$

where k_r, k_{vpd}, and β are parameters obtained by model optimization and are defined in Table 6.1. Equation 6.18 has been applied on maple trees (*Acer rubrum*) by Bauerle et al. (2002), while equations 6.19 and 6.20 were used in a sugarcane ET model in South Africa by Bastidas-Obando et al. (2017). Equation 6.21 was adopted from Egea et al. (2011) where θ_{FC} and θ_{WP} represent the volumetric soil water content at field capacity and permanent wilting point in the root zone. Hourly climate, transpiration, ET, soil water content and LAI data for days when there were complete eddy covariance ET measurements in the full-bearing 'Cripps' Pink' orchard in KBV during 2014/15 was used to calibrate the model. There was a total of 34 days spread throughout the growing season that met this criterion. Model optimization was done using the Marquardt iterative method in which parameter values that minimized the weighted sum of squared differences between the measured and modelled transpiration and ET were selected.

The soil surface resistance was derived from the soil water content in the top 15 cm (θ_{15}) by fitting a power function proposed by Poyatos et al. (2007) as:

$$r^{s}{}_{s}=\begin{cases}0 & \theta \geq \theta_{FC} \\ b_1\left(\dfrac{\theta_{15}}{\theta_{15FC}}\right)^{b_2} & \theta_{WP}<\theta<\theta_{FC} \\ 2000 & \theta<\theta_{WP}\end{cases} \quad (\mathrm{s\ m^{-1}}) \qquad (6.22)$$

b_1 and b_2 are model parameters which were obtained from hourly soil evaporation measurements from eight micro-lysimeters located at different sun/shade and wet/dry positions in the orchard according to the procedure by Poyatos et al (2007). Soil evaporation data was collected in KBV from 18 to 20 February 2015 in the full-bearing 'Golden Delicious' orchard and from 23 to 24 February 2015 in a non-bearing 'Golden Delicious Reinders' orchard. The symbol θ_{15} represents the hourly average soil water content of all the soil moisture sensors at the 15 cm depth, and θ_{15FC} is the volumetric water content at field capacity at the 15 cm depth.

6.3 Results and discussion

6.3.1 Partitioning of energy and water use in apple orchards

Typical partitioning of the energy balance components as measured by the eddy covariance system on three consecutive clear days in a mature ‘Golden Delicious’ orchard is shown in Fig. 6.2. At this time, canopy cover was maximum with a leaf area index greater than 3.0. Most of the available energy (R_n-G) was used for evapotranspiration (open dotted circles). A small proportion of the energy was converted to sensible heat (closed triangles) and this is in contrast to the situation in young orchards presented in Fig. 3.11. The soil heat flux (open diamond shapes) in the full-bearing orchard averaged between 10-20% of the net radiation.

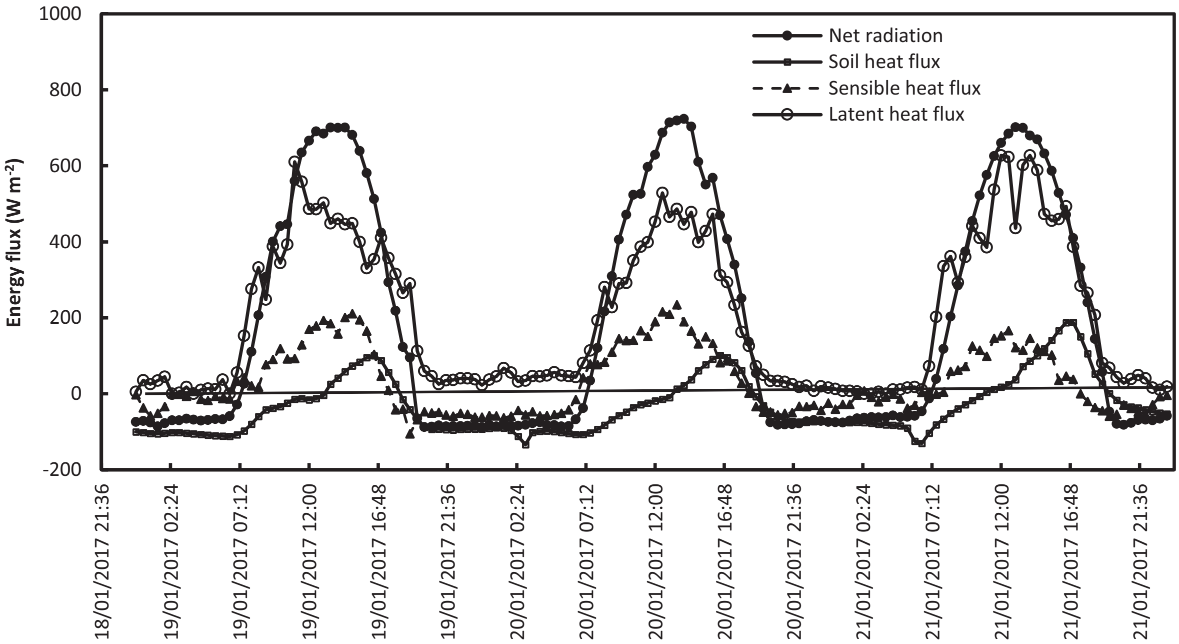


Fig. 6.2 Energy balance of a full-bearing ‘Golden Delicious’ apple orchard at peak canopy cover.

An example of how ET for a typical clear day, expressed in equivalent energy units, was partitioned in a full-bearing and a non-bearing ‘Golden Delicious’ orchard at maximum canopy cover is shown in Fig. 6.3. Transpiration was the dominant flux in the mature orchard accounting for 78% of ET. The remainder (22%) was evaporation from the orchard floor. The hourly transpiration, derived from the stem sap flow of the mature orchards, was out of phase with the measured ET and Fig. 6.3a illustrates this for the full-bearing ‘Golden Delicious’ orchard for one day.

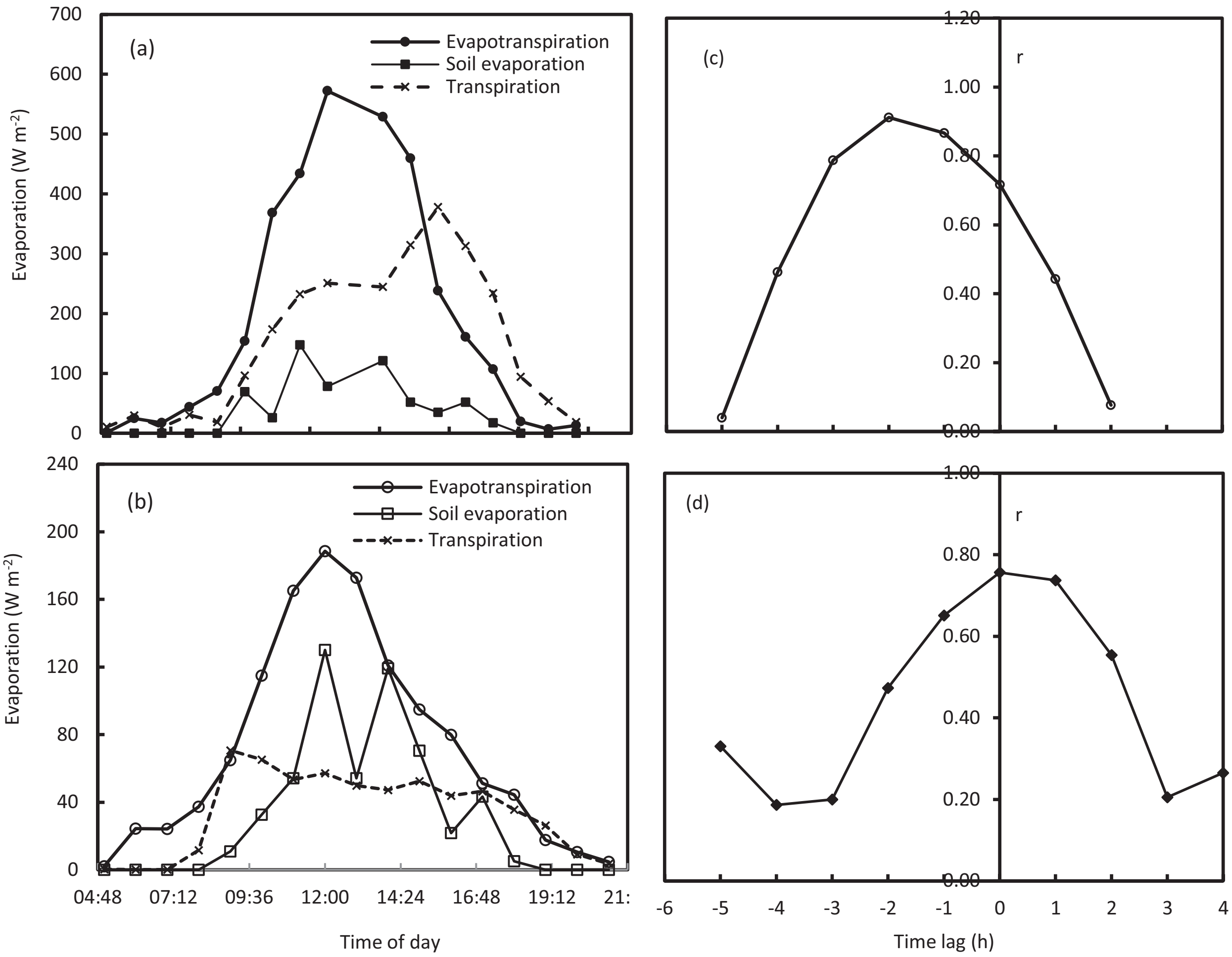


Fig. 6.3 Partitioning of ET into the transpiration and orchard floor evaporation components in: (a) a full-bearing, and; (b) a non-bearing apple orchard. Typical time lags between the measured ET and transpiration in: (c) a full-bearing, and; (d) a non-bearing apple orchard. The symbol "r" represents the correlation coefficient.

This phase shift could introduce substantial errors in model parameters given the dominance of climate driving variables which are in phase with ET in the Shuttleworth and Wallace model, which does not take into account the capacitance of the trees. By cross-correlating the ET with transpiration, it is apparent that mature orchard transpiration, as measured on the stems using sap flow sensors, lagged behind ET by up to 2 hours (Fig. 6.3b), and the symbol "r' represents the correlation coefficient. The transpiration data used for model calibration was subsequently adjusted for this time lag to minimize errors due to the mismatch between the climate driving variables and transpiration. In the young orchards, transpiration at full canopy cover accounted for approximately 47% of ET, with orchard floor evaporation contributing up to 53% of the observed ET (Fig. 6.3c). There were no time lags between the hourly sap flow derived transpiration and ET in the non-bearing orchards (Fig. 6.3d). The high capacitance in the full-bearing trees is the cause of the time lags between the sap flow-derived transpiration and the actual ET. However, there was no time lag in the young orchards consistent with results from other studies (e.g. (Dzikiti et al., 2010, Steppe et al., 2006)) which showed that fully grown trees relied more on internally stored water when leaf transpiration exceeded root water uptake or stem sap flow. In addition, younger trees have higher root-to-shoot ratios than older ones (Wolstenholme, 1981). So, it is probable that water supply to the evaporating sites in the leaves is more rapid in young trees, which also have a shorter hydraulic path length than in mature trees. Removing the mismatch between the transpiration derived from stem sap flow and the atmospheric evaporative demand improved the performance of the Shuttleworth and Wallace model run at the hourly time step as reported in the next section.

6.3.2 Model calibration and sensitivity tests

Parameters used in the modified Shuttle and Wallace model described in section 6.3 are shown in Table 6.2. Orchard-specific parameters such as the volumetric water content at field capacity and at the permanent wilting point are presented in Chapters 3, 4 and 5. Parameters related to evaporation from the orchard floor (i.e. b_1 and b_2) were different for orchards with and without cover crops (see Table 6.2). This is because in orchards with cover crops the effective surface resistance is the soil surface resistance in parallel with the cover crop canopy resistance. The presence of mulches and ridges further complicates this variable.

The parameters presented in Table 6.2 were used in all the 12 orchards investigated in this study. To establish the relative importance of each parameter on the simulated orchard ET, a sensitivity test was performed. This involved varying each parameter by an arbitrarily selected margin of ±30% and we observed the effects on the simulated ET. The parameters were varied one-at-a-time and the resulting effects on ET for a typical clear day are shown in Fig. 6.4. The VPD parameter (k_{vpd}) had the largest effect (~17%) on the simulated orchard water use. This was followed by the orchard floor evaporation parameters (b_1 and b_2) which changed ET by ~ 6 and 10%, respectively. The minimum stomatal resistance affected ET by a small margin, around 5%. Parameters which had the largest effect on ET received the most attention during model calibration.

Table 6.2 Parameter values for the modified Shuttleworth and Wallace model applied to high yielding and non-bearing apple orchards.

Parameter	Description	Value
$*b_1$	Value of soil surface resistance when $\theta_{15} = \theta_{FC}$ (in s/m)	200
$*b_2$	Describes the non-linear changes in surface resistance with soil moisture (-)	-5.83
β	Describes the curvature of f(θ) (-)	1.231
k	Extinction coefficient	0.6
k_{vpd}	Describes the influence of the VPD stress factor - f(VPD) (-)	1.33
k_r	Describes the curvature of f(R_s) (in W m^{-2})	302
r_{ST}	Minimum stomatal resistance (in s m^{-1})	80
r_b	Boundary layer resistance (s m^{-1})	26.6
T_{max}	Maximum temperature for complete stomatal closure (in °C)	45
T_{min}	Minimum temperature at which stomata close (in °C)	3
T_{opt}	Optimum temperature for growth of the trees (in °C)	23

$*b_1$ = 25 s m^{-1} for orchards without a cover crop.

$*b_2$ = -8.30 for orchards without a cover crop.

The model inputs were the:

average solar radiation (hourly, in W m^{-2});

average air temperature (hourly, °C);

relative humidity (hourly, %);

wind speed (hourly, m/s);

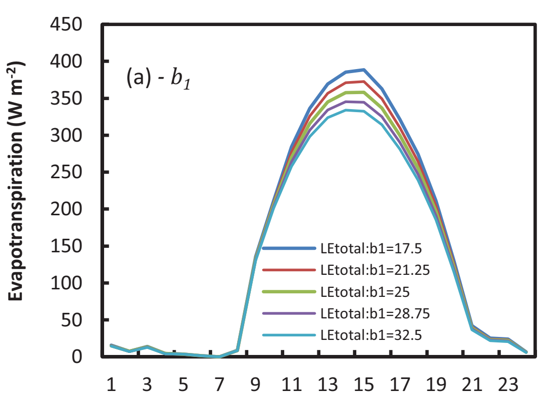
volumetric soil water content (hourly, cm^3 cm^{-3});

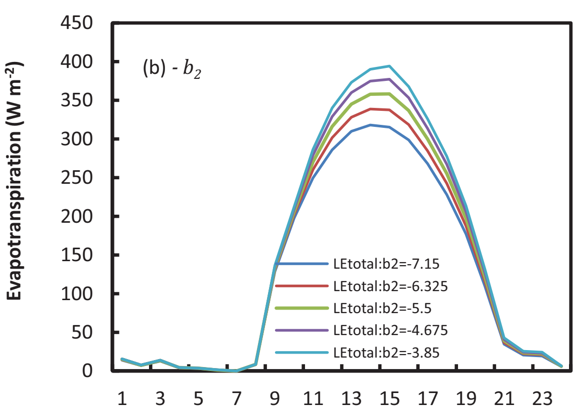
orchard leaf area index (dimensionless);

orchard surface albedo (dimensionless);

average canopy height (in m), and;

site elevation (m asl)





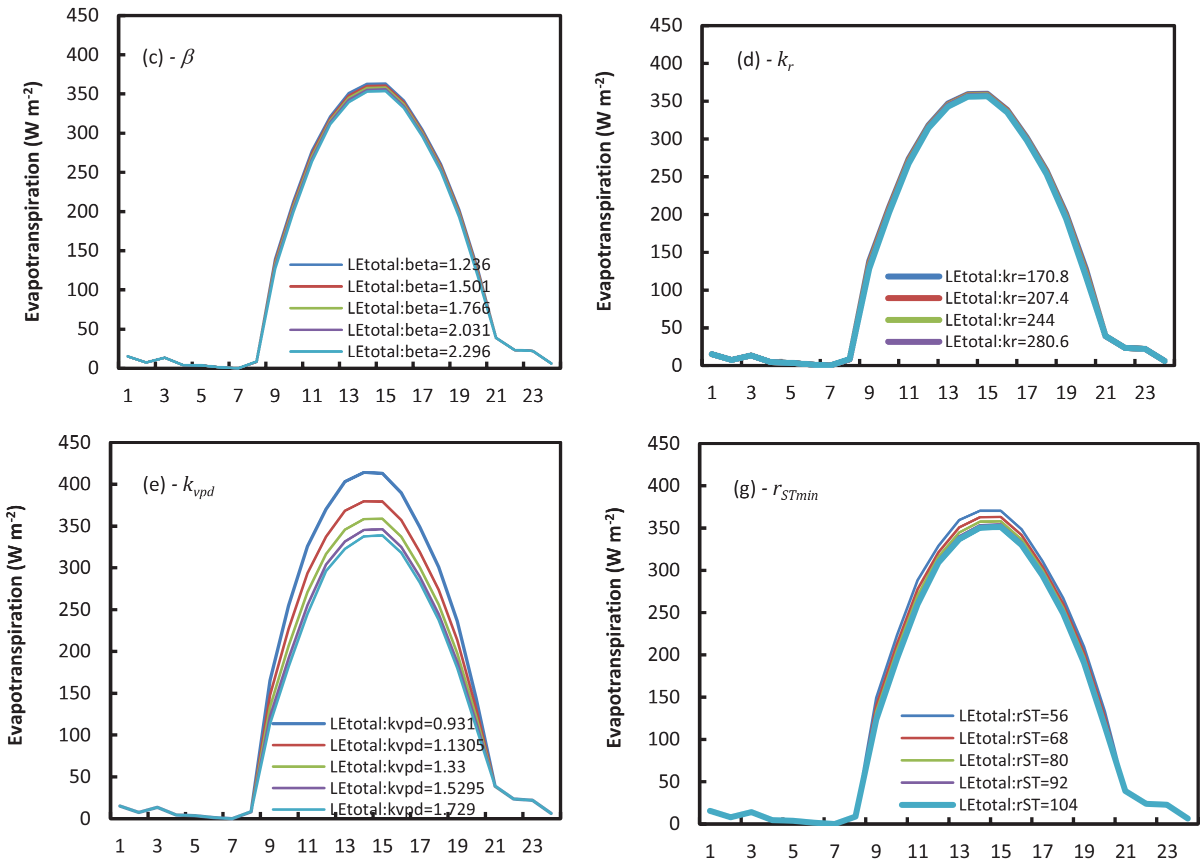


Fig. 6.4 Sensitivity tests for key parameters of the modified Shuttleworth and Wallace model using data collected on 15 November 2016 at Lindeshof farm.

6.3.3 Validation of the S-W model

6.3.3.1 Orchard transpiration simulation

The improved Shuttleworth and Wallace model predicted the daily transpiration rates for the entire season reasonably well. Typical examples for three orchards with low, medium and high canopy cover are shown in Fig. 6.5.

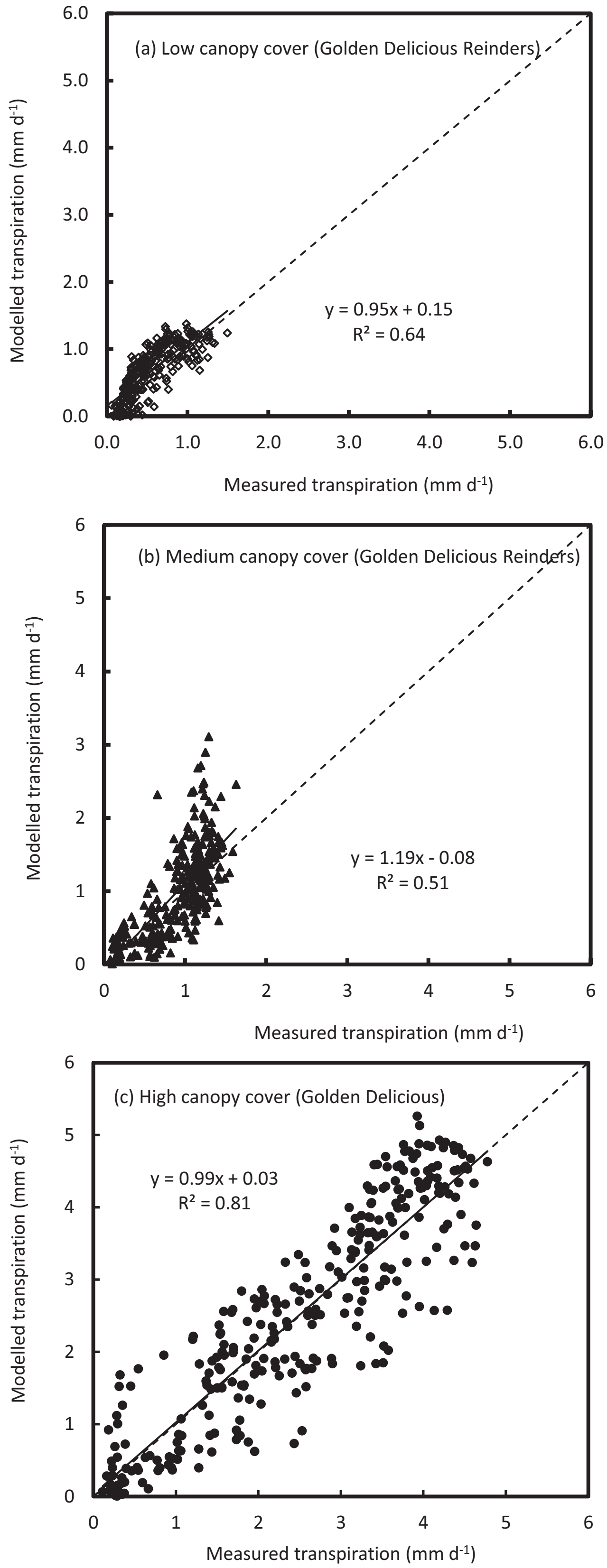


Fig. 6.5 Comparison between the measured and modelled daily transpiration in trees with: (a) Low, (b) Medium, and; (c) High canopy cover for entire growing seasons.

The trends in the other orchards were similar to those shown in Fig. 6.5 and the scatter tended to be somewhat larger in young orchards. Reasons for the low predictive ability of the model in young orchards are not clear. Table 6.3 summarises the model performance for predicting both the transpiration and evapotranspiration in all the 12 orchards. The Nash-Sutcliffe Efficiency ranged between 0 and 1.0 for both the transpiration and ET components. This indicates that the model performance was acceptable although error margins tended to be higher in younger orchards. The root mean square error for transpiration simulation was low ranging from ±0.20 to ±0.60 mm d^{-1}.

6.3.3.2 Orchard evapotranspiration simulation

Examples of model predictions of ET are shown in Fig. 6.6 for orchards with low, medium and high canopy cover. These graphs show model performance for selected window periods when actual ET data was collected.

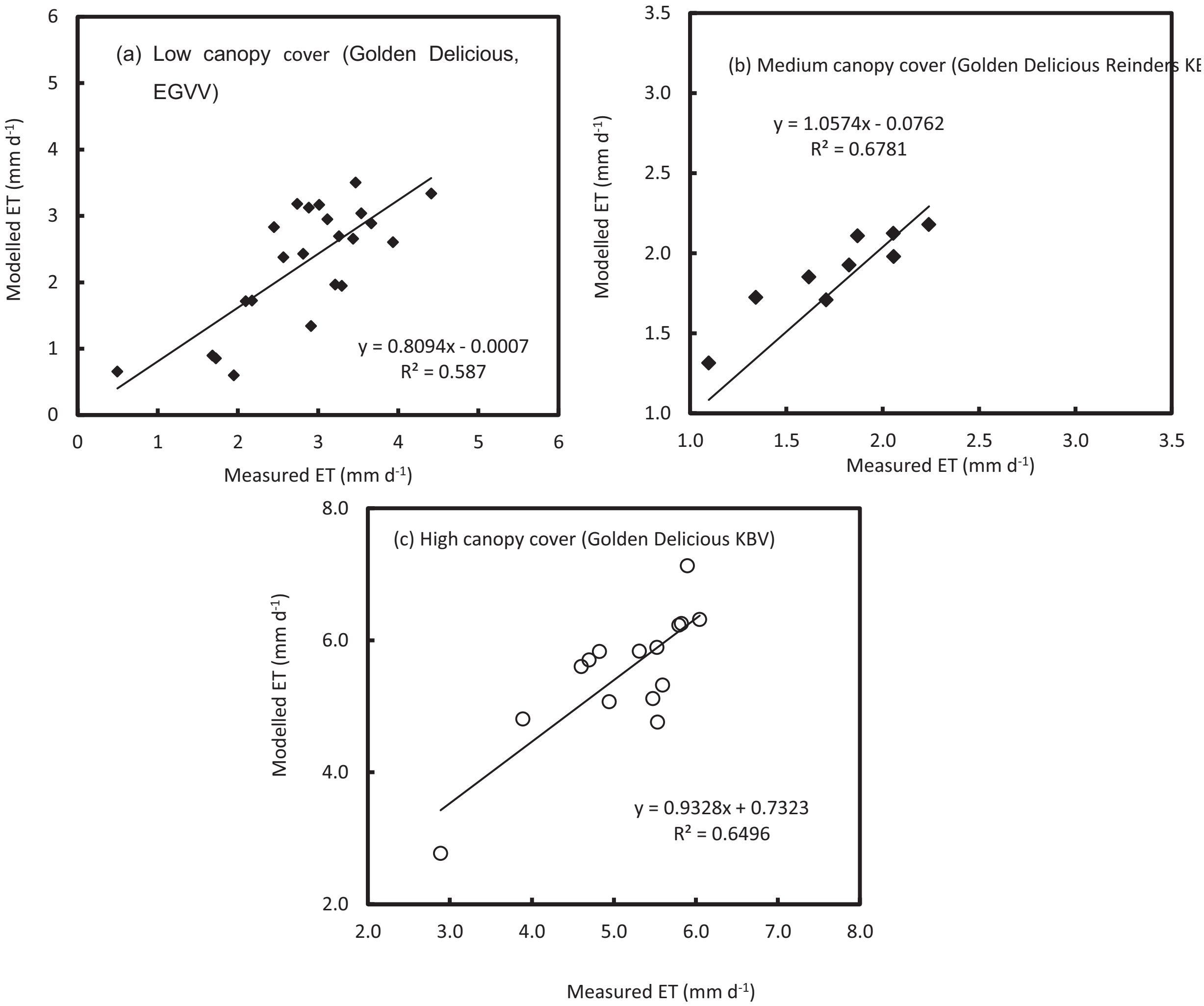


Fig. 6.6 Comparison of the measured and modelled evapotranspiration in orchards with: (a) Low, (b) Medium, and; (c) High canopy cover.

The root mean square error for the ET simulations was significantly higher reaching up to ±1.0 mm d^{-1}. This was mainly a result of the difficulties in modelling the orchard floor evaporation accurately. Future studies should focus on the orchard floor ET flux which is quite complex to model and there is very little information on the water use of different cover crop species.

Table 6.3 Summary statistics for the performance of the modified Shuttleworth and Wallace model for predicting transpiration (T) and orchard evapotranspiration (ET) at sites in KBV and EGVV during the 2014/15, 2015/16 and 2016/17 growing seasons. FBGD represents the full-bearing 'Golden Delicious', FBCP the full-bearing 'Cripps' Pink', NBGD the non-bearing Golden Delicious, NBRG the non-bearing 'Rosy Glow', NBCR the non-bearing 'Cripps' Red', IBGR the intermediate bearing 'Golden Delicious Reinders', and IBCP the intermediate bearing 'Cripps' Pink'. N = number of days of ET measurements.

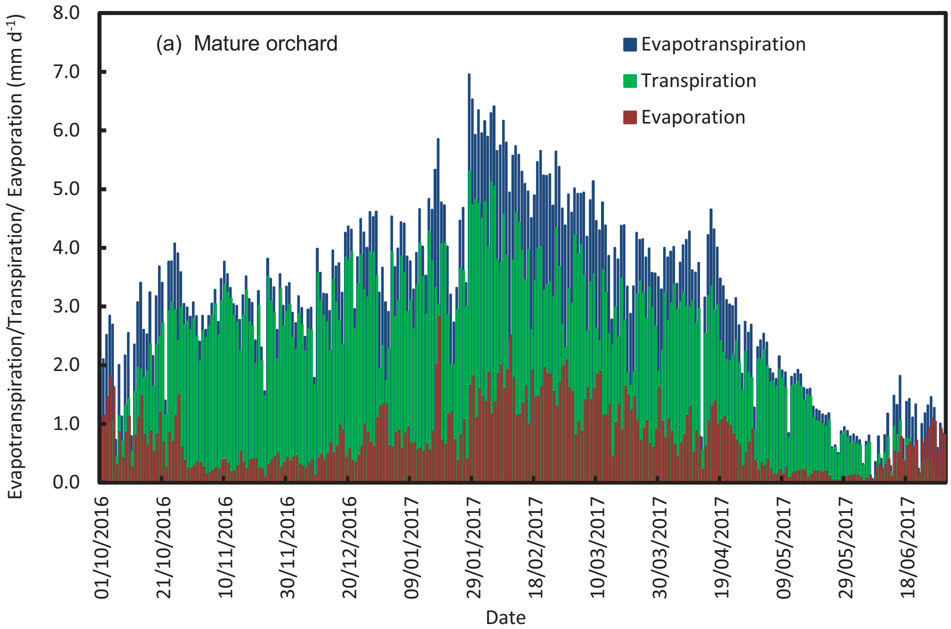
Region	Orchard	Canopy cover	Variable	Slope	Intercept	R^2	RMSE	MAE	NSE	N
KBV	FBGD	High	T	0.85	0.15	0.50	0.51	0.46	0.24	29
			ET	1.02	0.54	0.73	1.10	0.94	0.21	29
	FBCP	High	T	1.07	0.07	0.91	0.42	0.33	0.85	23
			ET	0.86	0.41	0.93	0.62	0.51	0.92	23
	NBGR	Low	T	0.68	0.30	0.45	0.19	0.14	0.32	43
			ET	0.75	0.44	0.70	0.62	0.52	0.66	43
	NBRG	Low	T	0.78	0.20	0.78	0.38	0.53	0.76	34
			ET	0.87	0.31	0.60	0.42	0.60	0.47	34
EGVV	FBGD	High	T	1.11	0.15	0.76	0.59	0.51	0.42	25
			ET	0.83	0.33	0.81	0.75	0.80	0.66	25
	FBCP	High	T	0.85	-0.34	0.82	0.87	0.73	0.27	38
			ET	1.18	-0.26	0.88	0.68	0.54	0.71	38
	NBGD	Low	T	0.99	0.14	0.76	0.20	0.17	0.46	12
			ET	1.34	-0.18	0.74	0.61	0.77	0.10	12
	NBCR	Low	T	0.97	-0.12	0.71	0.40	0.28	0.68	14
			ET	0.90	0.02	0.23	0.89	0.57	0.43	14
KBV	IBGR	Medium	T	0.93	0.23	0.75	0.21	0.17	0.11	11
			ET	1.05	-0.08	0.68	0.26	0.21	0.68	11
	*IBCP	Medium	T	-	-	-	-	-	-	-
			ET	-	-	-	-	-	-	-
EGVV	*IBGR	Medium	T	-	-	-	-	-	-	-
			ET	-	-	-	-	-	-	-
	IBCP	Medium	T	1.04	0.32	0.55	0.51	0.43	0.86	18
			ET	1.00	1.17	0.81	1.34	1.19	0.05	18

6.3.4 Seasonal water use patterns

6.3.4.1 Partitioning of daily water use

The modelled daily total ET and its components show that orchard floor evaporation dominated ET at the beginning of the season in early October in mature orchards (Fig. 6.7a) due to the low canopy cover. However, the rapid increase in leaf area after bud break resulted in transpiration being almost double the orchard floor evaporation by late October. Orchard floor ET increased again and reached a peak in summer due to the high atmospheric evaporative demand as a result of the hot and dry weather. The wet orchard floor due to high irrigation levels also contributed to the high orchard floor evaporation.

In the young orchards however, the picture was somewhat different. The orchard floor evaporation was higher than tree transpiration throughout the growing season (Fig. 6.7b) due to the low canopy cover even during the summer season when the canopy size was at its maximum. In this analysis, we do not distinguish between the role of cover crops, weeds mulch and the soil. The orchard floor surface resistance combined all the artefacts on the orchard floor.



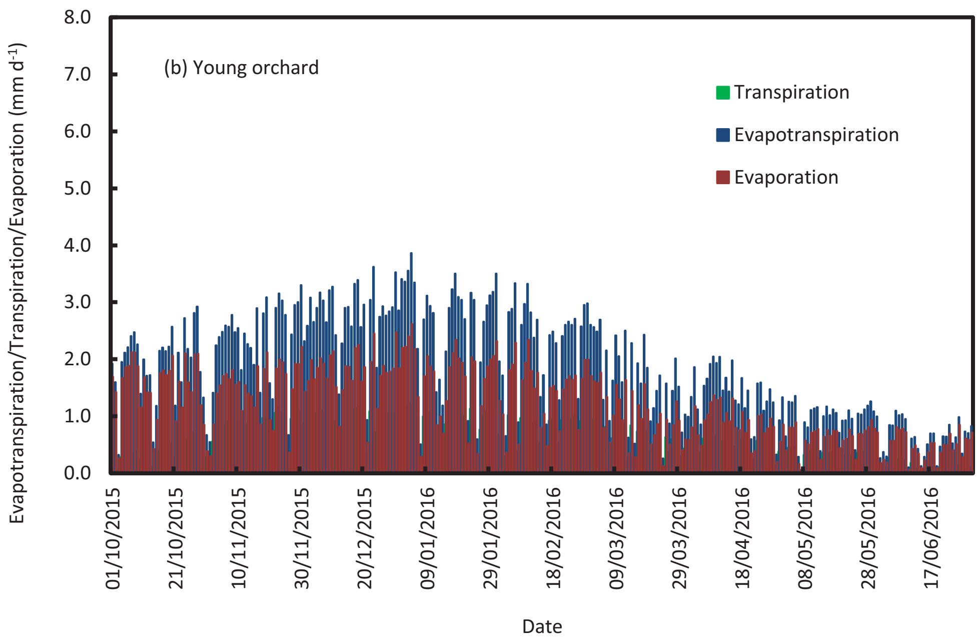


Fig. 6.7 Predicted seasonal partitioning of ET into orchard transpiration and soil evaporation for a: (a) mature, and (b) young orchard.

6.3.4.2 Monthly water use patterns for trees with high canopy cover

The predicted seasonal total crop water requirements (ET) were 10 860 and 11 100 m^3 ha^{-1} for the full-bearing 'Golden Delicious' orchards in KBV and EGVV, respectively (Tables 6.4 and 6.5). In the KBV full-bearing 'Golden Delicious' orchard total ET exceeded 1 000 m^3 ha^{-1} month^{-1} from October to April. The peak monthly crop water requirement was 1 830 m^3 ha^{-1}

reached in January 2015. This was split into 1 240 m^3 ha^{-1} in tree transpiration and 590 m^3 ha^{-1} in orchard floor evaporation. For the full-bearing 'Golden Delicious' orchard in EGVV, the monthly ET patterns were similar to those in KBV. However, the peak crop water requirements (~ 1 740 m^{3}ha^{-1}month^{-1}) were reached in December 2015 split into 1 180 m^3 ha^{-1} of transpiration and 560 m^{3}ha^{-1}in orchard floor evaporation. Monthly total ET was less than 1 000 m^3 ha^{-1} from May onwards in both production regions. It is important to note that the transpiration values presented in the tables are actual values measured using sap flow gauges.

Table 6.4 Monthly measured transpiration (T), modelled orchard evapotranspiration (ET) and orchard floor evaporation (E_s) in KBV for two full-bearing orchards during the 2014/15 growing season.

Month	***Full-bearing Golden Delicious (Kromfontein)***			***Full-bearing 'Cripps' Pink' (Kromfontein)***		
	T (mm)	***ET (mm)***	***E_s (mm)***	***T (mm)***	***ET (mm)***	***E_s (mm)***
October 14	95	105	10	76	106	30
November 14	107	135	28	73	128	55
December 14	124	182	58	88	148	60
January 2015	124	183	59	90	158	68
February 2015	107	156	49	82	134	52
March 2015	98	138	40	84	128	44
April 2015	78	105	27	58	98	40
May 2015	55	62	7	32	66	34
Total	***787***	***1 086***	***278***	***589***	***976***	***383***

The orchard floor values were calculated as the difference between the modelled ET and the measured transpiration given our low confidence in the orchard floor evaporation simulations. The orchard floor evaporation accounted for between 26 and 32% of the orchard ET in KBV and EGVV, respectively. The high orchard floor evaporation rates in EGVV may be a result of the wider row spacing (~2.0 m) than in KBV (~1.5 m). The estimated seasonal water requirements for the full-bearing 'Cripps' Pink' orchards were 976 mm in KBV and 902 mm in EGVV (Tables 6.4 and 6.5). January 2015 had the highest monthly ET of 1 580 m^3 ha^{-1} in KBV while May had the lowest water requirements of around 660 m^3 ha^{-1}. The ET in January 2015 was partitioned into 900 m^3 ha^{-1} in tree transpiration and 680 m^3 ha^{-1} in orchard floor evaporation. Orchard floor evaporation accounted for about 39% of the estimated seasonal water use (ET) in the full-bearing 'Cripps' Pink' orchard in KBV. In the EGVV full-bearing 'Cripps' Pink', December 2015 had the highest crop water requirements of approx. 1 450 m^3

ha^{-1} split into 1 000 m^3 ha^{-1} transpiration and 450 m^3 ha^{-1} in orchard floor evaporation. June 2016 had the lowest crop water requirements of around 410 m^3 ha^{-1} in EGVV. Orchard floor accounted for about 30% of the seasonal ET for the full-bearing 'Cripps' Pink' in EGVV.

Table. 6.5 Monthly total water use of the two full-bearing orchards in EGVV during the 2015/16 growing season. Transpiration is derived from sap flow measurements while the evapotranspiration was determined from the S-W model.

	Full-bearing Golden Delicious (Southfield)			***Full-bearing 'Cripps' Pink' (Radyn)***		
Month	***ET (mm)***	***T (mm)***	***E_s (mm)***	***ET (mm)***	***T (mm)***	***E_s (mm)***
Oct	122	70	52	100	72	28
Nov	157	98	59	126	84	42
Dec	174	118	56	145	100	45
Jan	168	122	46	139	95	44
Feb	141	104	37	116	76	40
Mar	121	86	35	95	74	21
Apr	101	62	39	80	55	25
May	73	61	12	59	45	14
Jun	53	38	15	41	30	11
Total	**1110**	**757**	**351**	**902**	**631**	**270**

6.3.4.3 Monthly water use patterns for trees with medium canopy cover in KBV

The measured actual seasonal total tree transpiration at Esperanto was 6 780 m^3 ha^{-1} compared to 6 640 m^3 ha^{-1}modelled, so there was less than 5% difference between the measured and modelled transpiration at the seasonal time scale (Table 6.6). The predicted seasonal total evapotranspiration was 8 710 m^3 ha^{-1}of which about 2 070 m^3 ha^{-1} was evaporation from the orchard floor (Table 6.6). Evaporation from the orchard floor accounted for about 24% of seasonal ET, which seems quite small given the dense cover crop. However, this also reflects the difficulties in adequately capturing the cover crop water use in the current model. We are working towards a three-layer version of the model where cover crop transpiration will be simulated separately and we hope this will improve the orchard water use estimates. The month of February 2017 had the highest water requirements of around 1 480 m^3 ha^{-1}.

Table 6.6 Monthly evapotranspiration (ET) and its partitioning into tree transpiration (T) and orchard floor evaporation (E_s) components for orchards with medium canopy cover in KBV during the 2016/17 growing season.

'Cripps' Pink' (Esperanto, KBV)					**Golden Delicious Reinders (Lindeshof, KBV)**			
Month	***$T_{measured}$ (mm)***	***$T_{modelled}$ (mm)***	***E_s (mm)***	***ET (mm)***	***$T_{measured}$ (mm)***	***$T_{modelled}$ (mm)***	***E_s (mm)***	***ET (mm)***
October 2016	74	58	26	84	32	34	52	85
November 2016	89	82	9	91	52	53	15	68
December 2016	105	92	18	110	52	62	25	87
January 2017	91	106	30	136	52	69	34	104
February 2017	75	104	44	148	50	59	34	93
March 2017	80	91	37	128	56	39	10	49
April 2017	73	76	25	100	36	29	7	37
May 2017	58	42	5	47	27	27	15	42
June 2017	33	14	14	28	12	7	24	31
Total	**678**	**664**	**207**	**871**	**369**	**379**	**217**	**596**

The measured actual seasonal total transpiration in the 'Golden Delicious Reinders' orchard with medium canopy cover at Lindeshof was much smaller than at Esperanto, being 3 690 m^3 ha^{-1}. This was similar to the modelled transpiration of 3 790 m^3 ha^{-1} (Table 6.6). The estimated seasonal total evapotranspiration was about 5 960 m^3 ha^{-1} of which 2 170 m^3 ha^{-1} (or 36%) was evaporation from the orchard floor. Most of the orchard floor evaporation occurred early in the growing season, quite likely before water saving measures were implemented to minimize the impact of the drought which affected the region during the study period. This could also be related to the fact that the spring flush occurs later in the 'Golden Delicious Reinders' trees than the long-season 'Cripps' Pink' resulting in a larger exposed surface fraction in the Golden orchards. Similar high early season values were also evident in the 'Golden Delicious Reinders' orchard at Vyeboom as will be discussed in the next section. January 2017 had the highest crop water requirement at Lindeshof of around 1 040 m^3 ha^{-1}.

6.3.4.4 Monthly water use patterns for trees with medium canopy cover in EGVV

The measured seasonal total transpiration in the 'Cripps' Pink' orchard at Dennebos was 4 680 m^3 ha^{-1} compared with the modelled total of about 5 100 m^3 ha^{-1}. This represented approx. 9% difference between the measured and modelled values (Table 6.7). The predicted seasonal total evapotranspiration was around 8 720 m^3 ha^{-1} of which 3 610 m^3 ha^{-1} (or 41%) was evaporation from the orchard floor. January 2017 had the highest crop water requirements at 1 310 m^3 ha^{-1}.

Table 6.7. Monthly evapotranspiration (ET) and its partitioning into tree transpiration (T) and orchard floor evaporation (E_s) components for orchards in EGVV.

	'Cripps' Pink' (Dennebos, EGVV)				Golden Delicious Reinders'(Vyeboom, EGVV)			
Month	**$T_{measured}$ (mm)**	**$T_{modelled}$ (mm)**	**E_s (mm)**	**ET (mm)**	**$T_{measured}$ (mm)**	**$T_{modelled}$ (mm)**	**E_s (mm)**	**ET (mm)**
October 2016	42	35	38	73	27	30	50	80
November 2016	60	85	45	130	36	49	35	84
December 2016	74	73	54	127	39	48	53	100
January 2017	71	79	52	131	37	52	46	98
February 2017	60	67	49	116	31	29	19	48
March 2017	64	68	57	125	32	31	29	60
April 2017	43	60	35	94	21	19	10	30
May 2017	35	29	14	43	18	10	2	12
June 2017	20	16	17	33	7	8	16	23
Total	**468**	**511**	**361**	**872**	**248**	**274**	**260**	**534**

Actual seasonal total transpiration in the 'Golden Delicious Reinders' orchard at Vyeboom measured with the sap flow sensors was 2 480 m^3 ha^{-1} (Table 6.7) compared with 2 740 m^3 ha^{-1}predicted by the model (i.e. 11% difference). The predicted seasonal total evaporation was about 5 340 m^3 ha^{-1} of which 2 600 m^3 ha^{-1} was evaporation from the orchard floor. The high proportion of evaporation from the orchard floor (~49%) was a result of the low LAI due to the small canopies of the trees and the wide spacing of the orchard (4 m x 2 m).

6.3.4.5 Monthly water use patterns for trees with low canopy cover

The estimated seasonal evapotranspiration for non-bearing 'Golden Delicious Reinders' orchard determined during the 2014/15 season at Lindeshof was about 4 810 m^3 ha^{-1}. The water requirements of the non-bearing 'Rosy Glow' at Paardekloof during the same period was approx. 5 620 m^3 ha^{-1} (Table 6.8). The monthly total ET was lower than 1 000 m^3 ha^{-1} in all the orchards throughout the growing season. However, the contribution of the orchard floor evaporation to seasonal orchard ET was quite high ranging from 47% in the 'Golden Delicious Reinders' to around 52% for the 'Rosy Glow'.

Table 6.8 Monthly measured transpiration, modelled evapotranspiration (ET) and orchard floor evaporation (E_s) in KBV during the 2014/15 season.

Month	*Non-bearing 'Golden Delicious Reinders' (Lindeshof)*			*Non-bearing 'Rosy Glow' (Paardekloof).*		
	***T* (mm)**	***ET* (mm)**	***E_s* (mm)**	***T* (mm)**	***ET* (mm)**	***E_s* (mm)**
October 2014	18	54	36	17	64	47
November 14	28	65	37	39	74	35
December 14	32	87	55	47	89	42
January 15	39	86	47	45	85	40
February 15	27	70	43	35	83	48
March 15	22	69	47	29	80	51
April 15	15	50	35	21	55	34
May 15	9	22	13	14	32	18
Total	***199***	***481***	***233***	***271***	***562***	***291***

The seasonal water requirements for the non-bearing 'Golden Delicious' and 'Cripps' Red' orchards in EGVV were similar during the 2015/16 season being around 5 000 m^3 ha^{-1} (Table 6.9). However, evaporation from the orchard floor accounted for a much higher proportion of seasonal ET ranging from 66% in the 'Golden Delicious' and 68% of ET in the 'Cripps' Red' orchard. The main reason for the very high orchard floor evaporation in EGVV is because of the low tree density which resulted in a much larger fraction of the soil surface being exposed. From these estimates, it appears that there is scope to save significant amounts of water in young orchards by reducing the wetted soil surface e.g. through mulching, use short range micro sprinklers and through drip irrigation, among other measures.

Table 6.9 Monthly total water use of the non-bearing orchards in EGVV during the 2015/16 growing season. Transpiration is derived from sap flow measurements while the evapotranspiration and orchard floor evaporation were determined via the S-W model.

Month	Non-bearing 'Golden Delicious' (Vyeboom)			Non-bearing 'Cripps' Red' (Vyeboom)		
	ET (mm)	***T (mm)***	***E_s (mm)***	***ET (mm)***	***T (mm)***	***E_s (mm)***
October 2015	59	11	47	58	9	47
November 2015	70	19	45	70	21	46
December 2015	86	31	55	85	27	57
January 2016	82	30	52	82	21	54
February 2016	66	20	42	66	13	44
March 2016	50	16	31	51	11	32
April 2016	41	10	26	41	11	26
May 2016	30	8	20	30	9	19
June 2016	18	7	14	18	8	14
Total	**501**	**151**	**331**	**500**	**129**	**340**

6.3.5 Comparison between the S-W and soil water balance derived ET

A comparison between the predicted monthly ET derived by the S&W model and that from the soil water balance approach is shown in Fig. 6.8. The performance of the model is quite mixed across the sites. The model estimates of ET are closer to the water balance derived values at Lindeshof and the performance is worst at Esperanto. The low accuracy in the simulations at Esperanto could be attributed to over-irrigation which resulted in a huge drainage flux which was not adequately accounted for in the soil water balance. Extensive validation, and possibly re-calibration of the model may be necessary to improve the accuracy of the water use estimates.

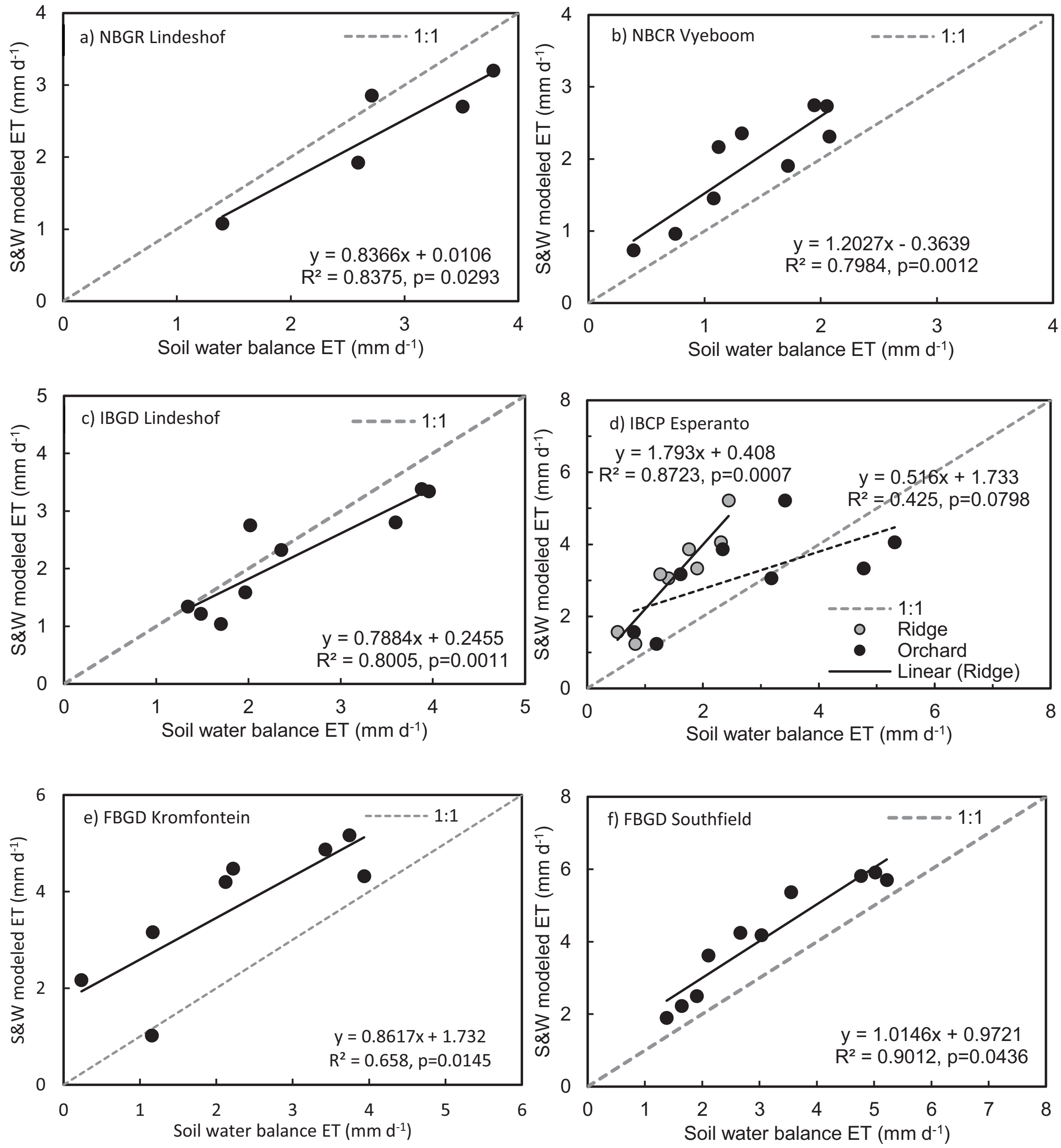


Fig. 6.8 Comparison of monthly averaged soil water balance determined ET and S&W modelled ET for low (a, b), medium (c, d) and high (e, f) canopy cover orchards.

6.3.6 Comparison between the S-W and FruitLook water use estimates

Lastly the modelled weekly ET was compared with that from the FruitLook product which is readily available to farmers in the Western Cape Province. Here we present data for orchards studied during the first two seasons (i.e. 2014/15 and 2015/16) in KBV and EGVV, respectively. Comparing the weekly ET from FruitLook with the eddy covariance validated Shuttleworth and Wallace model showed that FruitLook slightly over-estimated ET in full-bearing orchards in the coastal region in EGVV (Fig. 6.9 a & c). However, the differences between the two ET sources were much larger for the young non-bearing orchards (Fig. 6.9 b & d).

For the inland KBV, the order of magnitude of the FruitLook ET was similar (RMSE = ±1.0 mm d^{-1}) to that predicted by the Shuttleworth and Wallace model for orchards of all age groups (Fig. 6.9 e-h). The fact that FruitLook results are close to eddy covariance measurements in some parts of the Western Cape Province than others was also observed by other researchers (C. Jarmain pers. com.). The current comparisons with the Shuttleworth and Wallace model support this view, but it is not clear why this occurs.

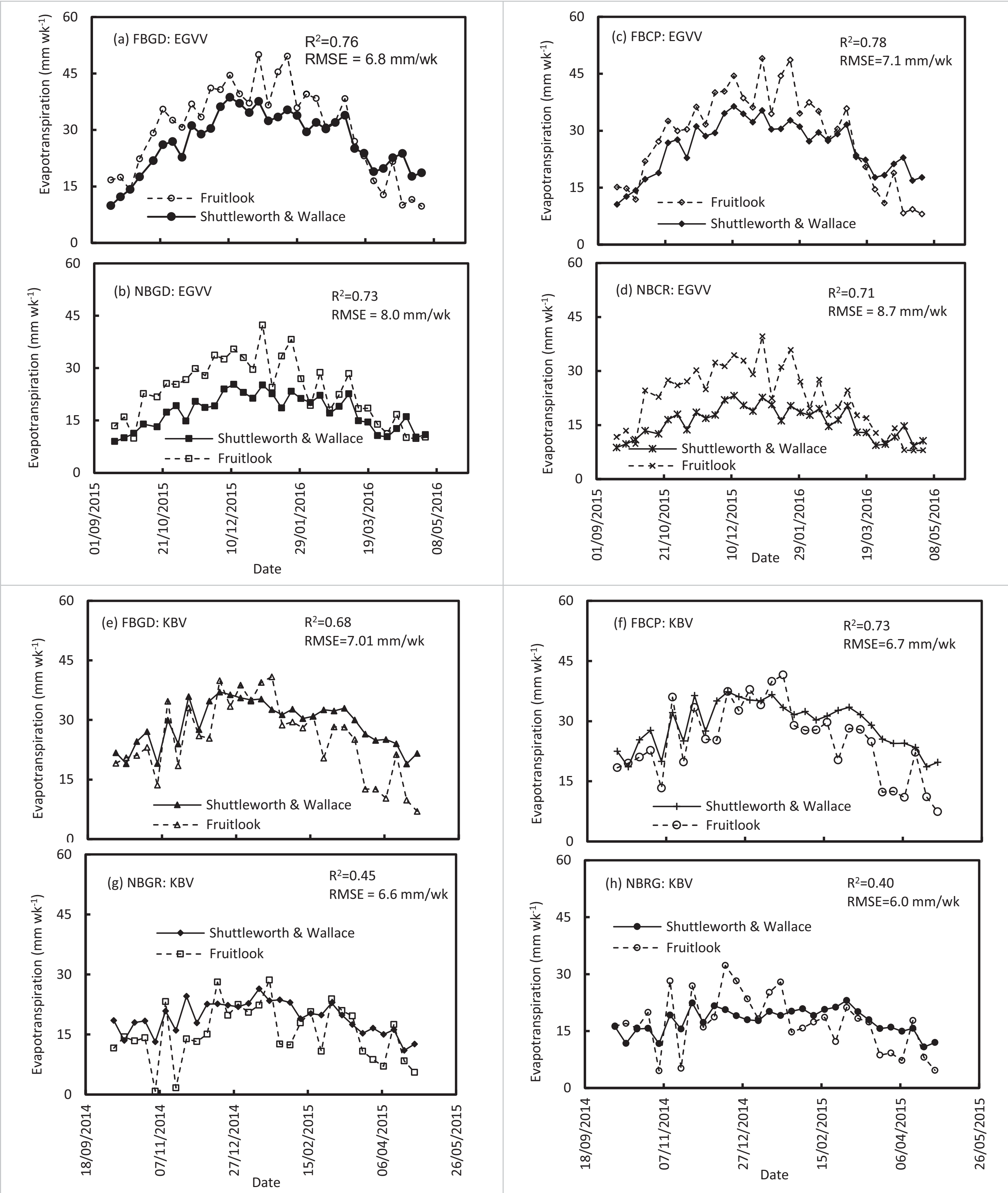


Fig. 6.9 Comparison of the seasonal variations in the weekly ET predicted by FruitLook ET and by the S-W model for the eight orchards monitored during the 2014/15 and 2015/16 seasons.

6.4 Conclusions

In this study we adopted, improved and applied a dual source evapotranspiration model in orchards with varying canopy cover. Model performance is satisfactory in most instances although further validation of the model with data from a range of sites is required to build confidence in the model. Model simulations of the transpiration component are most reliable, but uncertainties are higher with the orchard ET estimates given the difficulties to accurately model the orchard floor evaporation fluxes. Future studies should indeed focus on modelling orchard floor evaporation particularly quantifying water use from a range of cover crop species for which no data currently exists. Despite these uncertainties, the current model provides insights on the partitioning of water use in orchards with varying canopy covers. It appears that there is significant loss of water from the orchard floor in young orchards amounting close to 70% of the orchard ET. There is therefore a need to reduce the orchard floor losses especially given the increasing frequency of droughts which will put further strain on the already limited water resources. Actual water use by young orchards is quite low and there is room for water saving with improved irrigation scheduling and irrigation system designs in young orchards.

CHAPTER 7

FRUIT QUALITY, WATER USE EFFICIENCY AND WATER PRODUCTIVITY OF APPLE ORCHARDS

7.1 Introduction

For long-term sustainability, it is important for the fruit industry to adopt practices that increase the water efficiency and water productivity of the orchards. In this report we define the water use efficiency (WUE) of the orchards as kg of fruit produced per m^3 of water used. Increasing the WUE entails producing more or larger fruit per unit volume of water used. This goal can be achieved either by improving the genetic performance of fruit trees and horticultural practices, or by improving irrigation scheduling (Naor et al., 2008; Naschitz and Naor, 2005). Consequently, there is a growing trend in the deciduous fruit industry to grow improved high yielding apple cultivars which are often planted in high density orchards (Costa et al., 1997; Palmer, 1997; Wünsche and Lakso, 2000). This has led to significant increases in apple yields, so that yields of over 100 t ha^{-1} are now not uncommon.

However, the scientific literature and farmers' experience points out that fruit size and other fruit quality attributes can be negatively affected at very high crop loads. Competition between individual fruit for the available assimilates can lead to an unacceptably high proportion of commercially undersized fruit at harvest (Berman and De Jong, 1996; De Salvado et al., 2006; Natschitz and Naor, 2005; Naor et al., 2007; Mpelasoka, 2001). In particular, specific international markets (e.g. European Union) demand a minimum fruit size, which is set according to cultivar. The distribution of fruit size thus determines the Class 1 packout (for export) and has a strong impact on overall profitability of the harvest. Very high crop loads may also advance the maturity of the fruit (Palmer et al., 1997) which can affect marketing decisions and the long-term storability of the apples. Other quality attributes which could be influenced by high crop load in South Africa include sunburn, red colour intensity and percentage cover (in red or blushed cultivars) and total soluble solid content, an indication of the sugar concentration. The overall quality of the harvest, as indicated by the packout into different classes, determines gross income. From a commercial point of view and the economic sustainability of the South African apple industry, it is important to gain an understanding of the water productivity (WP) of high yielding apple orchards – here defined as the gross income (in Rand) obtained per m^3 of water used. This tells us where on the yield trajectory to expect optimum financial returns for every cubic meter of water used.

In this chapter we use water use data and calculations from Chapters 4, 5 and 6, together with quantification of yield, fruit quality, packout and value, to calculate both WUE and WP for the eight productive apple orchards studied. We aim to identify general patterns of WUE and WP between the two cultivars, the two production regions, and high- and intermediate-bearing orchards. Lastly, we present some key recommendations for optimising both WUE and WP.

7.2 Materials and methods

Eight orchards were used for this analysis, representing all bearing orchards studied during this project. These orchards had the medium and high canopy cover, with intermediate and high yields, respectively, and detailed descriptions are given in Chapters 4 and 5 of this report.

7.2.1 Measurements of fruit yield

In all the orchards, the strip harvesting of study trees was conducted by the research team a few days before the farm started the commercial harvest. In the case of 'Cripps' Pink', trees were strip-harvested on one day, and not on two or three days (based on developing fruit colour) as practiced commercially. This could have led to an underestimation of red colour for the laboratory sample but did not affect the calculation of WP which was based on pack house data.

The methods used to quantify the yield of individual study trees and the whole production block of the medium canopy orchards in 2017 are described below.

7.2.1.1 'Golden Delicious Reinders' (IBGR) orchard in KBV

- Trees were strip harvested on 14 March 2017;
- The six trees monitored for sap flow (see section 4.3 for details), as well as the ten trees used for eco-physiological measurements were harvested;
- Total fruit mass per tree was recorded;
- A sample of 25 apples per tree was collected at random and taken to the fruit laboratory at the Department of Horticultural Science at Stellenbosch University for the assessment of maturity and quality.

7.2.1.2 'Cripps' Pink' (IBCP) orchard in KBV

- Trees were strip harvested on 21 April 2017;
- The five trees monitored for sap flow, the tree monitored for soil water potential, and four of the other marked trees were harvested;
- Total fruit number per tree was counted (but not weighed in the orchard due to a faulty orchard balance);
- Mean fruit mass was determined in the fruit laboratory on a sample of between 50 and 100 fruits drawn at random from all areas of the canopy as a proportion of the crop;
- Total fruit mass per tree was estimated by calculation from the mean mass;
- A sample of 20 apples per tree was collected at random and taken to the fruit laboratory at the Department of Horticultural Science for the assessment of maturity and quality.

7.2.1.3 'Golden Delicious Reinders' (IBGR) in EGVV

- Trees were strip harvested on 3 March 2017;
- The three trees monitored for sap flow, and the ten trees used for eco-physiological measurements were harvested;
- Total fruit mass per tree was recorded;
- A sample of 25 apples per tree was collected at random and taken to the fruit laboratory at the Department of Horticultural Science for the assessment of maturity and quality.

7.2.1.4 'Cripps' Pink' (IBCP) orchard in EGVV

- Trees were strip harvested on 24 April 2017; commercial harvest was on 25 April 2017;
- The two trees monitored for sap flow, as well as the ten trees used for eco-physiological measurements, were harvested;
- Total fruit mass per tree was recorded;
- Since wind storm two days before harvest had resulted in fruit drop, the number of fallen fruit was counted underneath each tree and the mass of this fruit estimated using the mean fruit mass determined on the sample in the laboratory;
- This was added to the mass of fruit picked off the tree to estimate total fruit mass per tree;

- A sample of 20 apples per tree was collected at random and taken to the fruit laboratory at the Department of Horticultural Science for the assessment of maturity and quality.

The following methods were used to quantify the yield of individual study trees and the whole production block of the high canopy (full-bearing) orchards in 2015.

7.2.1.5 Full-bearing 'Golden Delicious' (FBGD) orchard in KBV

- Trees were strip harvested on 18 February 2015;
- Eleven trees were harvested including the tree monitored for soil water potential and the five trees monitored for sap flow.
- Total fruit mass per tree was recorded;
- A sample of 25 apples per tree was collected at random and taken to the fruit laboratory at the Department of Horticultural Science for the assessment of maturity and quality.

7.3.1.6 Full-bearing 'Cripps' Pink' (FBCP) orchard in KBV

- Trees were strip harvested on 24 March 2015;
- Twelve trees were harvested, including the tree monitored for soil water potential and the five trees monitored for sap flow;
- Total fruit mass per tree was recorded;
- A sample of 25 apples per tree was collected at random and taken to the fruit laboratory at the Department of Horticultural Science for the assessment of maturity and quality.

The following methods were used to quantify the yield of individual study trees and the whole production block of the high canopy (full-bearing) orchards in 2016:

7.2.1.7 Full-bearing 'Golden Delicious' (FBGD) orchard in EGVV

- Trees were strip harvested on 8 March 2016;
- Seven trees were harvested, including the tree monitored for soil water potential and three trees monitored for sap flow;
- Total fruit mass per tree was recorded;
- A sample of 20 apples per tree was collected at random and taken to the fruit laboratory at the Department of Horticultural Science for the assessment of maturity and quality.

7.2.1.8 Full-bearing 'Cripps' Pink' (FBCP) orchard in EGVV

- Trees were strip harvested on 11 April 2016;
- Seven trees were harvested, including the tree monitored for soil water potential and six trees monitored for sap flow;
- Total fruit mass per tree was recorded;
- No sample was taken for laboratory analysis since permission was not granted by the farm management.

In all cases, the production block yield (t ha^{-1}) was provided by the farm management, as well as the percentage orchard cull (fruit delivered directly to the juice factory).

7.2.2 Fruit quality assessment

A detailed maturity and quality assessment was performed on the fruit sample using standard procedures in the Fruit Laboratory at the Department of Horticultural Science at Stellenbosch University. Parameters measured in the laboratory included:

- Fruit size (equatorial diameter);
- Fruit mass;
- Fruit firmness, determined on opposite equatorial cheeks by means of a penetrometer (Fruit texture Analyzer, Guss Instruments, Strand, South Africa) with an 11-mm plunger;
- Percentage foreground red colour (for 'Cripps' Pink'/'Rosy Glow'/'Cripps' Red'), using the industry colour chart for Pink Lady®);
- Red colour intensity (for 'Cripps' Pink'/'Rosy Glow'/'Cripps' Red'), using the industry colour chart for Pink Lady®);
- Background (green/yellow) colour (using the industry colour chart, Unifruco Research Services, Bellville);
- Sunburn severity, using the Schrader and McFerson sunburn colour chart for 'Fuji' apples;
- Starch conversion, using the iodine test with a starch conversion chart (Unifruco Research Services, Bellville), and;
- Total soluble solids (TSS): a composite juice sample was prepared from all pooled fruit by cutting a slice on both sides of each fruit from both eastern and western sides of the row and blending the pieces in a liquidizer (AEG Electrolux, Type JE-107 no.

91100085/ PNC 950075206, P.R.C). TSS (%) was measured using a calibrated hand-held refractometer (TSS 0-32%, Model N1, Atago, Tokyo, Japan).

For all four orchards, data was obtained from the respective pack houses on grading of the apples into various classes, and the specific defects found in the fruit which had been delivered to the pack house, and which had been graded as Class 2 or 3. Class 1 is suitable for both the export and domestic markets, Class 2 is suitable for the domestic market, and Class 3 is used for juice (not suitable for fresh fruit marketing). The pack houses also supplied the size distribution of the harvest, and the prices obtained for each class. No sample grading was performed for the harvest from the FBCP EGVV orchard.

7.2.3 Calculations of gross income

Gross orchard income per hectare was estimated using farm data for yield, grading of the fruit delivered to the pack house, and orchard cull (either off the tree or off the orchard floor), together with market prices obtained for each class of apples. Pack house prices were not available for the IBCP orchard in KBV. In this case, we used the average price per class for 'Cripps' Pink' from the other three 'Cripps' Pink' orchards to arrive at an estimate of the gross value of the orchard. It should be noted that we have calculated gross values, and that these will not be exactly the same as the values shown in farm financial statements, but these are not made available by the farms.

In addition, we calculated gross value for the scenario that all producers of a specific cultivar would realise the same price for each class of apple marketed. We were interested in whether this levelling of the playing field (in the market) would provide clearer information on water productivity for each cultivar.

7.2.4 Water use efficiency and water productivity calculations

For the calculation of water use efficiency (WUE), two approaches were taken: a value based on the measured transpiration of the trees (productive water use), and a value based on the modelled orchard evapotranspiration, which is the sum of transpiration and evaporation from the orchard floor (unproductive water use). In both cases, the inputs for the calculation included the yield, seasonal water use per tree, and seasonal water use per hectare. The values used for water use per tree and for yield are the average of the trees instrumented for the measurement of sap flow. We also present the water use of production as m^3 water per ton of fruit, since this value is also sometimes presented in the literature.

The final value calculated was for water productivity (expressed on a gross value basis), which factors in the overall quality of the harvest. This was again calculated based on measured transpiration and modelled evapotranspiration, and gross values calculated from the average price per class and per cultivar from all the orchards studied. It was decided to use average prices since the 'levelling of the playing field' in the market provides values of water productivity which are comparable across the two regions and various farms.

7.3 Results and discussion

7.3.1 Yield and quality

The full-bearing 'Golden Delicious' orchards in KBV and EGVV had yields of 74.0 t ha^{-1} and 99.5 t ha^{-1}, respectively (Table 7.1). The study trees had higher yields in both cases compared to the whole block. The FBGD KBV orchard showed within-block variability in yield and fruit size (detailed data not shown) on either side of the road running through the block. The reasons for the spatial differences are not entirely clear, but possible reasons are differences in crop load or in the manifestation of the water stress which was experienced during the mid-season. In the FBGD EGVV orchard, the yield was high, with each tree carrying around 80 kg of fruit (Table 7.1). However, these trees were 29 years old with large trunks, and thus the yield efficiency was very similar to that of the FBGD KBV block.

The medium canopy 'Golden Delicious Reinders' orchards in KBV and EGVV had yields of 18.3 t ha^{-1} and 34.5 t ha^{-1}, respectively. In the IBGR EGVV orchard, the study rows had a lower yield at 22.5 t ha^{-1} compared to the whole block. This indicates that the study trees may have been slightly smaller and/or less productive than other areas of the orchard. Nevertheless, the yield efficiency of the study trees (0.565 kg cm^{-2} TCA) was good, and higher than that of the IBGR KBV orchard (0.430 kg cm^{-2} TCA).

The full-bearing 'Cripps' Pink' orchards had similar yields in the two regions (109.8 and 109.0 t ha^{-1}). However, the study rows in KBV had a lower yield (85.7 t ha^{-1}) and those in EGVV had a higher yield (125.8 t ha^{-1}) compared to the whole block. Again, this could be ascribed to differences in tree size and/or yield efficiency between the study areas and other parts of the orchards. The FBCP EGVV study trees had a particularly high crop load. Since these trees were older and had larger trunks than those of FBCP KBV, the yield efficiency was slightly lower than that of FBCP KBV.

Table 7.1 Yield per tree, yield per hectare, and trunk cross-sectional yield efficiency of bearing apple orchards used in this study. Yield (kg/tree) was measured for individual harvested trees, but calculated (calc.) for the whole production block using farm data for total commercial yield. The symbols used to describe the cultivar and production region are as defined above.

Cultivar	Study site	No. trees harvested	Yield (kg/tree)	Yield (t ha^{-1})	Trunk cross-sectional area (TCA) (cm^2)	Yield efficiency (kg/cm^2 TCA)
FBGD KBV	Study rows	11	58.2	97.0	91.91	0.633
FBGD KBV	Production block	All	44.4 (calc.)	74.0		
FBGD EGVV	Study rows	7	95.3	119.1	172.78	0.552
FBGD EGVV	Production block	All	79.6 (calc.)	99.5		
IBGR KBV	Study rows	16	13.1	21.9	30.46	0.430
IBGR KBV	Production block	All	11.0 (calc.)	18.3		
IBGR EGVV	Study rows	13	18.0	22.5	31.85	0.565
IBGR EGVV	Production block	All	27.6 (calc.)	34.5		
FBCP KBV	Study rows	12	51.4	85.7	68.90	0.746
FBCP KBV	Production block	All	65.9 (calc.)	109.8		
FBCP EGVV	Study rows	7	75.4	125.8	124.37	0.606
FBCP EGVV	Production block	All	65.4 (calc.)	109.0		
IBCP KBV	Study rows	10	62.2	69.1	58.89	1.056
IBCP KBV	Production block	All	55.0 (calc.)	61.2		
IBCP EGVV	Study rows	12	47.4	59.2	71.68	0.665
IBCP EGVV	Production block	All	46.4 (calc.)	58.0		

The 'Cripps' Pink' orchards with medium canopy cover in KBV and EGVV gave yields of 61.2 and 58.0 t ha^{-1}, respectively, with study trees having a comparable yield. Trees in the IBCP KBV orchard (even though slightly older) had smaller trunks than those of IBCP EGVV, but carried a higher crop load per tree (62.2 kg tree^{-1} compared to 47.4 kg tree^{-1}), which resulted in a very high yield efficiency of 1.056 kg cm^{-2} TCA. This may have been too high for these trees of this size; the target yield had been 55 t ha^{-1}. Across all the orchards, 'Cripps' Pink' had a higher trunk cross-sectional area-based yield efficiency (on average 0.768 kg cm^{-2} TCA) than 'Golden Delicious' (average 0.545 kg cm^{-2} TCA). Although fruit quality as assessed in the Fruit Laboratory (samples taken at harvest) was generally good across all the orchards, a few problems should be highlighted. The average fruit size and mass of full-bearing 'Golden Delicious' trees were below optimum compared to trees with medium canopy cover (Table 7.2). This is also evident in the fruit size distribution (Fig. 7.1). 'Cripps' Pink' did not show this trend. The 'Cripps' Pink' orchard with medium canopy cover in KBV had below optimum fruit size and mass, possibly due to a crop load that was too high for the age and size of the trees, as indicated by the high yield efficiency. There was also evidence of water stress in this orchard early in the season and from January to March 2017. The later stress was due to over-irrigation. In FBGD, there was a discrepancy between mean fruit diameter and fruit mass between the KBV and EGVV orchards. Although apples were much lighter in EGVV than in KBV, they were slightly larger. The reasons for this are not known but indicate possible differences in fruit density and relative water content.

Fruit maturity parameters (firmness, background colour, starch conversion, TSS) at harvest fell within the range acceptable for marketing. The apples from FBGD EGVV were more mature at harvest than is ideal. This is shown by the low firmness and high starch conversion level. TSS was lower in fruit from full-bearing trees compared to trees with medium canopy cover. The FBCP KBV harvest was marred by the poor colour development experienced in this block during the 2014-2015 season. From our harvest, 50% of the fruit had no or insufficient red colour. The value for red colour intensity was around 0.35, on a scale of 0 (no colour) to 12 (well coloured and bright red), and the percentage coverage of blush was less than 4%. For marketing as Pink Lady® it needs to be greater than 50%. The lack of red colour development was unusual since the orchard is managed to optimise the light environment and fruit were generally well exposed to sunlight. However, our harvest date was earlier than is usual for this cultivar, and the data for starch conversion (13.9%) and TSS (12.0%) suggest that fruit were not sufficiently mature. It is possible that better colour could have developed if the harvest had been conducted later. However, the commercial harvest was conducted a few days later, and the pack house data still indicate poor red colour (see Table 7.3). The best red colour was obtained in the IBCP KBV orchard. It is well known that red and blushed apple cultivars, including 'Cripps' Pink', develop better colour in KBV than in EGVV owing to the different climates of the two regions.

Table 7.2 Fruit maturity and quality as assessed in the laboratory on samples taken during the harvest in each orchard. Background colour chart values range from 0 (green) to 5 (yellow). Foreground red colour (intensity) chart values range from 1 (no red pigment) to 12 (dark red pigment). Red colour (percentage) is an estimate of the coverage of red pigmentation over the fruit. Sunburn colour chart categories (charts for yellow and blushed cultivars) range from 0 (no sunburn) to 5 (sunburn necrosis). TSS = total soluble solids concentration.

Cultivar	Diameter (mm)	Mass (g)	Firmness (kg)	Background colour (chart)	Red colour – intensity (chart)	Red colour (percentage) - chart	Sunburn severity (chart)	Starch conversion (%)	TSS (%)
FBGD KBV	58.8	151.5	7.80	3.0	-	-	0.80	28.8	13.2
FBGD EGVV	64.3	112.0	7.65	2.9	-	-	0.91	72.8	12.4
IBGR KBV	74.6	161.8	6.89	2.9	-	-	1.19	52.3	16.0
IBGR EGVV	75.2	172.4	6.87	3.5	-	-	1.52	67.3	16.7
FBCP KBV	72.4	169.2	8.71	2.9	0.35	3.8	0.16	13.9	12.0
FBCP EGVV	-	-	8.34*	-	-	-	-	-	14.9*
IBCP KBV	68.4	114.8	8.89	2.3	8.9	63.3	0.49	38.3	15.4
IBCP EGVV	74.7	162.1	7.62	2.4	4.3	32.1	0.13	66.6	13.4

*Data provided by the pack house

More 'Golden Delicious'/'Golden Delicious Reinders' apples were scored for higher levels of sunburn severity than 'Cripps' Pink' (averages of 1.1 and 0.3, respectively, on the sunburn chart, see also Table 7.3). The younger 'Golden Delicious Reinders' with medium canopy size were most susceptible to sunburn. This reflects common trends across the industry. Sunburn is also less visible on red and blushed apple cultivars since the red pigment anthocyanin masks the discolouration of the peel to a large degree. The differences in sunburn assessment performed by the researchers (Table 7.2) and by the pack house (Table 7.3) can be ascribed to the smaller sample used by the researchers, taken from all the fruit on the tree, compared to a larger sample in the pack house, but where more seriously sunburnt fruit have already been culled in the orchard.

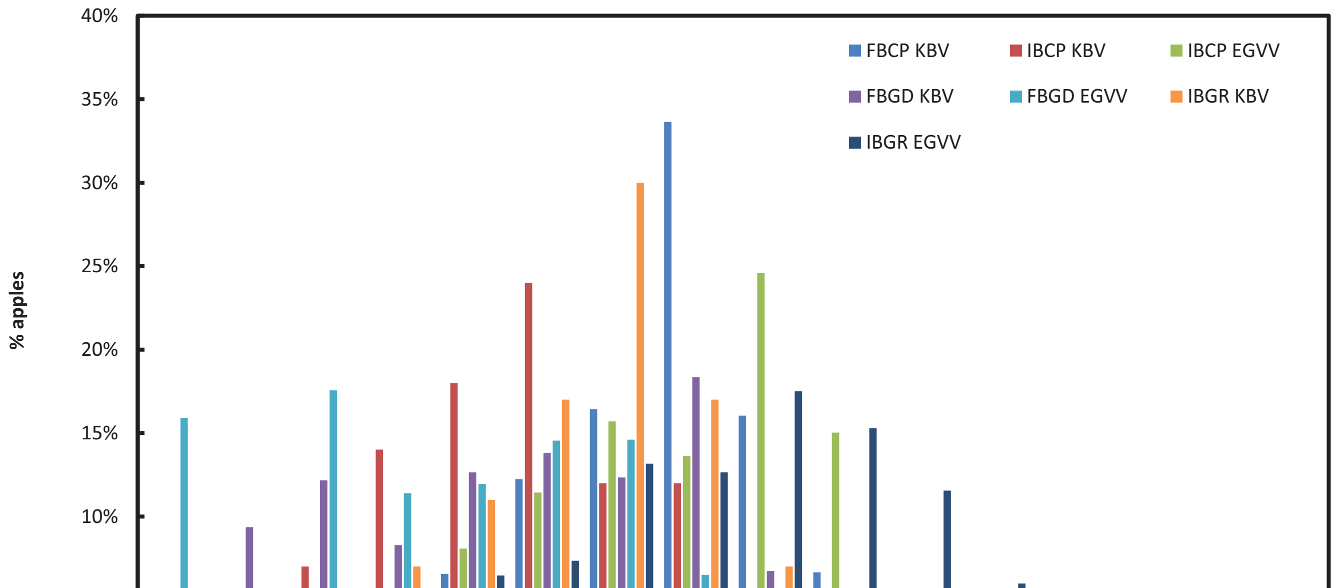


Fig. 7.1 Fruit size distribution of fruit delivered to the pack house. Data not available for FBCP EGVV.

Apart from sunburn, the most prevalent quality defect in 'Golden Delicious'/'Golden Delicious Reinders' was bruising (Table 7.3). This is a common problem in this cultivar. The young IBGR KBV orchards was particularly susceptible. Other defects included stem-end russeting (FBGD KBV), weevil damage (FBGD KBV), bollworm damage (IBGR KBV) and pink blush (both orchards in KBV). In addition to sunburn and poor colour (FBCP KBV) in 'Cripps' Pink', other quality defects (Table 7.3) included injuries, bruising, weevil and bollworm damage (KBV), woolly aphid (IBCP EGVV) and hammering (FBCP KBV)-a distinct ridging of the fruit surface which is a common defect in this cultivar.

Table 7.3 Main defects (≥2%) of fruit assessed in each pack house and leading to grading as Class 2 or 3. Value expressed as a percentage of all fruit delivered to the pack house. This does not include fruit culled in the orchard and juiced.

Defects*	FBGD KBV	%	FBGD EGVV	%	IBGR KBV	%	IBGR EGVV	%	FBCP KBV	%	FBCP EGVV	%	IBCP KBV	%	IBCP EGVV	%
1	Stem-end russeting	18.8	Sunburn	5.0	Sunburn	36	Scald	3	Poor colour	43.8	Injuries	6.3	Injuries - cracks	9	Sunburn	6
2	Sunburn	15.8	Bruise	4.2	Large bruise	15	Injuries	2	Sunburn	12.8	Sunburn	3.5	Large bruise	5	Woolly aphid	2
3	Weevil damage	10.1			Bollworm damage	5	Sunburn	2	Weevil damage	12.7	Bruising/ handling	2.2	Injuries dry	5	Leaves	2
4	Large bruise	4.3			Pink blush	5	Overripe	2	Fusi/Septoria	6.6			Sunburn	4	Colour	2
5	Small bruise	4.2			Small bruise	4			No colour	6.5			Weevil damage	4		
6	Misshapen	4.0			Wind marks	4			Large bruise	4.9			Minimum colour	2		
7	Fusi/Septoria	2.2			Weevil damage	3			Hammered	3.5						
8	Pink blush	2.0			% Colour	3			Stem out	2.8						
9					% Weak colour	3			Bollworm damage	2.0						
10					Old bruise	2			Old bruise	2.0						
11					Stem out	2			Small bruise	2.0						
12					Stem injury	2										
13					Stem-end russeting	2										

*Listed in descending order of incidence

Table 7.4 Packout and estimated gross value of each apple harvest. Values shown up to the third-last column are for fruit delivered to the pack house. The second-last column shows the percentage of the total harvest culled in the orchard (either off the tree or off the orchard floor) and sent directly to the juice factory. This is added to the Class 3 analysis for the calculation of total yield and gross value per hectare. Prices were supplied by the pack houses for each class. Commercial yields are used for these calculations.

Cultivar		**Class 1***	**Class 1****	**Class 1*****	**Class 1**	**Class 2**	**Class 3#**	**Sent to pack house**	**Not sent to pack house (orchard cull)#**	**Total yield and gross value (Rand) per ha**
FBGD KBV	Percentage	30.9	33.9	18.9	-	1.7	14.6	93.8%	6.2%	
	Yield (t ha^{-1})	21.5	23.5	13.1	-	1.2	10.1	69.4 t ha^{-1}	4.6 t ha^{-1}	74.0 t ha^{-1}
	Price (R/t)	9410	7177	5982	-	3712	1017		1017	
	Value (R ha^{-1})	202 127	168 875	78 484	-	4380	10 302		4 668	**R468 836**
FBGD EGVV	Percentage	-	-	-	35.9	59.7	4.4	93.8%	6.2%	
	Yield (t ha^{-1})	-	-	-	33.5	55.7	4.1	93.3 t ha^{-1}	6.2 t ha^{-1}	99.5 t ha^{-1}
	Price (R/t)	-	-	-	4882	1667	828		828	
	Value (R ha^{-1})	-	-	-	163 596	92 885	3 395		5 109	**R264 985**
IBGR KBV	Percentage	0	28	0	-	60	12	60%	40%	
	Yield (t ha^{-1})	0	3.1	0	-	6.6	1.3	11.0 t ha^{-1}	7.3 t ha^{-1}	18.3 t ha^{-1}
	Price (R/t)	-	8100	-	-	6279	1200		1200	
	Value (R ha^{-1})	-	24 867	-	-	41 253	1 584		8 772	**R76 476**
IBGR EGVV	Percentage	-	-	-	69.9	19.8	10.3	64.6%	35.4%	
	Yield (t ha^{-1})	-	-	-	15.6	4.4	2.3	22.3 t ha^{-1}	12.2 t ha^{-1}	34.5 t ha^{-1}
	Price (R/t)	-	-	-	2862	933	-717		1400	
	Value (R ha^{-1})	-	-	-	44 647	41 05	-1 649		17 080	**R64 183**

FBCP KBV	Percentage	9.0	31.5	26.7	-	4.6	28.2	89.9%	10.1%	
	Yield (t ha^{-1})	8.9	31.1	26.4	-	4.5	27.8	98.7 t ha^{-1}	11.1 t ha^{-1}	109.8 t ha^{-1}
	Price (R/t)	10 515	8 297	6 042	-	3 365	951		951	
	Value (R ha^{-1})	93 373	257 954	159 267	-	15 277	26 476		10 547	**R562 894**
FBCP EGVV	Percentage	-	-	-	60.9	29.1	10.0	71.8%	28.2%	
	Yield (t ha^{-1})	-	-	-	47.7	22.8	7.8	78.3 t ha^{-1}	30.7 t ha^{-1}	109.0 t ha^{-1}
	Price (R/t)	-	-	-	8184.70	2393.72	182.48		182.48	
	Value (R ha^{-1})	-	-	-	390 328	54 553	1 429		5 608	**R451 918**
IBCP KBV	Percentage	-	-	-	88.7	6.3	5.0	79%	21%	
	Yield (t ha^{-1})	-	-	-	42.9	3.0	2.4	48.3 t ha^{-1}	12.9 t ha^{-1}	61.2 t ha^{-1}
	Price (R/t)	-	-	-	8 139§	3 028§	794§		794§	
	Value (R ha^{-1})	-	-	-	349 163	9 084	1 906		10 243	**R370 396**
IBCP EGVV	Percentage	-	-	-	84.8	11.2	4.0	72%	28%##	
	Yield (t ha^{-1})	-	-	-	35.4	4.7	1.7	41.8	16.2	58 t ha^{-1}
	Price (R/t)	-	-	-	7 934	3 325	1 250		1 250	
	Value (R ha^{-1})	-	-	-	280 943	15 561	2 087		20 300	**R318 891**

**EU Class 1 export (blue)*

***EU Class 1 export and SA premium (green)*

****SA Class 1*

#Juice

§Pack house QC data collected during 18 packing runs. Only the 9 runs using only fruit from Block B6 (673 bins) were used for the analysis presented here. Other packing runs were mixed consignments of Blocks B6, B2 and B12 (314 bins). The data presented are the means of the results of the 9 runs.

9.5% of this was windfall

§ Prices not available for this orchard. Average prices for each class calculated from the other three CP orchards.

The packouts for the eight harvests were as follows (Table 7.4):

FBGD KBV: Class 1 (export) packout percentage for the whole block was 64.8%, and the Class 1 (South Africa) packout was 18.9%. 14.6% of fruit (sorted in the pack house) was marketed for juice (Class 3). The remainder (1.7%) was marketed as Class 2 in South Africa. The orchard cull which was sent directly for juicing, was 6.2%.

FBGD EGVV: 35.9% of the harvest was sold as Class 1 (export), 59.7% as Class 2 (local), and 4.4% as Class 3 (juice, graded in the pack house). An additional 6.2% was culled in the orchard and sent directly to the juice factory (Table 7.4). Thus, the high crop load affected fruit size but had no other deleterious impacts on fruit quality.

IBGR KBV: Class 1** packout of 28% was sold on the South African market, with a further 60% sold locally as Class 2, and 12% as Class 3. The orchard cull was 40%. The main problems were bruising and sunburn.

IBGR EGVV: The packout breakdown for this orchard was 69.9% (Class 1), 19.8% (Class 2) and 10.3% (Class 3). The orchard cull was 35.4%. The fruit delivered to the pack house had good size and good background (green/yellow) colour, with very few defects.

FBCP KBV: The poor Class 1* (export as Pink Lady®) packout of 9% was largely attributable to the colour problem: 40.5% of the fruit was suitable for the EU market, with 26.7% South African Class 1, 4.6% SA Class 2, and 28.2% Class 3 (juice, graded in the pack house). The orchard cull sent directly for juicing was 10.1%.

FBCP EGVV: Fruit quality was good, although the orchard cull was high. The reasons for this are not known. The Class 1 packout was 60.9%. The biggest problem was injuries (Class 3 defect), followed by sunburn (the biggest reason for sorting into Class 2). The three different grades of Class 2 yielded a total Class 2 packout of 29.1%, while 10.0% of the harvest (graded in the pack house) was juiced. The percentage of fruit culled in the orchard as Class 3 (sent directly to the juice factory) was 28%.

IBCP KBV: Although fruit tended to be on the smaller side, and there was a high incidence of cracks, fruit quality was high and the Class 1 packout was very good at 88.7%. The remaining fruit was sold as Class 2 (6.3%) and Class 3 (5.0). The orchard cull was 21%.

IBCP EGVV: A wind storm a few days before the start of the harvest unfortunately blew many fruit off the trees, as reflected in the orchard cull rate of 28% of which 9.5% was ascribed to windfall. Nevertheless, the remaining fruit were of high quality and a Class 1 packout of 84.8% was achieved. Class 2 and Class 3 were 11.2% and 4.0%, respectively.

Overall across all eight orchards, there was no indication of defects possibly relating to water stress, except possibly for FBGD KBV and IBGR KBV (see Chapters 4 and 5). Both FBGD orchards had small mean fruit size and a size class distribution skewed towards the middle to lower end. While small fruit size is a wide-spread problem in South African apple orchards, Golden Delicious is one of the more susceptible cultivars. The problem in these two orchards was likely exacerbated by the heavy crop loads. However, crop loads were not as high in KBV as in EGVV and there was a likely influence of a period of water stress in mid-season in this orchard which lowered the fruit growth rate. There was a high orchard cull rate in IBGR KBV owing to sunburn and bruising. The stored apples also developed further bruising which, together with smaller sunburn marks on many apples resulted in fruit from this orchard not being packed for export to African markets (Class 1*).

The levels of sunburn damage in all eight orchards were typical of those seen across the industry. Sunburn is a major factor in reducing Class 1 packout and income from apple orchards in South Africa. Water deficits and resulting physiological stress in apples increase the risk of sunburn development in 'Cripps' Pink' apples (Makeredza et al., 2013), but damage also occurs in well-watered orchards. Sunburn is a greater problem in 'Golden Delicious' than in 'Cripps' Pink' in South Africa (although 'Golden Delicious is less sensitive than 'Granny Smith'). Red or blushed apple cultivars are less likely to show sunburn symptoms due to the masking effect of the red anthocyanin pigmentation.

Bruising during harvesting, sorting and packaging processes is also responsible for a high proportion of fruit not being suitable for the export market. Larger fruit are generally more sensitive to bruising, and Golden Delicious is a sensitive cultivar. Both under- and over-irrigated apple orchards develop fruit which is less firm and more prone to bruising, compared to orchards which receive optimal irrigation. Fruit which are more mature and have a lower firmness bruise more easily. In this study, bruising across all eight orchards (except IBGR KBV) was between 2.2 and 8.5% (of fruit delivered to the pack house). This is within the normal range and does not indicate any impact of high crop loads or water deficit/excess. This was the case even in FBGD EGVV, where high crop load resulted in a more rapid rate of ripening as indicated by more advanced starch conversion rate in high crop load versus medium crop load treatments (data gathered from a separate trial in adjacent rows of the same orchard; not shown in this report). For the IBGR KBV harvest, bruising was around 21%, of which 15% were large bruises. At harvest, fruit had an average firmness of 6.89 kg which is on the lower side of the acceptable range. However, similar low firmness (6.87kg) was measured for the IBGR EGVV orchard, which did not show any significant bruising (at least not in the pack house quality control results). This suggests that other factors were also at play, possibly relating to water stress.

Calculations of the estimated gross value of each harvest are also presented in Table 7.5. The figures should, however, be viewed with caution and are only seen as indicative. Prices and marketing decisions are influenced by many factors, some of which are market- and management-related and not to the quality of the crop. It should also be remembered that apples are routinely cold stored until they are packed, and the fruit quality can change significantly during the period in storage. For instance, the initial quality control on fruit from the IBGR KBV orchard indicated a 50% Class 1** packout, and 39% Class 1** packout. The final figures were 28% and 0%, respectively, as a result of the further development of bruising during cold storage. Another factor in pricing is the contracts negotiated between specific producers and buyers.

Nevertheless, one generalised observation can be made from our results (although this is well known by the industry!). Cripps' Pink is a more lucrative cultivar than Golden Delicious Reinders. Apart from the fruit size consideration in 'Golden Delicious', export-quality 'Cripps' Pink' (Pink Lady®) fetches a high price.

Table 7.5 Packout and estimated gross value of each apple harvest based on average prices per class for 'Golden Delicious'/'Golden Delicious Reinders' and 'Cripps' Pink' orchards used in this study. Commercial yields are used for these calculations.

Cultivar		**Class 1***	**Class 1****	**Class 1*****	**Class 1**	**Class 2**	**Class 3**	**Sent to pack house**	**Not sent to pack house (orchard cull)**	**Total yield and gross value (Rand) per ha**
FBGD KBV	Percentage	30.9	33.9	18.9	-	1.7	14.6	93.8%	6.2%	
	Yield (t ha^{-1})	21.5	23.5	13.1	-	1.2	10.1	69.4 t ha^{-1}	4.6 t ha^{-1}	74.0 t ha^{-1}
	Price (R/t)	6 000	6 000	6 000	-	3 000	1 000		1 000	
	Value (R ha^{-1})	129 000	141 000	78 600	-	3 600	10 100		4 600	**R366 900**
FBGD EGVV	Percentage	-	-	-	35.9	59.7	4.4	93.8%	6.2%	
	Yield (t ha^{-1})	-	-	-	33.5	55.7	4.1	93.3 t ha^{-1}	6.2 t ha^{-1}	99.5 t ha^{-1}
	Price (R/t)	-	-	-	6 000	3 000	1 000		1 000	
	Value (R ha^{-1})	-	-	-	201 000	167 100	4 100		6 200	**R378 400**
IBGR KBV	Percentage	0	28	0	-	60	12	60%	40%	
	Yield (t ha^{-1})	0	3.1	0	-	6.6	1.3	11.0 t ha^{-1}	7.3 t ha^{-1}	18.3 t ha^{-1}
	Price (R/t)	-	6 000	-	-	3 000	1 000		1 000	
	Value (R ha^{-1})	-	18 600	-	-	19 800	1 300		7 300	**R47 000**
IBGR EGVV	Percentage	-	-	-	69.9	19.8	10.3	64.6%	35.4%	
	Yield (t ha^{-1})	-	-	-	15.6	4.4	2.3	22.3 t ha^{-1}	12.2 t ha^{-1}	34.5 t ha^{-1}
	Price (R/t)	-	-	-	6 000	3 000	1 000		1 000	
	Value (R ha^{-1})	-	-	-	93 600	13 200	2 300		12 200	**R121 300**
FBCP KBV	Percentage	9.0	31.5	26.7	-	4.6	28.2	89.9%	10.1%	

	Yield (t ha^{-1})	8.9	31.1	26.4	-	4.5	27.8	98.7 t ha^{-1}	11.1 t ha^{-1}	109.8 t ha^{-1}
	Price (R/t)	8 000	8 000	8 000	-	3 000	800		800	
	Value (R ha^{-1})	71 200	248 800	211 200	-	13 500	22 240		8 880	**R575 820**
FBCP EGVV	Percentage	-	-	-	60.9	29.1	10.0	71.8%	28.2%	
	Yield (t ha^{-1})	-	-	-	47.7	22.8	7.8	78.3 t ha^{-1}	30.7 t ha^{-1}	109.0 t ha^{-1}
	Price (R/t)	-	-	-	8 000	3 000	800		800	
	Value (R ha^{-1})	-	-	-	381 600	68 400	6 240		24 560	**R480 800**
IBCP KBV	Percentage	-	-	-	88.7	6.3	5.0	79%	21%	
	Yield (t ha^{-1})	-	-	-	42.9	3.0	2.4	48.3 t ha^{-1}	12.9 t ha^{-1}	61.2 t ha^{-1}
	Price (R/t)	-	-	-	8 000	3 000	800		800	
	Value (R ha^{-1})	-	-	-	343 200	9 000	1920		10,320	**R364,440**
IBCP EGVV	Percentage	-	-	-	84.8	11.2	4.0	72%	28%	
	Yield (t ha^{-1})	-	-	-	35.4	4.7	1.7	41.8	16.2	58 t ha^{-1}
	Price (R/t)	-	-	-	8 000	3 000	800		800	
	Value (R ha^{-1})	-	-	-	283 200	14 100	1 360		12 960	**R311 620**

Table 7.6 Water use efficiency of the eight bearing orchards used in this study. Two cultivars ('Golden Delicious'/'Golden Delicious Reinders' and 'Cripps' Pink') were studied in two production regions (KBV and EGVV). Four orchards had medium canopy cover (intermediate-bearing) and four orchards had high canopy cover (full-bearing).

	FBGD KBV	FBGD EGVV	IBGR KBV	IBGR EGVV	FBCP KBV	FBCP EGVV	IBCP KBV	IBCP EGVV
Yield (kg/tree) of study trees	50.92	110.41	9.55	8.66	52.95	84.35	63.95	42.72
Yield (t ha^{-1}) of study trees	84.90	138.00	15.91	10.83	88.30	140.60	71.05	53.40
Planting density (trees ha^{-1})	1 667	1 250	1 667	1 250	1 667	1 667	1 111	1 250
MEASURED TRANSPIRATION:								
Seasonal water use per tree (L/tree)	4 721	6 128	2 228	1 991	3 725	3 929	6 133	3 765
Seasonal water use per hectare (m^3 ha^{-1})	7 870	7 660	3 714	2 489	6 210	6 550	6 814	4 706
Water use (m^3 ton^{-1})	92.7	55.5	233.4	229.8	70.3	46.6	95.9	88.1
Water Use Efficiency (kg m^{-3})	10.8	18.0	4.3	4.4	14.2	21.5	10.4	11.3
MODELLED ET								
Seasonal water use per tree (L $tree^{-1}$)	5 765	8 152	3 593	4 300	5 843	5 855	7 881	7 012
Seasonal water use per hectare (m^3 ha^{-1})	9 610	10 190	5 990	5 375	9 740	9 760	8 756	8 765
Water use (m^3 ton^{-1})	113.2	73.8	376.5	496.3	110.3	69.4	123.2	164.1
Water Use Efficiency (kg m^{-3})	8.8	13.5	2.7	2.0	9.1	14.4	8.1	6.1

Table 7.6 presents the water use efficiency for the eight orchards used in the study, for the two cultivars in two production regions, and representing both full-bearing and intermediate-bearing orchards. We discuss the results calculated using measured transpiration values, as well as those provided through modelling of both transpiration and evaporation.

As discussed in Chapter 4 of this report, seasonal water use per hectare (transpiration-based) of full-bearing trees was higher in the 'Golden Delicious' orchards compared to the 'Cripps' Pink' orchards. The reasons for this related mainly to the larger canopy (total leaf area) of 'Golden Delicious' trees. In South Africa, vegetative growth of 'Cripps' Pink' trees is actively managed through pruning the application of the growth regulator Regalis®. This lowers the whole-tree water use compared to 'Golden Delicious' under the same environmental conditions and sufficient water supply. There was little difference between the regions (KBV and EGVV) for each cultivar. Higher values of water use per tree in FBGD EGVV than in FBGD KBV were levelled once the lower planting density in EGVV was factored in to give water use per hectare.

The water use efficiency of full-bearing 'Cripps' Pink' orchards was higher than that of the full-bearing 'Golden Delicious' orchards (Table 7.6). This result related to the lower seasonal water use of 'Cripps' Pink' compared to 'Golden Delicious' rather than to differences in yield. For both cultivars, WUE was higher in EGVV than in KBV. The reason was the higher tonnage on the trees in EGVV.

It is not possible to compare all four intermediate-bearing orchards, since they had very different canopy sizes, seasonal water uses and yield. However, comparisons are possible within cultivar. The two IBGR orchards, planted in 2011 and 2013, had yields of less than 16 t ha^{-1} (for study trees; expected yields for the orchards were 30-50 t ha^{-1}). Seasonal water use per hectare was higher in KBV (3 714 m^3 ha^{-1}) than in EGVV (2 489 m^3 ha^{-1}), but yield was also higher, so that WUE was very similar between the orchards (4.3 and 4.4 kg m^{-3}, respectively). The two IBCP orchards, planted in 2009 and 2011, had an expected yield of 40-55 t ha^{-1}. In both orchards, actual yields were higher. Seasonal water use was substantially higher in IBCP KBV than in IBCP EGVV, but the higher yield resulted in only a small reduction in WUE in IBCP KBV (10.4 kg m^{-3}) compared to IBCP EGVV (11.3 kg m^{-3}).

These outcomes are somewhat altered when the calculation is made on the evapotranspiration of the whole area (trees and orchard floor) (Table 7.7). Seasonal water use per hectare was similar across all four full-bearing orchards, although slightly higher in FBGD EGVV and slightly lower in FBGD KBV. Water use efficiency was again higher in EGVV than in KBV in both cultivars. However, differences between the two cultivars all but disappeared, with ‘Cripps’ Pink’ remaining marginally higher than ‘Golden Delicious’. This was because the evaporation component (orchard floor) of evapotranspiration was higher in ‘Cripps’ Pink’ than in ‘Golden Delicious’ (see Chapter 6), and factoring in this water use (unproductive use) component resulted in a steeper decline in the total WUE figure for ‘Cripps’ Pink’ than for ‘Golden Delicious’.

In the intermediate-bearing orchards, the difference in seasonal water use per hectare on a modelled ET basis between IBGR KBV (5 990 m^3 ha^{-1}) and IBGR EGVV (5 375 m^3 ha^{-1}) became smaller, resulting in a higher WUE in the KBV orchard because of the higher yield in KBV. For IBCP, the large difference in seasonal water use between the KBV and EGVV disappeared (8 756 and 8 765 m^3 ha^{-1}, respectively), so that WUE on an ET basis was higher in the KBV orchard (8.1 kg m^{-3}) compared to EGVV (6.1 kg m^{-3}). Thus, the calculations suggest that intermediate-bearing (lower canopy cover) orchards had a slightly better WUE in the KBV region than in EGVV.

A recent study by Gush et al. (in review) on ‘Cripps’ Pink’ orchards in the Koue Bokkeveld region of South Africa showed actual annual evapotranspiration rates of 952 and 966 mm for the 2008/2009 and 2009/2010 periods. The corresponding yields were 54 and 69 t ha^{-1}, respectively. The WUE for each of the growing periods were therefore 5.67 and 7.14 kilograms of fruit produced per cubic meter of water evapotranspired in 2008/2009 and 2009/2010, respectively. Average WUE for the two years was 6.40 kg m^{-3}. The evapotranspiration information includes data collected during the winter dormant period and therefore the WUE could be even higher if water use is considered only for the apple growing period in South Africa (September to May). The average WUE for the ‘Cripps’ Pink’ apples in South Africa is much higher than the value of 2.58 kg m^{-3} observed for apple orchards in California (Renault and Wallender, 2000). In the California study, annual evapotranspiration was about 1 037 mm while average yield was only 26.8 t ha^{-1}. The WUE of apple at both sites was significantly higher than that of other deciduous fruit e.g. peach which ranged from 0.44 to 0.80 kg m^{-3} in Tunisia (Ghrab et al., 2013).

Table 7.7 Water productivity of the eight bearing orchards used in this study. Two cultivars ('Golden Delicious'/'Golden Delicious Reinders' and 'Cripps' Pink') were studied in two production regions (KBV and EGVV). Four orchards had medium canopy cover (intermediate-bearing) and four orchards had high canopy cover (full-bearing). Calculations were based on average prices per class calculated across each cultivar group, and on measured transpiration and modelled evapotranspiration. Gross values were obtained as described above.

	FBGD KBV	FBGD EGVV	IBGR KBV	IBGR EGVV	FBCP KBV	FBCP EGVV	IBCP KBV	IBCP EGVV
Commercial yield (t ha^{-1})	74.0	99.5	18.3	34.5	109.8	109.0	61.2	58.0
MEASURED TRANSPIRATION:								
Seasonal water use per hectare (m^3 ha^{-1})	7 870	7 660	3 714	2 489	6 210	6 550	6 814	4 706
Orchard gross income (R ha^{-1})	366 900	378 400	47 000	121 300	575 820	480 800	364 440	311 620
Water productivity (R m^{-3})	46.6	49.4	20.7	48.7	92.7	73.4	53.5	66.2
MODELLED ET								
Seasonal water use per hectare (m^3 ha^{-1})	9 610	10 190	5 990	5 375	9 740	9 760	8 756	8 765
Orchard gross income (R ha^{-1})	366 900	378 400	47 000	121 300	575 820	480 800	364 440	311 620
Water productivity (R m^{-3})	38.2	37.1	7.8	22.6	59.1	49.3	41.6	35.6

In all orchards, the ET-based calculation of water productivity was lower than the transpiration-based calculation. This is explained by the inclusion of evaporative water losses in the seasonal water use figure. As discussed in earlier sections of this report, the evaporation component of water use was higher in 'Cripps' Pink' and the transpiration component was lower due to the smaller canopy size of this cultivar compared to 'Golden Delicious'. For the four high canopies cover full-bearing orchards, 'Cripps' Pink' had a higher water productivity than 'Golden Delicious' in both regions (Table 7.8). In the Koue Bokkeveld region, full-bearing 'Cripps' Pink' had a water productivity of 92.7 R m^{-3} (transpiration-based) and 59.1 R m^{-3} (evapotranspiration-based), whereas these figures for 'Golden Delicious' were 46.6 R m^{-3} and 38.2 R m^{-3}, respectively. In the EGVV region, transpiration- and ET-based water productivity for 'Cripps' Pink' was 73.4 R m^{-3} and 49.3 R m^{-3}, whereas the values for 'Golden Delicious' were 49.4 R m^{-3} and 37.1 R m^{-3}, respectively. The primary reason for this is that export-quality 'Cripps' Pink' (Pink Lady®) fetches a higher price than export-quality 'Golden Delicious' and this has a significant influence on orchard gross value. A secondary reason was that the two full-bearing 'Golden Delicious' orchards produced a high proportion of small fruit, which are not suitable for the export market and thus have a lower value. When all water uses were accounted for (ET-based calculation), there was little difference in the water productivity of high canopy cover 'Golden Delicious' orchards in KBV (Kromfontein, 38.2 R m^{-3}) and EGVV (Southfield, 37.1 R m^{-3}). Although seasonal water use in EGVV was higher, so was the orchard gross income. In 'Cripps' Pink', the water productivity of the KBV orchard (Kromfontein, 59.1 R m^{-3}) was slightly higher than that of the EGVV orchard (Radyn, 49.3 R m^{-3}). Since the seasonal water use per hectare of these two orchards were almost identical, and we have standardised the prices for each class of fruit, this outcome must be linked to the differential pack out figures which indicate differences in fruit quality. The EGVV orchard had a higher orchard cull rate of 28.2% (in KBV it was 10.1%) which explains most of the difference in gross value.

The medium canopy covers intermediate-bearing 'Golden Delicious Reinders' orchard in EGVV (Vyeboom), with a commercial yield of 34.5 t ha^{-1}, achieved a similar water productivity based on transpiration (48.7 R m^{-3}) as the two high canopy covers 'Golden Delicious' orchards (46.6 and 49.4 R m^{-3}). However, since the evaporation component of total seasonal water loss was higher than in the high canopy cover orchards, ET-based water productivity was lower (22.6 R m^{-3} compared to 38.2 and 37.1 R m^{-3}). The medium canopy cover 'Golden Delicious Reinders' orchard in KBV (Lindeshof), with a commercial yield of 18.3 t ha^{-1}, had a significantly lower water productivity (7.8 R m^{-3} based on ET) than the other 'Golden Delicious' orchards. This can be ascribed to a lower than expected gross value linked to high levels of sunburn and bruising, together with a slightly higher seasonal water use relative to the age and productivity of the orchard. The water productivity of the two medium canopy covers ‘Cripps’ Pink’ orchards in KBV (Esperanto) and EGVV (Dennebos) was slightly higher in EGVV (66.2 R m^{-3}) than in KBV (53.5 R m^{-3}) when expressed on a transpiration basis owing to the lower seasonal water use in the EGVV orchard. However, when expressed on an ET basis, seasonal water use was almost identical and the lower gross value of the EGVV orchard (which had a slightly lower Class 1 packout) led to a slightly lower water productivity in this orchard compared to the KBV orchard.

7.4 Conclusions

This study on water use efficiency (WUE) and water productivity (WP) was conducted on eight well-watered orchards which are either already high-yielding or are expected to be high-yielding when they are in full production, for two cultivars (‘Golden Delicious’/’Golden Delicious Reinders’ and ‘Cripps’ Pink’) and for two regions (KBV and EGVV). This provided us with a range of yields and seasonal water uses from which to calculate the WUE and the water productivity. The WUE (based on measured transpiration) of full-bearing orchards was higher in ‘Cripps’ Pink’ than in ‘Golden Delicious’ in both regions. This was not related to yield, but reflects the lower seasonal water use of ‘Cripps’ Pink’ trees, which are managed to have a smaller canopy leaf area to optimise red colour development. However, when evaporation is added to transpiration (modelled), these differences in WUE were almost eliminated, since evaporative water loss from the orchard floor is higher in ‘Cripps’ Pink’ orchards.

The WUE of both cultivars (transpiration of full-bearing orchards) was higher in the EGVV region compared to the KBV region, due to the higher yields obtained in EGVV. The same result was obtained when the data were modelled based on evapotranspiration. However, we would not expect this result to always hold true since high yields are achieved in both regions. In fact, only small differences in WUE were found between the two regions for intermediate-bearing orchards (transpiration-based), and ET-based values were higher for KBV than for EGVV. Overall, across all eight orchards, a clear trend was discernible for greater WUE under higher yields. This provides clear support for continued efforts to introduce superior genetic material, combined with best practice crop management to achieve the best possible yields. This study also investigated the water productivity of apple orchards in South Africa. Very high yields may negatively affect fruit quality and the value of the harvest and would then be counter-productive to the goal of profitable farming for every unit of water used. From this perspective, ‘Cripps’ Pink’ clearly has a higher water productivity. Two reasons were identified for this result: first, export quality ‘Cripps’ Pink’ (and especially when marketed as Pink Lady®) achieves a much better price per ton in the market than export quality ‘Golden Delicious’;

second, at very high yields, 'Golden Delicious' fruit size is negatively affected, thus reducing the Class 1 packout and value of the crop. It is likely that optimum water productivity for 'Golden Delicious' is reached at relatively high yield (our results suggest between 75 and 100 t ha^{-1}) but that with further increases in yield this cultivar will experience stable or even declining water productivity due to small fruit size. Interestingly, the water productivity of an orchard yielding only 34.5 t ha^{-1} was similar to those of the high yielding orchards when expressed on a transpiration basis, indicating that evaporative losses in younger orchards are responsible for lower water productivity. This suggests opportunities for reducing evaporative losses in younger orchards to maximise water productivity.

Compared to efforts to increase yield, much less attention has been given to practices which could increase the beneficial use of water (transpiration) against the non-beneficial losses (evaporation, leaching). One approach would be to enhance the effective use of rainfall, of the water stored in the soil, and of the marginal quality water (use the available water resources more efficiently). This study investigated the relationships between marketable yield and both the transpiration and evaporative components of orchard water use in high-yielding apple orchards. The information can potentially be used to develop and guide the uptake of horticultural and irrigation technologies and practices (e.g. use of water-productive cultivars, improved irrigation scheduling, or mulching) with the potential to increase water productivity of apple orchards in South Africa.

Molden et al. (2010) stated the following: "Priority areas where substantive increases in water productivity are possible include: (i) areas where poverty is high and water productivity is low, (ii) areas of physical water scarcity where competition for water is high, (iii) areas with little water resources development where high returns from a little extra water use can make a big difference, and (iv) areas of water-driven ecosystem degradation, such as falling groundwater tables, and river desiccation. However, achieving these gains will be challenging at least, and will require strategies that consider complex biophysical and socioeconomic factors." A number of these situations apply to the South African apple production environment, and thus efforts to increase water productivity could provide a pathway towards continued competitive production under conditions of increasingly unreliable water supply and increasing water scarcity over the longer term.

CHAPTER 8

SUMMARY OF KEY FINDINGS

8.1 Drivers of leaf level water use and productivity

This section summarizes the leaf level responses of different apple cultivars with varying canopy cover in the KBV and EGVV regions, respectively. Leaf level processes, particularly gas exchange (photosynthesis and transpiration) and leaf water status influence the water use and productivity of apple trees. Yet there is currently no information on how this varies with canopy cover, cultivar and production region in South Africa. Understanding these relationships is important in explaining the differences in tree and fruit growth, yield and fruit quality and orchard water requirements.

8.1.1 Effect of canopy cover

Selected relationships for the factors “canopy cover” and “production region” are presented where these indicate interesting and relevant findings in the overall context of this study. The results showed clearly that the atmospheric/leaf variables (VPD_{leaf}, T_{leaf}, and by inference also RH – data not shown) were the main drivers of leaf level gas exchange, including water loss through transpiration. Across all measurement points from all 12 orchards over three seasons, A increased curvilinearly with increasing g_s (Fig. 8.1a). This relationship represents intrinsic water use efficiency, and A decreased linearly with increasing VPD_{leaf} (Fig. 8.1b). The decrease in A result from the relationship between g_s and VPD_{leaf} (Fig.8.1c). High canopy cover trees showed a slightly lower A for the same g_s compared to low and medium canopy trees in the mid-range of g_s. No noticeable differences in correlations between various parameters were found for the factors “cultivar” and “time of day”.

The g_s/VPD_{leaf} relationship also differed between the three classes of canopy cover (i.e. High, Medium and Low). Under mild conditions of evaporative demand (VPD_{leaf} < 1.2 kPa), g_s was lower in low canopy trees than in medium and high canopy trees. As VPD_{leaf} increased, g_s decreased rapidly in medium canopy trees and was similar to that of low canopy trees at higher VPD_{leaf} values, indicating a limitation in water supply.

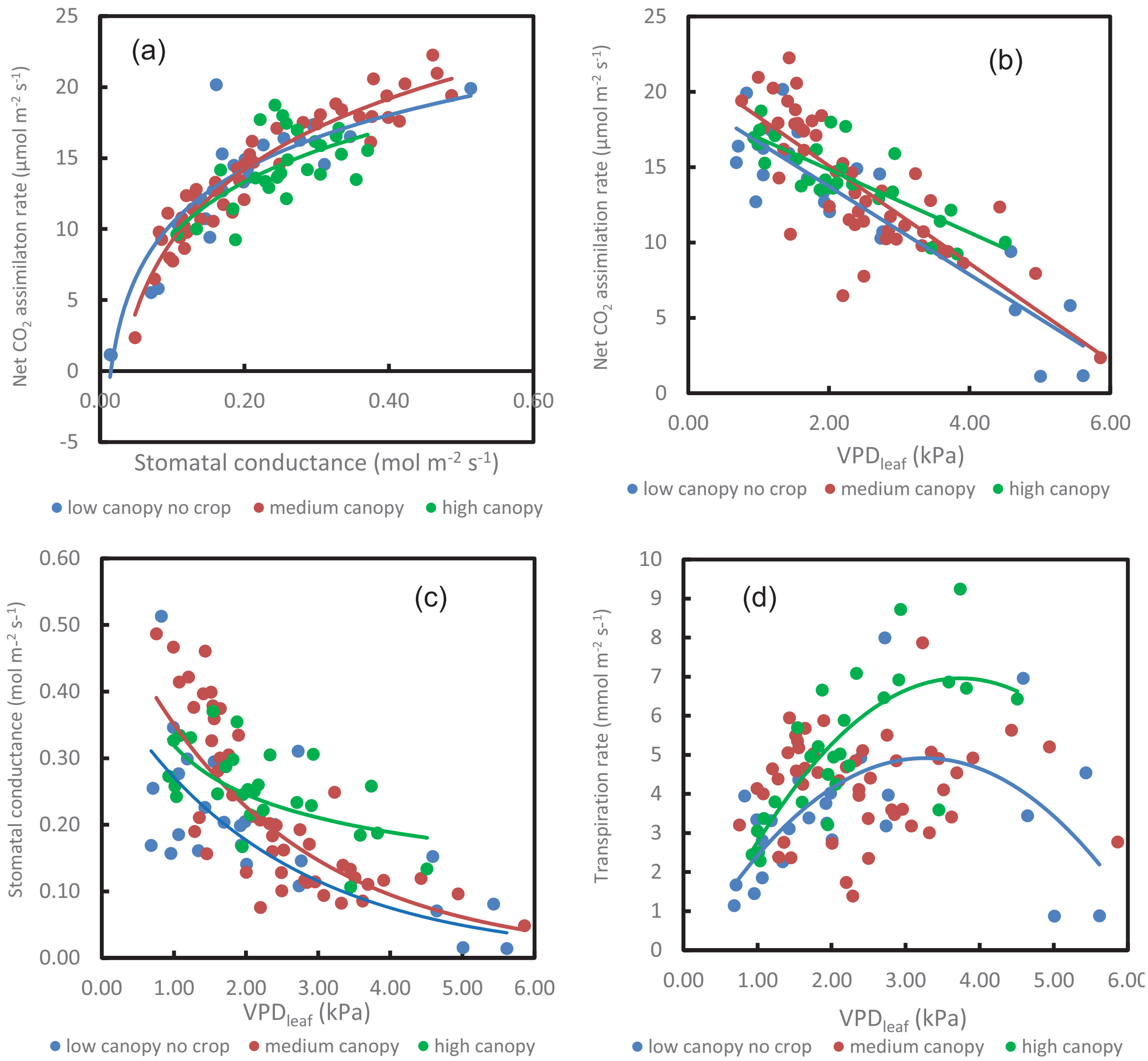


Fig. 8.1 Influence of three different canopy cover classes on the relationships between a) net CO_2 assimilation rate (A) and stomatal conductance (g_s), b) A and leaf-to-air vapour pressure deficit (VPD_{leaf}), c) g_s and VPD_{leaf}, and d) transpiration rate (E) and VPD_{leaf}.

In contrast, g_s decreased at a lower rate with increasing VPD_{leaf} in high canopy trees. Since the data was scattered and there were no measurements for high canopy trees at very high VPD_{leaf}, these trends should be further investigated. Nevertheless, the data suggest that high canopy trees (with high crop loads) can keep their stomata more widely open under high evaporative demand conditions. This suggests that they can tolerate higher water use (Fig. 8.1d) under these conditions than low and medium canopy trees.

The relationships between A and T_{leaf} (data not shown) were similar to those of A and VPD_{leaf}, which is expected given the dependence of VPD_{leaf} on T_{leaf}. The high canopy trees' A values were the least reduced by increases in T_{leaf} and the A values of the low canopy trees were the worst reduced by increases in T_{leaf}.

A positive relationship was found in all orchards between g_s and midday Ψ_{stem}. The relationship presented in Fig. 8.2b suggests that midday Ψ_{stem} in high canopy trees is similar to that of low and medium canopy trees at a given VPD_{leaf}. This supports the hypothesis that larger high canopy trees with many fruit have an internal water buffer which is used for the higher rate of transpiration during the day allowing for higher g_s and thus higher A to respond to the high demand for assimilates.

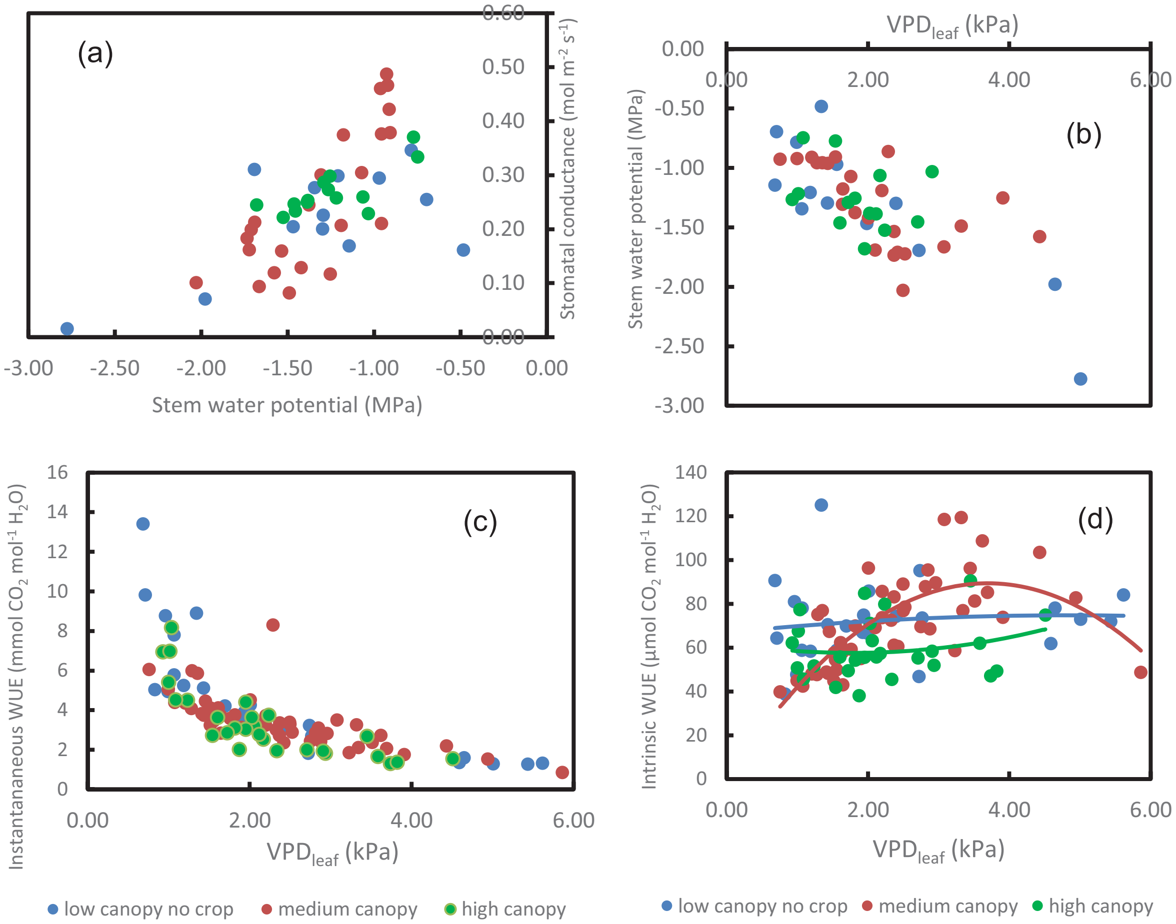


Fig. 8.2 Influence of three different canopy cover classes on the relationships between a) stomatal conductance, (g_s) and midday stem water potential (Ψ_{stem}), b) Ψ_{stem} and VPD_{leaf}, c) instantaneous water use efficiency (WUE) and VPD_{leaf}, d) intrinsic water use efficiency (WUE) and VPD_{leaf},

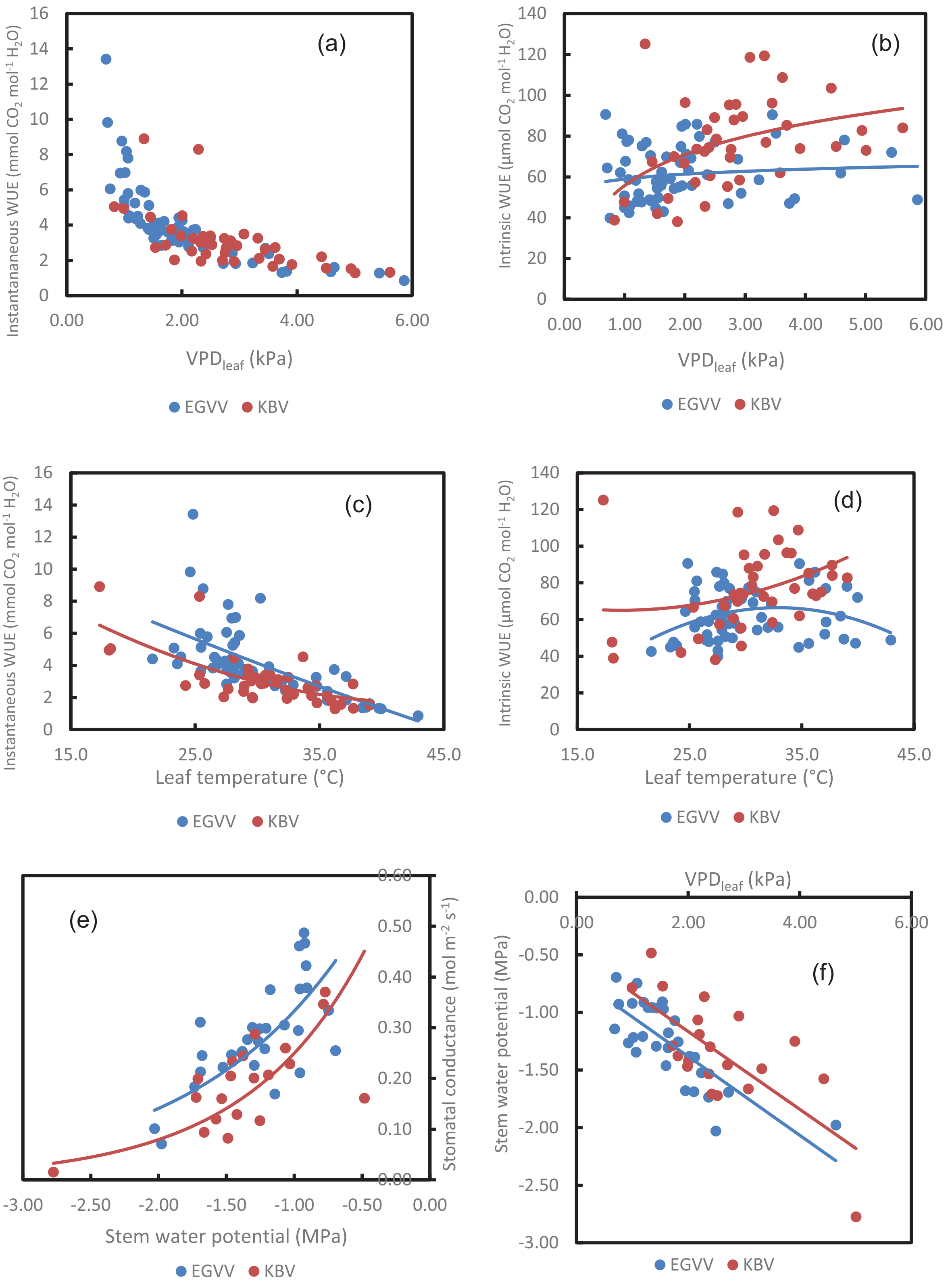


Fig. 8.3 Influence of two production regions on the relationships between a) instantaneous WUE and VPD_{leaf}), b) intrinsic WUE and VPD_{leaf}, c) instantaneous WUE and leaf surface temperature (T_{leaf}), d) intrinsic WUE and T_{leaf}, e) g_s and Ψ_{stem}, and f) Ψ_{stem} and VPD_{leaf}.

Low canopy trees with a much smaller demand for assimilates and a limited water buffer keep g_s lower even under mild evaporative conditions, to reduce transpired water losses and prevent stronger reductions in Ψ_{stem}. Fig. 8.2c shows that the ratio of carbon assimilation to transpirational water loss (A/E, or instantaneous WUE), does not differ noticeably between different canopy size classes. It is maximised under low VPD_{leaf}, decreases rapidly as VPD_{leaf} increases, and then flattens out at high VPD_{leaf}. On the other hand, intrinsic WUE (A/g_s, Fig. 8.2d) showed different trends against VPD_{leaf} between the three canopy size classes. This parameter is regarded as a good indicator of longer term integrated plant water relations. For mid-range VPD_{leaf} (around 2-4 kPa) the intrinsic WUE was higher in the low and medium canopy trees compared to the high canopy trees. This can be explained by the lower g_s (Fig. 8.1c) but similar A (Fig. 8.1b) at a given VPD_{leaf} in low/medium canopy trees compared to high canopy trees.

8.1.2 Effect of production region on leaf level processes

The relationships between gas exchange and water relations parameters were also influenced by the production region, in some key respects. Instantaneous WUE was slightly higher in KBV trees in the mid-range of VPD_{leaf} (Fig. 8.3a). Intrinsic WUE was higher in KBV compared to EGVV under higher VPD_{leaf} conditions (Fig. 8.3b), and this related to lower g_s values at a given higher VPD_{leaf} (data not shown). The influence of T_{leaf} (as an important factor in determining VPD_{leaf}) was also apparent. At mild T_{leaf}, A/E was higher in EGVV than KBV due to a higher A value (not shown), but the regions did not differ at higher T_{leaf} (Fig. 8.3c). On the other hand, A/g_s was higher in KBV than EGVV at higher T_{leaf} (Fig. 8.3d). The results shown in Figs 8.3b and 8.3d are explained by the finding that apple leaves in KBV have lower g_s at higher levels of T_{leaf} and VPD_{leaf} (more stressful conditions) but not lower A.

An interesting finding is the differential relationship between midday Ψ_{stem} and g_s (Fig. 8.3e) and VPD_{leaf} (Fig. 8.3f) between KBV and EGVV. In the KBV region, atmospheric evaporative demand is on average higher than in the EGVV region (see section 3.4.1). Minimum relative humidity is lower in KBV, and this means that VPD and ETo are generally higher, in addition to the higher maximum and seasonal solar radiation experienced in the high-lying KBV. Some of these trends are partially explained by the higher incidence of cloud cover in EGVV compared to KBV in summer. Figs 8.3e and 8.3f suggest that under prevailing atmospheric conditions in KBV a similar Ψ_{stem} is measured in trees as for trees under prevailing conditions in EGVV. Such acclimation may result from changes in xylem hydraulic characteristics, but this requires further investigation.

It is known that apple leaves and canopies are tightly coupled to the atmosphere within and surrounding the canopy. In other words, daily weather conditions exert a significant influence on leaf and canopy level gas exchange (photosynthesis and transpiration) which also influence fruit growth, yield quality and quantity. This analysis illustrates that under average atmospheric conditions in the KBV and EGVV regions, well-watered apple trees are probably routinely constrained by high levels of atmospheric evaporative demand, high canopy temperatures and a high radiation load which imposes stress on leaves and fruit. Any form of soil moisture deficit can interact with these conditions to have an impact on leaf gas exchange. Nevertheless, high yields are still achieved in these regions.

Instantaneous WUE decreased with increasing VPD_{leaf} as a result of the decline in A but the continued rise in E, with stomata not closing enough to keep E constant as ET_o increases. International literature confirms that these trends scale up to the canopy so that canopy-level transpiration increases with rising VPD, but the rise in canopy E through the day is moderated by partial stomatal closure which allows for continued carbon gain. When atmospheric conditions are unusually mild the tree can alter this pattern and capitalise on the conditions to escalate carbohydrate manufacture with low levels of water loss. Thus, the best strategy is not always to aim for high WUE, but to aim for high carbon gain (which can mean low WUE) when conditions will not lead to severe water stress (e.g. under well-watered conditions). However, when VPD_{leaf} rises to 3.0 kPa and above, rapid stomatal closure sets in and the transpiration rate stabilises or decreases to prevent a dangerous decline in the tree water status. This threshold is quite high in apple trees compared to other crops, for example grapevines. Apple stomata are normally highly coupled to the photosynthesis, avoiding excessive opening, and maintaining very good WUE (Lakso et al., 2014). These inherent physiological characteristics of apple trees are likely why apple orchards in the KBV and EGVV regions can give very high yields despite the atmospheric constraints experienced during most of the summer growth period. Furthermore, the results of this analysis suggest that there are no significant functional differences between the two cultivars Golden Delicious and Cripps' Pink with respect to regulation of stomata, carbon assimilation and water loss on a leaf area basis.

Naor (2014) stated that apple trees with a high crop load can extract more water from the soil profile compared to those with a low crop load, by maintaining higher stomatal conductance as stem water potential decreases (i.e. they become more anisohydric). However, “in spite of the adjustment of tree water relations by the crop load, higher water potentials should be maintained in order to maximize commercial crop yield at high crop loaded trees.”

8.2 Water balance in apple orchards from planting to full-bearing

Three methods were used to quantify the orchard evapotranspiration (ET) to reduce uncertainties in the water use estimates. These included the open path eddy covariance method, which was deployed at selected window periods during the growing season due to equipment limitations. The second technique was the soil water balance approach which was used in two orchards each season, also due to equipment limitations. Thirdly, additional ET data were derived from the remote sensing “FruitLook” product. Interpolation of the eddy covariance ET to seasonal water use was done using a dual source ET model. Comparison of soil water balance-based ET to seasonal ET estimates obtained by other techniques was not possible since measurement periods differed and periodic excessively wet conditions in some orchards prevented reliable ET estimates representative of the whole season. Transpiration was measured using sap flow monitoring techniques.

Typical water balance estimates for orchards of different age groups are as follows:

a) Low canopy cover ‘Golden Delicious Reinders’ orchard in KBV (Lindeshof Farm)

Season	: 2014-15
Orchard age (years)	: 3
Rootstock	: M793
Tree density (trees/ha)	: 1 667
Peak LAI (-)	: 1.0
Reference evapotranspiration (mm)	: 1 264
Seasonal total transpiration (sap flow) (m^3 ha^{-1})	: 1 990
*Seasonal total evapotranspiration (FruitLook) (m^3 ha^{-1})	: 4 610
Seasonal total evapotranspiration (Shuttleworth & Wallace model) (m^3 ha^{-1})	: 4 810
Total full surface irrigation (m^3 ha^{-1})	: 5 130
Rainfall (mm)	: 281
Yield (t ha^{-1})	: 0

**Represents the period from 01 October 2014 to 28 April 2015*

Transpiration data was from 01 October 2014 to 30 June 2015.

b) Low canopy cover 'Rosy Glow' orchard in KBV (Paardekloof Farm)

Season	: 2014-15
Orchard age (years)	: 4
Rootstock	: MM109
Tree density (trees/ha)	: 2 285
Peak LAI (-)	: 1.3
Reference evapotranspiration (mm)	: 1 264
Seasonal total transpiration (sap flow) (m^3 ha^{-1})	: 2 710
Seasonal total evapotranspiration (FruitLook) (m^3 ha^{-1})	: 5 150
*Seasonal total evapotranspiration (Shuttleworth & Wallace model) (m^3 ha^{-1})	: 5 620
Total full surface irrigation (m^3 ha^{-1})	: 2 714
Rainfall (mm)	: 281
Yield (t/ha)	: 0

**Represents the period from 01 October 2014 to 28 April 2015*

Transpiration data was from 01 October 2014 to 30 June 2015.

c) Low canopy cover 'Golden Delicious' orchard in EGVV (Vyeboom Farm)

Season	: 2015-16
Orchard age (years)	: 3
Rootstock	: MM109
Tree density (trees ha^{-1})	: 1 250
Peak LAI (-)	: 0.7
Reference evapotranspiration (mm)	: 1 064
Seasonal total transpiration (sap flow) (m^3 ha^{-1})	: 1 550
*Seasonal total evapotranspiration (FruitLook) (m^3 ha^{-1})	: 7 340
Seasonal total evapotranspiration (Shuttleworth & Wallace model) (m^3 ha^{-1})	: 5 010
Total full surface irrigation (m^3 ha^{-1})	: 1 494
Rainfall (mm)	: 247
Yield (t/ha)	: 0

**Represents the period from 01 October 2015 to 28 April 2016*

Transpiration data was from 01 October 2015 to 30 June 2016.

d) Low canopy cover 'Cripps' Red' orchard in EGVV (Vyeboom Farm)

Season	: 2015-16
Orchard age (years)	: 3
Rootstock	: MM109
Tree density (trees ha^{-1})	: 1 250
Peak LAI (-)	: 0.8
Reference evapotranspiration (mm)	: 1 064
Seasonal total transpiration (sap flow) (m^3 ha^{-1})	: 1 330
*Seasonal total evapotranspiration (FruitLook) (m^3 ha^{-1})	: 7 040
Seasonal total evapotranspiration (Shuttleworth & Wallace model) (m^3 ha^{-1})	: 5 000
Total full surface irrigation (m^3 ha^{-1})	: 1 271
Rainfall (mm)	: 247
Yield (t/ha)	: 0

**Represents the period 01 October 2015 to 29 April 2016.*

Transpiration data was from 01 October 2015 to 30 June 2016.

e) Medium canopy cover 'Golden Delicious Reinders' orchard in KBV (Lindeshof Farm)

Season	: 2016-17
Orchard age (years)	: 5
Rootstock	: M793
Tree density (trees ha^{-1})	: 1 667
Peak LAI (-)	: 1.5
Reference evapotranspiration (mm)	: 1 487
Seasonal total transpiration (sap flow) (m^3 ha^{-1})	: 4 200
*Seasonal total evapotranspiration (FruitLook) (m^3 ha^{-1})	: 6 520
Seasonal total evapotranspiration (Shuttleworth & Wallace model) (m^3 ha^{-1})	: 5 960
Total full surface irrigation (m^3 ha^{-1})	: 5 601
Rainfall (mm)	: 149
Yield (t/ha)	: 22

**Represents the period 01 October 2016 to 02 May 2017*

Transpiration data was from 01 October 2016 to 30 June 2017.

f) Medium canopy cover 'Cripps' Pink' orchard in KBV (Esperanto Farm)

Season	: 2016-17
Orchard age (years)	: 8
Rootstock	: M793
Tree density (trees ha^{-1})	: 1 111
Peak LAI (-)	: 2.0
Reference evapotranspiration (mm)	: 1 487
Seasonal total transpiration (sap flow) (m^3 ha^{-1})	: 5 470
*Seasonal total evapotranspiration (FruitLook) (m^3 ha^{-1})	: 8 190
Seasonal total evapotranspiration (Shuttleworth & Wallace model) (m^3 ha^{-1})	: 8 710
Total full surface irrigation (m^3 ha^{-1})	: 9 030
Rainfall (mm)	: 149
Yield (t/ha)	: 69

**Represents the period 01 October 2016 to 02 May 2017*

Transpiration data was from 01 October 2016 to 30 June 2017.

g) Medium canopy cover 'Golden Delicious Reinders' orchard in EGVV (Vyeboom Farm)

Season	: 2016-17
Orchard age (years)	: 7
Rootstock	: M7
Tree density (trees ha^{-1})	: 1 250
Peak LAI (-)	: 1.3
Reference evapotranspiration (mm)	: 1 147
Seasonal total transpiration (sap flow) (m^3 ha^{-1})	: 2 490
*Seasonal total evapotranspiration (FruitLook) (m^3 ha^{-1})	: 6 290
Seasonal total evapotranspiration (Shuttleworth & Wallace model) (m^3 ha^{-1})	: 5 340
Total full surface irrigation (m^3 ha^{-1})	: 3 375
Rainfall (mm)	: 218
Yield (t/ha)	: 22

****Represents the period 01 October 2016 to 02 May 2017*

Transpiration data was from 01 October 2016 to 30 June 2017.

h) Medium canopy cover 'Cripps' Pink' in EGVV orchard (Dennebos Farm)

Season	: 2016-17
Orchard age (years)	: 8
Rootstock	: MM109
Tree density (trees ha^{-1})	: 1 250
Peak LAI (-)	: 1.8
Reference evapotranspiration (mm)	:1 147
Seasonal total transpiration (sap flow) (m^3 ha^{-1})	: 4 710
*Seasonal total evapotranspiration (FruitLook) (m^3 ha^{-1})	: 7 280
Seasonal total evapotranspiration (Shuttleworth & Wallace model) (m^3 ha^{-1})	: 8 720
Total full surface irrigation (m^3 ha^{-1})	: 2 275
Rainfall (mm)	: 218
Yield (t/ha)	: 59

****Represents the period 01 October 2016 to 02 May 2017*

Transpiration data was from 01 October 2016 to 30 June 2017.

i) Full-bearing 'Golden Delicious' orchard in KBV (Kromfontein Farm)

Season	: 2014-15
Orchard age (years)	: 22
Rootstock	: M793
Tree density (trees ha^{-1})	: 1 667
Peak LAI (-)	: 3.6
Reference evapotranspiration (mm)	: 1 264
Seasonal total transpiration (sap flow) (m^3 ha^{-1})	: 8 130
*Seasonal total evapotranspiration (FruitLook) (m^3 ha^{-1})	: 7 550
Seasonal total evapotranspiration (Shuttleworth & Wallace model) (m^3 ha^{-1})	: 10 860
Total full-surface irrigation (m^3 ha^{-1})	: 7 870
Rainfall (mm)	: 281
Yield (t/ha)	: 88

**Represents the period from 01 October 2014 to 28 April 2015*

Transpiration data was from 01 October 2014 to 30 June 2015.

j) Full-bearing 'Cripps' Pink' orchard in KBV (Kromfontein Farm)

Season	: 2014-15
Orchard age (years)	: 9
Rootstock	: M793
Tree density (trees ha^{-1})	: 1 667
Peak LAI (-)	: 2.6
Reference evapotranspiration (mm)	: 1 264
Seasonal total transpiration (sap flow) (m^3 ha^{-1})	: 5 890
*Seasonal total evapotranspiration (FruitLook) (m^3 ha^{-1})	: 7 500
Seasonal total evapotranspiration (Shuttleworth & Wallace model) (m^3 ha^{-1})	: 9 740
Total full-surface irrigation (m^3 ha^{-1})	:12 020
Rainfall (mm)	: 281
Yield (t/ha)	: 110

**Represents the period from 01 October 2014 to 28 April 2015*

Transpiration data was from 01 October 2014 to 30 June 2015.

k) Full-bearing 'Golden Delicious' orchard in EGVV (Southfield Farm)

Season	: 2015-16
Orchard age (years)	: 29
Rootstock	: M793
Tree density (trees ha^{-1})	: 1 250
Peak LAI (-)	: 3.3
Reference evapotranspiration (mm)	: 1 064
Seasonal total transpiration (sap flow) (m^3 ha^{-1})	: 7 570
*Seasonal total evapotranspiration (FruitLook) (m^3 ha^{-1})	: 9 520
Seasonal total evapotranspiration (Shuttleworth & Wallace model) (m^3 ha^{-1})	: 11 100
Total full surface irrigation (m^3 ha^{-1})	: 8 200
Rainfall (mm)	: 247
Yield (t/ha)	: 100

**Represents the period 01 October 2015 to 29 April 2016.*

Transpiration data was from 01 October 2015 to 30 June 2016.

l) Full-bearing 'Cripps' Pink' orchard in EGVV (Radyn Farm)

Season	: 2015-16
Orchard age (years)	: 12
Rootstock	: M793
Tree density (trees ha^{-1})	: 1 667
Peak LAI (-)	: 2.8
Reference evapotranspiration (mm)	: 1 064
Seasonal total transpiration (sap flow) (m^3 ha^{-1})	: 6 310
*Seasonal total evapotranspiration (FruitLook) (m^3 ha^{-1})	: 9 020
Seasonal total evapotranspiration (Shuttleworth & Wallace model) (m^3 ha^{-1})	: 9 760
Total full surface irrigation (m^3 ha^{-1})	: 8 370
Rainfall (mm)	: 247
Yield (t/ha)	: 109

**Represents the period 01 October 2015 to 29 April 2016.*

Transpiration data was from 01 October 2015 to 30 June 2016.

In young orchards (~ 3 yr.) seasonal total transpiration ranged from 1 300 m^3 ha^{-1} in the low-density plantings in EGVV to 2 700 m^3 ha^{-1} in the high-density orchards in KBV. Seasonal ET was around 5 000 m^3 ha^{-1} suggesting fairly high evaporative losses from the orchard floor due to the large exposed orchard floor area.

For trees with medium canopy cover (30-44%), the seasonal transpiration varied from 2 500 to 5 500 m^3 ha^{-1}. The simulated seasonal total ET ranged from 5 300 to 8 700 m^3 ha^{-1}.

The maximum unstressed seasonal transpiration of mature high yielding 'Cripps' Pink' and 'Golden Delicious' orchards is in the range 6 000 to 8 000 m^3 ha^{-1} depending on canopy cover. The maximum orchard ET varied from 9 000 to just over 11 000 m^3 ha^{-1} per season (Oct-Jun).

The long growing season of 'Cripps' Pink' orchards did not translate into high seasonal water use compared to the 'Golden Delicious' which has a short growing season. This is because the winter (May and June) transpiration contributed less than 12% of the seasonal total transpiration in these orchards. Tree transpiration contributed between 65 and 82% to the total orchard ET in full-bearing orchards depending on canopy cover. In young orchards, orchard floor evaporation accounted for more than 60% of ET, which was clearly excessive.

8.3 Water productivity of high yielding apple orchards

8.3.1 Water use efficiency dynamics by cultivar, canopy cover, and production region

Water use efficiency (WUE) and water productivity (WP) values were calculated for the eight bearing orchards included in this study. WUE is defined as kilogram of fruit produced per cubic meter of water used. WP is defined as the gross income (in Rand) obtained per cubic meter of water used. Both parameters were expressed on the basis of the trees only (using measured transpiration values) and the whole orchard area (using modelled evapotranspiration (ET) values).

WUE was calculated using yield and water use data. Under similar crop loads 'Cripps' Pink' had a higher WUE (transpiration-based) than 'Golden Delicious/Reinders' owing to its lower seasonal water use (Table 8.1; Fig. 8.4a). This stems from a smaller canopy and lower total leaf area than 'Golden Delicious'. For full-bearing trees of both cultivars, WUE was higher in EGVV than in KBV, and this related to the higher tonnage in EGVV.

Table 8.1 Water use efficiency of high yielding apple orchards. High and medium canopy cover represent >45 and 30-44% canopy cover, respectively.

Cultivar	Canopy cover	Region	Yield of measured trees (t/ha)	Water use efficiency (kg/m^3)	
				Tree basis (measured transpiration)	Orchard basis (modelled evapotranspiration)
Golden Delicious	High	KBV	84.9	10.8	8.8
Golden Delicious	High	EGVV	138.0	18.0	13.5
Golden Delicious Reinders	Medium	KBV	15.9	4.3	2.7
Golden Delicious Reinders	Medium	EGVV	10.8	4.4	2.0
Cripps' Pink	High	KBV	88.3	14.2	9.1
Cripps' Pink	High	EGVV	140.6	21.5	14.4
Cripps' Pink	Medium	KBV	71.0	10.4	8.1
Cripps' Pink	Medium	EGVV	53.4	11.3	6.1

The calculations based on modelled evapotranspiration indicated that WUE of full-bearing orchards was still higher in EGVV than in KBV in both cultivars. However, owing to the greater evaporation component for water use in ‘Cripps’ Pink’ than ‘Golden Delicious’ the ET-based WUE was only marginally higher in the former (Table 8.1; Fig. 8.4b). Overall, WUE increased with increasing yield (Figure 8.4) in what appears to be a linear relationship under the yields achieved in this study.

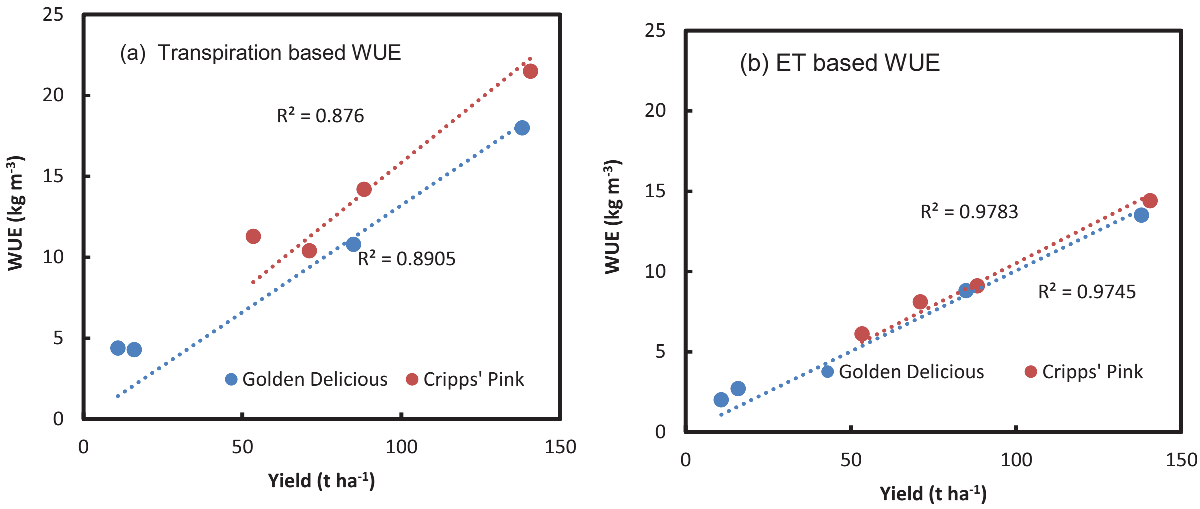


Fig. 8.4 The relationship between water use efficiency (WUE) of bearing apple trees and crop yield of four ‘Golden Delicious’ and four ‘Cripps’ Pink’ orchards. (a) Transpiration-based WUE; (b) evapotranspiration-based WUE.

However, owing to the greater evaporation component for water use in ‘Cripps’ Pink’ than ‘Golden Delicious’ the ET-based WUE was only marginally higher in the former (Table 8.1; Fig. 8.4b). Overall, WUE increased with increasing yield (Fig. 8.4) in what appears to be a linear relationship under the yields achieved in this study.

8.3.2 Water productivity variations by cultivar, and canopy cover

The calculation of WP required data for yield, the quality of the fruit, packouts and prices per class of fruit, and thus the value of the harvest in Rand. Fruit quality was generally good with a few exceptions: both full-bearing ‘Golden Delicious’ orchards produced a high proportion of smaller fruit; and the intermediate-bearing ‘Golden Delicious Reinders’ orchard in KBV suffered from bruising at harvest and during storage. Sunburn was also prevalent in most orchards.

’Cripps’ Pink’ had a higher WP (transpiration-based) than ‘Golden Delicious/Reinders’ in both regions under similar crop loads (Table 8.2; Fig. 8.5a). The primary reason for this was that export-quality ‘Cripps’ Pink’ (Pink Lady®) fetches a higher price than export-quality ‘Golden

Delicious' and this has a significant influence on orchard gross value. A secondary reason was that the two full-bearing 'Golden Delicious' orchards produced a high proportion of small fruit, which were not suitable for the export market. The calculations based on modelled ET indicated that WP was still higher (by ca. 10 R/m^3 water) in 'Cripps' Pink' than in 'Golden Delicious' (Table 8.2; Fig. 8.5b).

Overall, WP increased with increasing yield (Figure 1) in what appears to be a saturating relationship, particularly for 'Golden Delicious'. This cultivar showed no further improvements in transpiration-based WP above a yield of 35 t/ha, and no improvements in ET-based WP above a yield of 74 t/ha.

Table 8.2 Water productivity of high yielding apple orchards.

Cultivar	Canopy cover	Region	Commercial yield (t ha^{-1})	Water productivity (R m^{-3})	
				Tree basis (measured transpiration)	Orchard basis (modelled evapotranspiration)
Golden Delicious	High	KBV	74.0	46.6	38.2
Golden Delicious	High	EGVV	99.5	49.4	37.1
Golden Delicious Reinders	Medium	KBV	18.3	20.7	7.8
Golden Delicious Reinders	Medium	EGVV	34.5	48.7	22.6
Cripps' Pink	High	KBV	109.8	92.7	59.1
Cripps' Pink	High	EGVV	109.0	73.4	49.3
Cripps' Pink	Medium	KBV	61.2	53.5	41.6
Cripps' Pink	Medium	EGVV	58.0	66.2	35.6

Discussions with production managers suggest that 'Golden Delicious' could be "pushed" to just over 100 t ha^{-1} for optimal profitability, but that the small fruit problem would likely preclude further financial gains at even higher yields. When the results of this study are extrapolated, it appears that 'Cripps' Pink' could well be "pushed" to yields exceeding 110 t ha^{-1}, with associated continued increases in WP. In both cultivars, WP would also be significantly increased if (1) high evaporative (orchard floor) losses in younger orchards are reduced, or (2) evaporative losses in red/blushed cultivars such as 'Cripps' Pink', which are managed for a smaller canopy leaf area, are reduced.

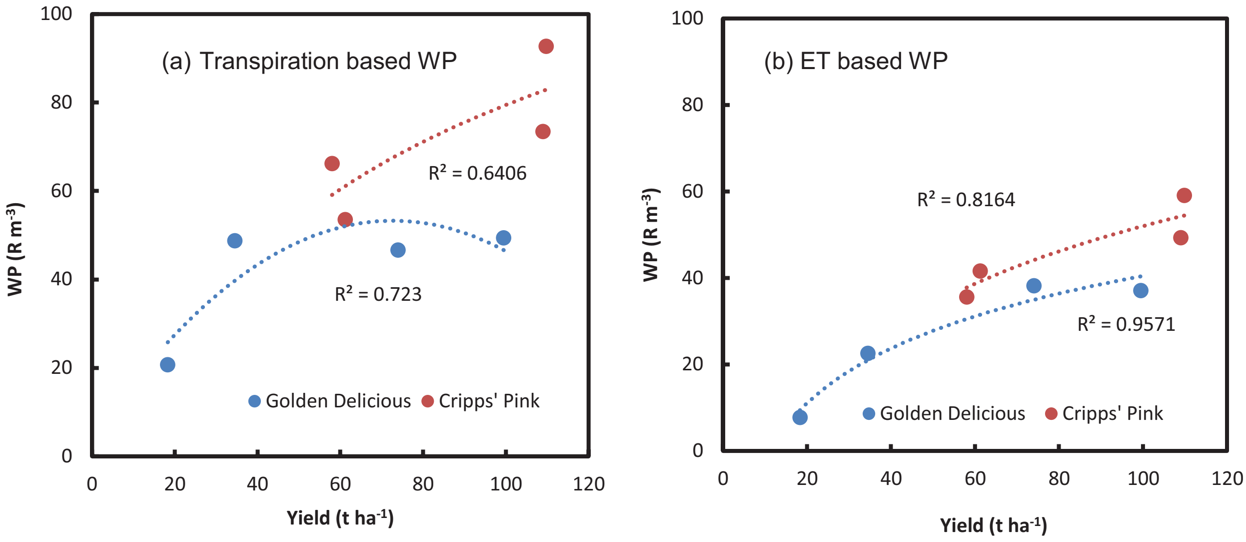


Fig. 8.5. The relationship between water productivity (WP) of bearing apple trees and crop yield of four 'Golden Delicious' and four 'Cripps' Pink' orchards. (a) Transpiration-based WP; (b) evapotranspiration-based WP.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 General conclusions

In this study we quantified the water requirements of high performing commercial apple orchards. We also established the key drivers for water use and productivity of the orchards through detailed eco-physiological and orchard water balance assessments. Focus was on orchards growing in the prime apple producing regions namely the Koue Bokkeveld (KBV) and the Elgin/Grabouw/Vyeboom/Villiersdorp (EGVV) areas. Microclimatic conditions of these regions differ and we studied both the mature exceptionally high yielding (>100 t ha^{-1}) and young orchards which have the potential to produce high yields.

In young orchards with a low canopy cover, there were no significant differences in tree level transpiration between the 'Golden Delicious'/Reinders' and the red cultivars namely the Rosy Glow/'Cripps' Red'. Variations in orchard scale transpiration were mainly a result of differences in tree density which influenced the sap wood area index of the orchard. High density orchards (large no. of trees per ha) had higher transpiration rates than less dense orchards in both production regions. Key climatic factors that controlled tree water use were the solar radiation and the vapour pressure deficit of the air. Soil water deficit or excessively wet soils through over-irrigation both reduced orchard transpiration rates.

For mature trees orchards planted to the Golden Delicious cultivar had higher water use rates than those under Cripps' Pink. This is because the Cripps' Pink trees had relatively small canopy sizes to allow radiation penetration to promote the development of the red colour on the fruit. Despite the low transpiration rates, the 'Cripps' Pink' orchards studied had higher yields than those under the 'Golden Delicious'. Therefore, canopy cover rather than crop load had the largest influence on transpiration rates. The low transpiration rates and higher yield in the 'Cripps' Pink' orchards resulted in a higher water use efficiency which peaked at about 17 kg/m^3 compared to around 13 kg/m^3 for the 'Golden Delicious'. So, the very high yields appeared to increase the water use efficiency of the mature orchards.

9.2 Recommendations and future research needs

Given that both the WUE and WP were higher in ‘Cripps’ Pink’ than ‘Golden Delicious’ trees which had large canopies, options to improve WP of ‘Golden Delicious’ orchards include:

1) growing the trees with small more open canopies under shade nets. This will likely reduce the transpiration rates and sun burn damage although further research is required to confirm this.
2) using dwarfing rootstocks with the ‘Golden Delicious’ cultivar to reduce canopy cover and to lower water use rates
3) limiting the yield of the ‘Golden Delicious’ orchards to a maximum around 100 t ha^{-1} to produce more class one export quality fruit as fruit size appears to be substantially affected under high crop loads for this cultivar. However, further research is required to obtain a more accurate yield threshold.

Evaporation from the orchard floor was fairly high in orchards with low canopy cover, approaching 70% in young orchards. It is important to reduce orchard floor evaporation e.g. through:

1) using shorter range micros, conventional or sub-surface drip in young orchards;
2) using mulching to reduce soil evaporation;
3) more accurate irrigation scheduling especially in young orchards;
4) using cover crop species with conservative water use characteristics yet maintaining other benefits to the orchards. However, further research is required to identify appropriate cover crops, and;
5) carefully managing the cover crop through mowing to avoid excessive growth.

Lastly, this study developed an ET model for the purposes of scaling up the results of the present study to other apple growing regions. However, there is need to further calibrate and validate the model in a wide range of growing conditions to improve accuracy.

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DATA STORAGE

All the processed data have been stored on the:

I: drive of the CSIR, Natural Resources and Environment
Jan Cilliers Street
Stellenbosch
7600
South Africa

CAPACITY BUILDING

Staff development

The project provided training for two CSIR technicians namely Mr Phumudzo Tharaga and Mr Johannes Masinge. Both technicians gained exposure on the installation and maintenance of the heat pulse velocity sap flow systems, automatic weather stations, eddy covariance systems and collecting plant growth data such as the leaf area index, and canopy dimensions. They were also trained on the data download/upload routines on various data loggers.

Community development

The project was done in the Koue Bokkeveld, Villiersdorp and Vyeboom communities. Members of the community were hired to perform various tasks on the project. This raised awareness of the project within the communities.

Students on course for graduation

Qamani Doko, MSc in Agriculture, University of Pretoria (completed).
Solomon Zirebwa, PhD Agriculture, University of Stellenbosch.
Zanele Ntshidi, PhD Environmental and Water Science, University of Western Cape.
Nompumelelo Mobe, PhD Environmental and Water Science, University of Western Cape.
Catherine Wilson, MSc in Agriculture, University of Pretoria.

The focus and contribution of each student's study to the overall project is summarized below:

Mr Qamani Doko

Mr Doko is registered in the Department of Plant and Soil Science at the University of Pretoria for his M. Agric. (Horticulture) degree, which is entitled "*Quantifying the water use of apple orchards*". Qamani's completed his MSc and graduated in March 2018. Qamani collected the water use, micro-lysimeter, and radiation interception data during the 2014/15 season.

Mr Solomon Zirebwa

Mr Solomon Zirebwa enrolled as a PhD Agric. student in the Department of Horticultural Science at Stellenbosch University in February 2015 under a bursary provided by the project. The title of his thesis is: *"Establishing quantitative relationships between water relations, growth, yield and quality of high performing commercial apple orchards"*

Solomon has now completed his fieldwork and he is busy with data analysis and thesis write up. Solomon conducted all leaf level gas exchange measurements, and most of the crop harvests and laboratory fruit quality assessments in the second and third seasons.

Ms Zanele Ntshidi

Zanele registered for her PhD entitled: *'Investigating the partitioning of evapotranspiration in apple orchards of different age groups'* at the Institute for Water Studies at the University of Western Cape in January 2017. She is in the second and final year of data collection and she has made good progress with key tasks. Zanele collected the water use and water use partitioning data during the 2015 to 2017 seasons. She secured additional funding the Young Researchers Establishment Fund (YREF) at the CSIR and from the NRF's Thuthuka Program so that she completes her studies.

Ms Nompumelelo Thelma Mobe

Nompumelelo registered her PhD with the Institute for Water Studies at the University of the Western Cape in January 2017. Her study is entitled: *"Measurement and modelling of water* *use in apple orchards of different age groups".* The aim of her study is to improve our ability to reliably estimate water use in orchards with different canopy cover using *in situ* and remote sensing based approaches. She has 3 yr. funding from the DST-NRF's Professional Development Program (PDP). Most of her research is desktop research utilizing the extensive data set that was collected on the project. She is also involved with limited fieldwork to close important data gaps.

Ms Catherina Wilson

Ms Wilson' MSc study is entitled "*Determining the active apple root growth and carbohydrate production in orchards from different climatic zones and in different aged orchards*". She registered her degree in the Department of Plant and Soil Science at the University of Pretoria under the supervision of NJ Taylor and E Lötze (Stellenbosch University).

ABSTRACTS

Qamani Doko et al (M. Agric. Horticulture) QUANTIFYING WATER USE OF HIGH YIELDING APPLE ORCHARDS

INTRODUCTION

High yielding apple orchards (>100 t ha^{-1}) are becoming a norm in South Africa and it is assumed that as yields increase, transpiration rates increase. This raises the need for improved knowledge on water use of these orchards in relation to water availability, given the increasing pressure on scarce water resources. A project was therefore solicited, managed and funded by the Water Research Commission. Accurate estimates of transpiration are therefore necessary to assess the possible link between yield and water use. The aim of this study is therefore to quantify the water use and water relations of high yielding apple trees.

MATERIALS AND METHODS

The heat pulse velocity sap flow technique was used to monitor transpiration rates in full bearing 'Golden Delicious' and 'Cripps Pink' orchards in the Koue Bokkeveld. Measurements of water relations included stomatal conductance and leaf and stem water potential. Estimates of canopy size were obtained by measuring the interception of photosynthetically active radiation and leaf area index of trees. Weather parameters were recorded by an automatic weather station and were used to calculate reference evapotranspiration.

RESULTS AND DISCUSSION

The transpiration rates for both 'Golden Delicious' and 'Cripps Pink' cultivars increased from spring to summer and decreased in autumn. Average daily rates were 3.1 $mm.day^{-1}$ in spring, 3.96 $mm.day^{-1}$ in summer and 2.5 $mm.day^{-1}$ in autumn for the 'Golden Delicious' trees. The yield was 98 t ha^{-1}, with a total of 786 mm transpired throughout the season. 'Cripps Pink' trees had lower rates of 2.73 $mm.day^{-1}$, 2.86 $mm.day^{-1}$ and 1.82 $mm.day^{-1}$ in the three seasons. The yield was 85 t ha^{-1} with a seasonal transpiration total of 594 mm. The higher seasonal transpiration in the 'Golden Delicious' orchard was likely a result of a higher LAI (3.43 $m^2.m^{-2}$) of these trees as compared to the 'Cripps Pink' trees (2.82 $m^2.m^{-2}$). The daily stomatal conductance varied with weather conditions, reaching a maximum at midday and minimum at sunrise and sunset.

CONCLUSION

The results show that tree water use varies according to climatic conditions and canopy size. There was no clear relationship between transpiration rates and yield in this current study. 'Golden Delicious' trees transpired more water than 'Cripps Pink' trees throughout the season; and this was a result of a bigger canopy size. These results can be used as a basis for future modeling exercises.

KNOWLEDGE DISSEMINATION & TECHNOLOGY TRANSFER

Scientific Articles

Dzikiti S., Gush MB., Volschenk T., Taylor NJ., Midgley SJE., Lötze E., Schmeisser M, Doko Q. 2017. Measurement and modelling of water use in high yielding apple orchards and orchards of different age groups in South Africa. Acta Horticulturae. 1150: 31-37. ISHS 2017. DOI 10.17660/ActaHortic.2017.1150.5 Proc. VIII International Symposium on Irrigation of Horticultural Crops. Eds.: J. Marsal and J. Girona.

Jovanovic NZ., Dzikiti S., Gush MB (2018). Integrated approach for the estimation of crop water requirements based on soil, plant and atmospheric measurements. Book Chapter - Burleigh Dodds Publishing.

Dzikiti, S., Volschenk T., Midgley SJE, Gush MB., Lötze E., Schmeisser M., Taylor NJ., Steyn W., Zirebwa SF., Ntshidi Z., Doko Q., Jarmain C., Piennar H (under review). Quantifying the water requirements of high yielding and young apple orchards in the winter rainfall areas of South Africa using *in situ* and high resolution remote sensing data. Agricultural Water Management Journal.

Mobe NT, S. Dzikiti, Z.Ntshidi, D. Mazvimavi, Volschenk T., E Lötze, W. Steyn, S.J.E. Midgley (in preparation). Seasonal transpiration dynamics and water status of 'Golden Delicious' and 'Cripps' Pink' apple orchards of varying age groups in the Western Cape Province of South Africa. (to be submitted to Scientia Horticulturae).

Midgley, S.J.E., Dzikiti, S., Zirebwa, F.S., Volschenk, T., Taylor, N.J., Gush, M.B., Lötze, E., Ntshidi, Z. and Mobe, N. (in preparation). Water use productivity of high performing apple orchards in the winter rainfall area of South Africa. (To be submitted to Acta Horticulturae)

Selected presentations

FS Zirebwa, SJE Midgley, S Dzikiti and E Lötze. Use of continuous stem and fruit growth measurements for detecting water stress in apple orchards. Combined Congress, 23 – 26 January 2017, Klein Kariba: Oral presentation

S. Dzikiti, Z. Ntshidi, T. Volschenk, S. Midgley (2017). Estimating crop water requirements using an improved Shuttleworth and Wallace model. 14th IWA Specialist Conference. 31 Oct 2017

Z. Ntshidi, S. Dzikiti, T. Mobe, D. Mazvimavi. (2017). Partitioning of water use in apple orchards: Quantifying the contribution of cover crops. 14th IWA Specialist Conference. 31 Oct 2017

Z. Ntshidi, S. Dzikiti, T. Mobe, D. Mazvimavi (2017). Water use dynamics in SA apple orchards from planting to full-bearing age: Implications on ET partitioning. 18th Waternet Symposium, Namibia.

Z Ntshidi., S Dzikiti., MB Gush.,SJE Midgley., T Volschenk., N Taylor., E Lötze., WJ Steyn., D. Mazvimavi. 2016. Water requirements of apple orchards in the western cape province of South Africa. Pietermaritzburg.

Volschenk T, Dzikiti,S, Gush MB, Midgley S, Taylor NJ, Lotze E, Schmeisser M, Doko Q, Zirebwa SF. (2016) Soil water dynamics of apple orchards in two Western Cape producing regions. SANCID Symposium 2016: "Sustainable Irrigation Water Management and Drainage for Food Production: Vision 2030". Goudini Spa, Worcester, 13 October 2016.

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Volschenk T, Dzikiti,S, Gush MB, Midgley S, Taylor NJ,. (2018) Irrigation management of apple orchards in sandy soils in two water management areas in the Western Cape. African Combined Congress, Ratanga Junction – Cape Town, 16January 2018.

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Mobe NT., Dzikiti, S., Mazvimavi D., and Ntshidi, Z. (2017) Seasonal transpiration dynamics and water status of 'Golden Delicious' and 'Cripps' Pink' apple orchards in the Western Cape Province of South Africa. Young Water Professionals, Cape Town.

Popular articles

Dzikiti. S. 2015. Growing fruit with less water: The 8th international symposium on the irrigation of horticultural crops. South African Fruit Journal (October/ November issue).

Dzikiti S., Gush MB., Taylor NJ., Volschenk T., Midgley S., Lötze E., Schmeisser M. 2015. How thirsty is your apple orchard? *South African Fruit Journal (November/December issue).*

Dzikiti S., Gush MB., Taylor NJ., Volschenk T., Midgley S., Lötze E., Schmeisser M. 2014. How much water do high yielding apple orchards require for sustainable production? *South African Fruit Journal (November/December issue)*

Appendix A: Installation of soil water monitoring equipment

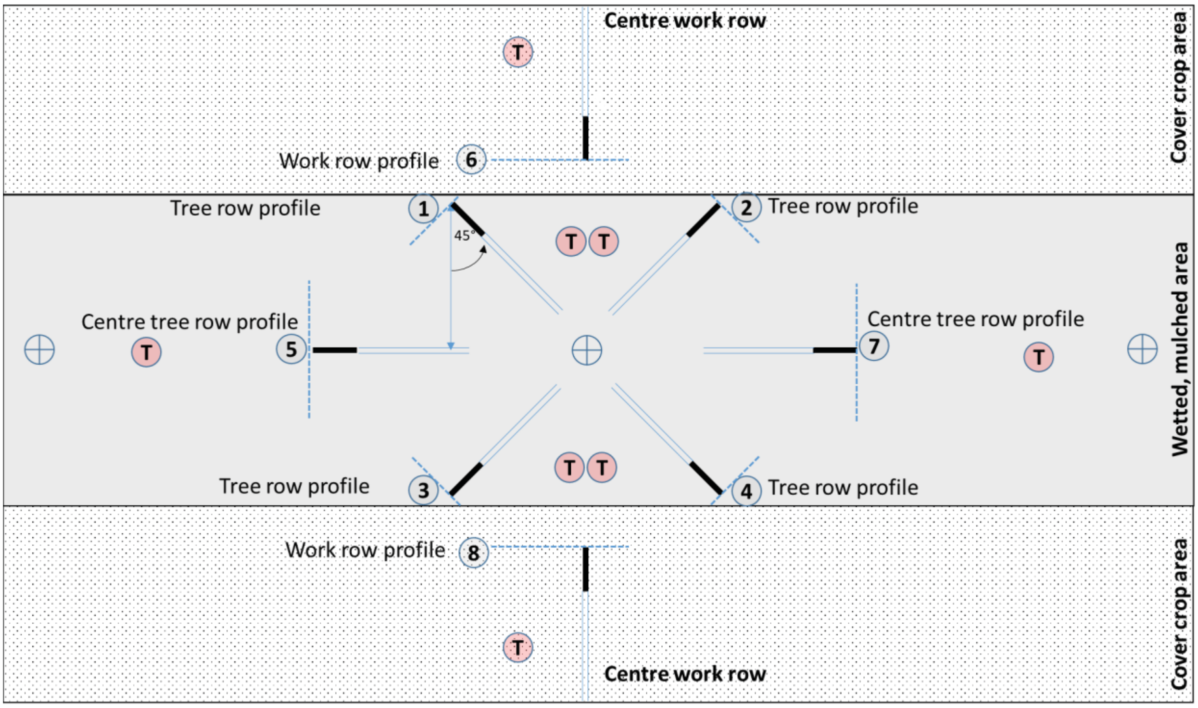

Fig. A1 Illustration of the position and orientation of eight soil profiles relative to the tree (encircled cross) in which CS616 sensors and thermocouples (encircled T) were installed in a low canopy cover 'Golden Delicious' orchard at Lindeshof in 2014/15.

Table A1. Positioning of CS616 soil water content and thermocouple sensors installed in 8 soil profiles in the low canopy cover 'Golden Delicious' orchard at Lindeshof in 2014/15. Sensors were installed at 150 mm, 300 mm, 600 mm and 800 mm soil depths.

Soil profile ID	**Position relative to tree trunk[1] (mm, orientation)**		
	In tree row	**Perpendicular to tree row**	**Angle relative to tree row**
SE Tree row	375 S	400 E	45°
NE Tree row	375 N	400 E	45°
E Workrow[2]	0	1580 E	90°
N Tree row[3]	750 N	0	0°
S Tree row[5]	750 S	0	0°
SW Tree row	375 S	400 W	45°
NW Tree row	375 N	400 W	45°
W Workrow[4]	0	1580 W	90°

1 Subtract a radius of 15 mm from all values to obtain distance relative to the edge of the tree trunk.

2 No equipment available for 800 mm depth.

3 Thermocouples installed at an adjacent tree South of the main installation.

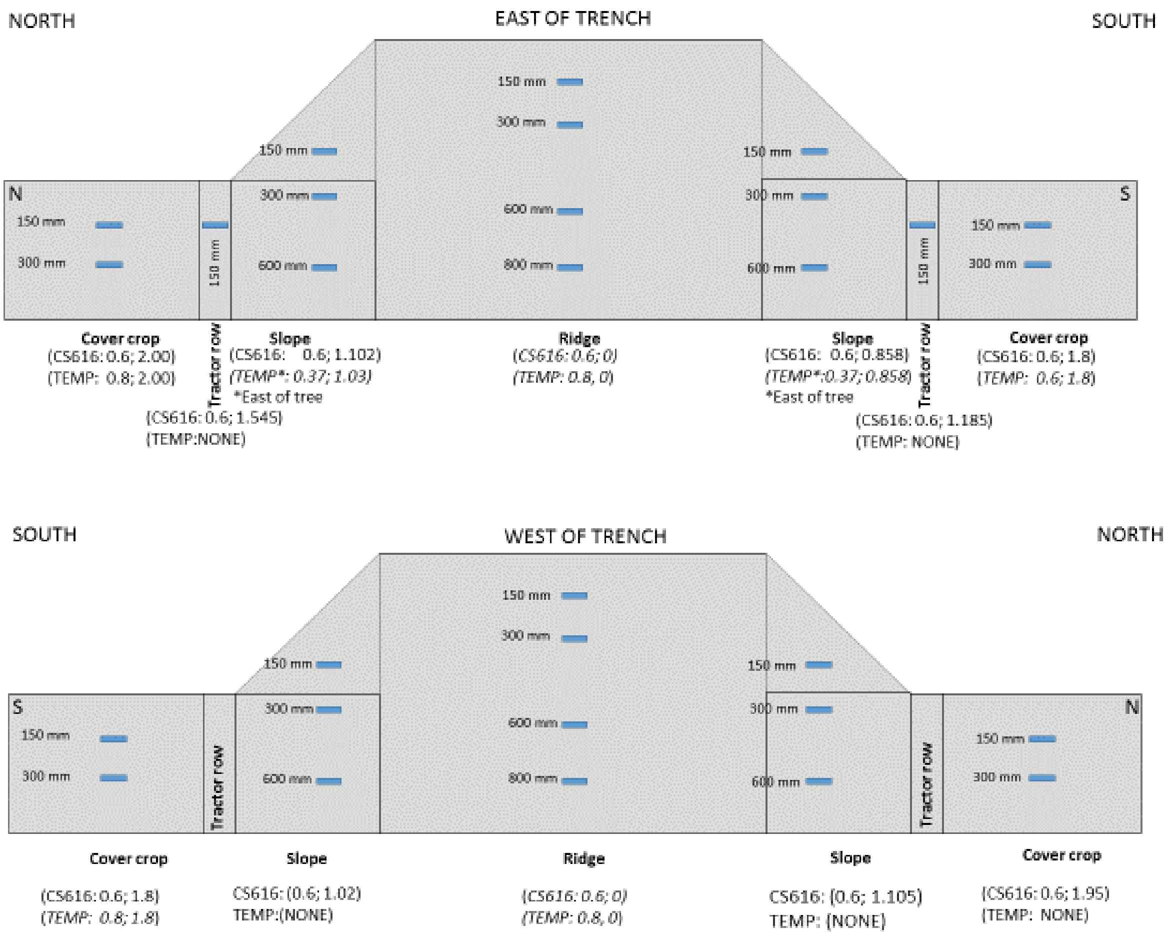

Fig. A2. Illustration of the position and depths of the CS616 sensors and thermocouples installed in soil relative to ridged Sundowner trees at Vyeboom Boerdery in EGVV in 2015/16. Diagrams indicate tree position East and West, respectively, relative to a trench between two trees. The X and Y co-ordinates of installation positions are indicated in brackets.

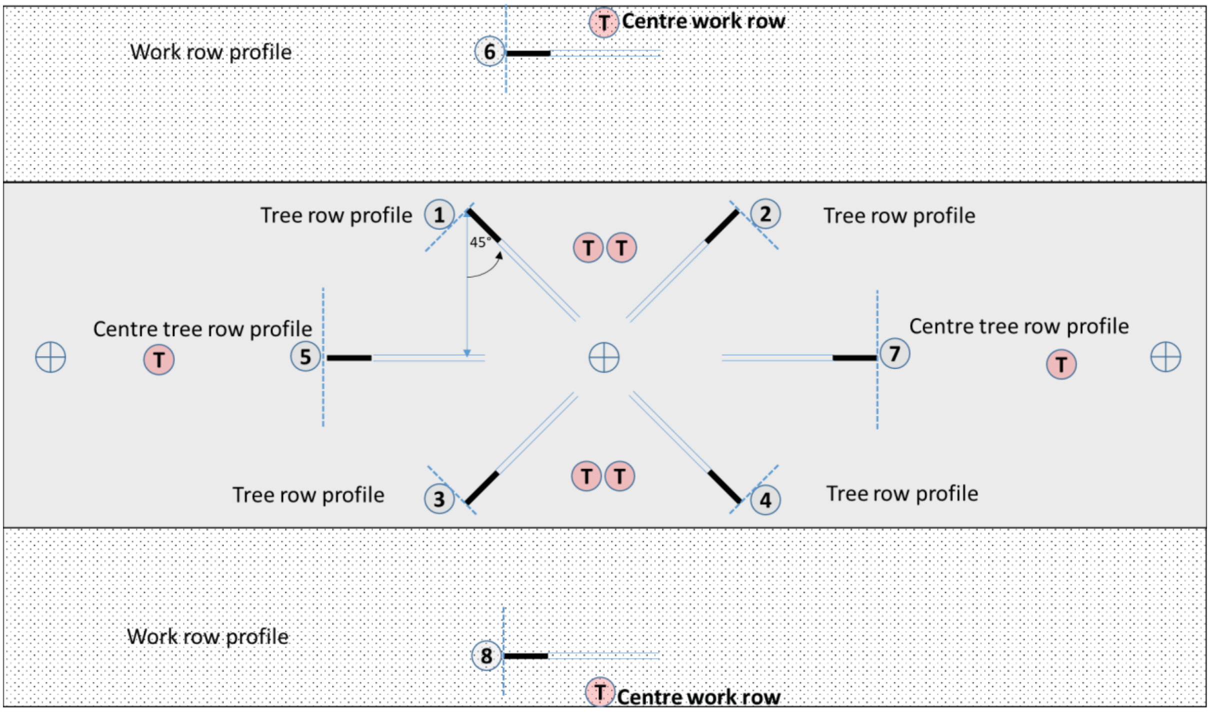

Fig. A3. Illustration of the position and orientation of eight soil profiles relative to the tree (encircled cross) in which CS616 sensors and thermocouples (encircled T) were installed in medium and high canopy cover 'Golden Delicious' orchards.

Table A2. Identification (ID) and positioning of CS616 soil water content sensors installed in 8 soil profiles in the medium canopy cover 'Golden Delicious' orchard at Lindeshof in 2016/17. Sensors were installed at 150 mm, 300 mm, 600 mm and 800 mm soil depths.

Soil profile ID	**Position relative to tree trunk[1] (mm, orientation)**		
	In tree row	**Perpendicular to tree row**	**Angle relative to tree row**
E Workrow[2]	265	1800	0°
SE Tree row	375	435	45°
NE Tree row	320	435	45°
N Tree row	715	0	0°
S Tree row	722	0	0°
SW Tree row	375	435	45°
NW Tree row	375	435	45°
W Workrow[2]	239	1800	0°

[1] Subtract a radius of 35 mm from all values to obtain distance relative to the edge of the tree trunk.

[2] Sensor orientation in cover crop area parallel to tree row; no equipment for 800 mm depth.

Table A3. Identification (ID) and positioning of CS616 soil water content sensors installed in 8 soil profiles in the high canopy cover 'Golden Delicious' orchard at Kromfontein in 2014/15. Sensors were installed at 150 mm, 450 mm, 750 mm and 1050 mm soil depths.

Soil profile ID	Position relative to tree trunk[1] (mm, orientation)		
	In tree row	**Perpendicular to tree row**	**Angle relative to tree row**
NE Tree row	375 N	500 E	45°
SE Tree row	375 S	500 E	45°
E Workrow[2]	270 S	1800 E	0°
S Tree row	750 S	0	0°
N Tree row	750 N	0	0°
NW Tree row[3,4]	375 N	500 W	45°
SW Tree row[4]	375 S	500 W	45°
W Workrow[2]	270 S	1800 W	0°

[1] Subtract a radius of 68 mm from all values to obtain distance relative to the edge of the tree trunk.

[2] No equipment available for 1050 mm depth.

[3] CS616 sensor at 450 mm depth (GD22) located 60 mm to the right of the other sensors in the soil profile due to roots preventing installation in original profile position.

[4] CS616 sensor at 750 mm depth installed in a rebuilt profile due to stone preventing installation in original profile.

Table A4. Identification (ID) and positioning of CS616 soil water content sensors installed in 8 soil profiles in the high canopy cover 'Golden Delicious' orchard at Southfield in 2015/16. Sensors were installed at 150 mm, 450 mm, 750 mm and 1100 mm soil depths.

Soil profile ID	Position relative to tree trunk[1] (mm, orientation)		
	In tree row	**Perpendicular to tree row**	**Angle relative to tree row**
N Workrow[2]	390 W	1790 N	0°
NE Tree row	540 E	650 N	45°
NW Tree row	588 W	645 N	45°
E Tree row	1000 E	0	0°
W Tree row	1000 W	0	0°
SE Tree row	545 E	622 S	45°
SW Tree row[3]	586 W	555 S	45°
	533 W	653 S	45°
S Workrow[2, 3]	317 W	1990 S	0°
	326 W	2100 S	0°

[1] Subtract a radius of 90 mm from all values to obtain distance relative to the edge of the tree trunk.

[2] Sensors in cover crop area, orientation parallel to tree row; no equipment for 1100 mm depth.

3 Roots prevented installation in original profile position.

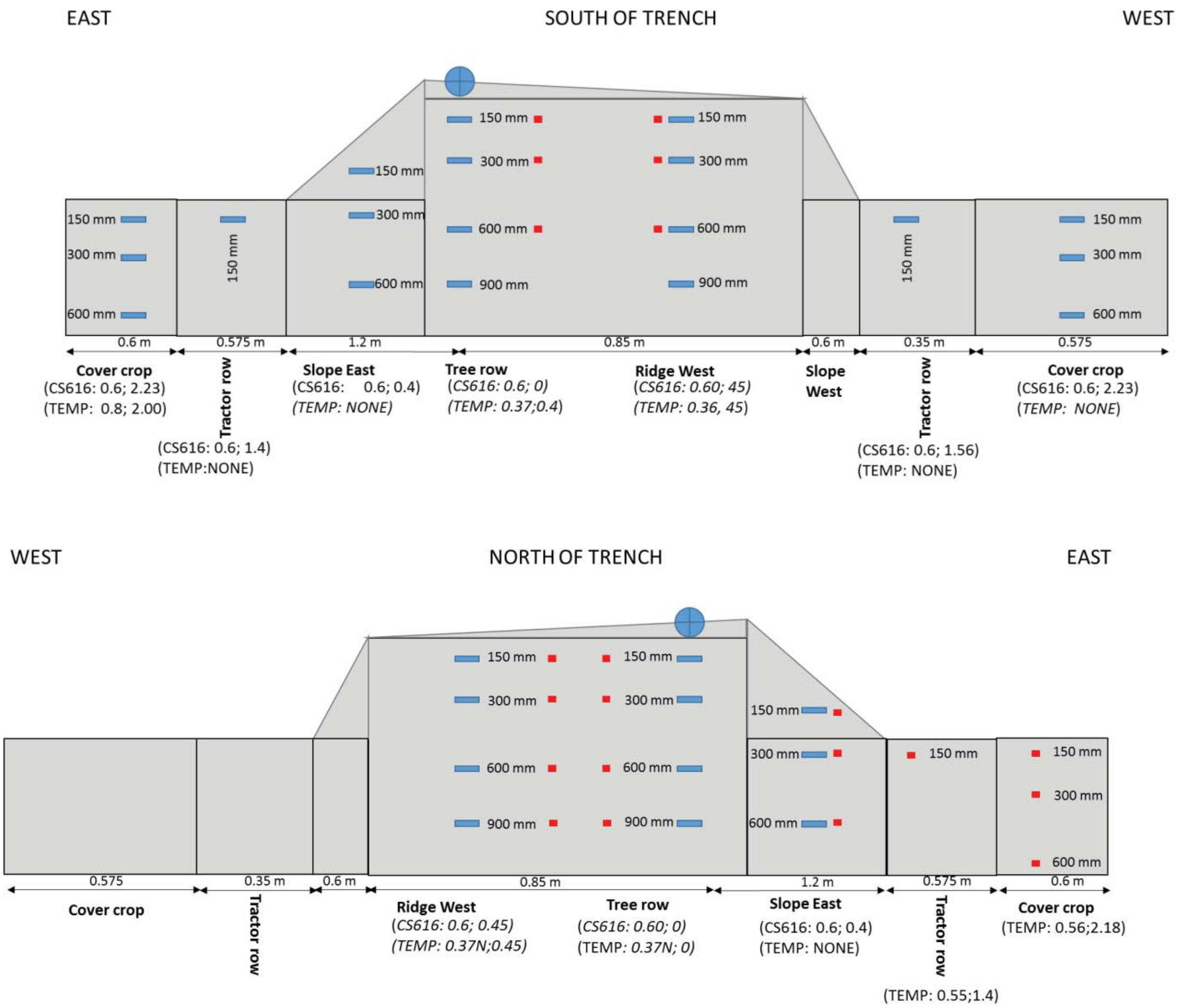

Fig. A4 Illustration of the position and depths of the CS616 sensors (blue blocks) and thermocouples (red dots) installed in soil relative to ridged 'Cripps' Pink' trees at Esperanto in the KBV in 2016/17. Diagrams indicate tree position South and North, respectively, relative to a trench between two trees. The X and Y co-ordinates of installation positions are indicated in brackets.

Appendix B. Soil particle size and chemical analysis

Table. B1 Texture class and particle size analysis for different soil depth increments of the soils sampled at the low canopy cover orchards.

Orchard	Depth increment (cm)	Texture class	Clay	Silt %	Sand	Stone (v/v)
Lindeshof W03	0-50	Sandy loam	14.2	2.0	83.8	5.0
(NBGR)	50-225	Sandy loam	14.2	4.0	81.8	4.0
	225-450	Sandy loam	16.2	2.0	81.8	7.0
	450-700	Sandy loam	16.2	4.0	79.8	12.0
	700-900	Sandy loam	16.2	4.0	79.8	28.0
Paardekloof	0-100	Sand	6.2	2.0	91.8	3.0
(NBRG)	100-450	Sand	6.2	2.0	91.8	3.0
	450-750	Sand	6.2	2.0	91.8	2.0
	750-105	Sand	6.2	2.0	91.8	3.0
Vyeboom- Blok 14	0-225	Sandy loam	11.2	8.0	80.8	18.0
(NBCR)	225-450	Sandy loam	11.2	6.0	82.8	6.9
	450-700	Sandy loam	11.2	6.0	82.8	7.2
	700-900	Sandy loam	13.2	8.0	78.8	23.7
Vyeboom- Blok 24	0-450	Sandy clay	43.2	40.0	16.8	0.0
(NBGD)	450-700	Sandy clay	53.2	26.0	20.8	0.0
	700-900	Clay	57.2	36.0	6.8	0.0

APPENDIX B. (Continues)

Table. B2 The electrical conductivity of the saturated soil extract (ECe), pH, extractable phosphate (P Bray II) and potassium (K), exchangeable sodium (Na), K, calcium (Ca) and magnesium (Mg) and carbon (C) content of soil sampled at different soil increments in the low canopy cover orchards. Norms available for the different variables are indicated at the bottom of the table.

Orchard	Depth increment (mm)	EC_e (mS/m)	pH (KCl)	P Bray II (mg/kg)	K (mg/kg)	Exchangeable cations				C (%)
						Na cmol(+)/kg	K cmol(+)/kg	Ca cmol(+)/kg	Mg cmol(+)/kg	
Lindeshof W03 (NBGR)	0-50	22.2	5.6	54	93	0.12	0.24	3.21	0.98	1.37
	50-220	13.7	5.6	23	75	0.09	0.19	2.17	0.57	0.81
	220-450	12.0	5.6	17	75	0.09	0.19	2.16	0.64	0.79
	450-700	10.5	5.5	14	67	0.09	0.17	1.79	0.61	0.59
	700-900	8.2	5.4	11	57	0.09	0.15	1.46	0.48	0.53
Paardekloof (NBRG)	0-100	19.1	4.4	281	60	0.07	0.15	1.01	0.34	0.74
	100-450	16.1	5	164	59	0.09	0.15	1.55	0.42	0.66
	450-750	9.8	5.4	88	52	0.08	0.13	1.32	0.44	0.59
	750-1050	5.5	4.7	21	28	0.07	0.07	0.49	0.22	0.57
Vyeboom- Blok 14 (NBCR)	0-225	25.3	5.8	101.8	73.7	0.08	0.19	3.79	0.92	1.0
	225-450	20.6	6.0	131.7	84.6	1.07	0.22	4.98	1.02	1.3
	450-700	18.1	6.2	190.1	96.0	3.17	0.25	4.31	1.17	1.1
	700-900	16.1	5.7	46.0	59.0	0.13	0.15	2.57	0.70	0.9
Vyeboom- Blok 24 (NBGD)	0-450	19.0	4.3	19.0	131.4	0.73	0.34	2.94	0.72	1.3
	450-700	9.0	3.6	9.5	56.8	0.15	0.15	1.06	0.43	0.9
	700-900	15.3	3.2	15.3	33.2	0.12	0.08	0.86	0.36	0.8
Low			<5.5	<25	<80	-	<0.21	<2.80	<0.60	<0.8
Acceptable			5.5-6.5	25-150	80-190		0.2-0.5	>2.80	0.60-1.2	0.8-1.5
Excessive			>6.5	>150	>190		>0.5		>1.5	>1.5

APPENDIX B. (Continues)

Table B3. Texture class and particle size analysis for different soil depth increments of the soils sampled at the medium canopy cover orchards.

Orchard	Depth increment (mm)	Texture class	Clay	Silt %	Sand	Stone (v/v)
Lindeshof W04	0-225	Sandy loam	13	6	81	6.1
(IBGR)	225-450	Sandy loam	13	6	81	21.9
	450-700	Sand	0	11	89	22.5
	700-900	Sand	0	9	91	33.5
Esperanto B15	0-450	Loamy sand	1	16	83	0
(IBCP)	450-700	Loamy sand	1	14	85	0
	700-900	Loamy sand	9	8	83	0
Vyeboom- Block B6	0-300	Sandy clay loam	27	12	61	0
(IBGR)	300-600	Sandy clay loam	27	14	59	12.5
	600-800	Sandy clay loam	25	22	53	37.9
Dennebos Block 13B	0-300	Clay loam	37	28	35	46.5
(IBCP)	300-450	Clay	45	20	35	75.8

APPENDIX B. (Continues)

Table B4. The electrical conductivity of the saturated soil extract (ECe), pH, extractable phosphate (P Bray II) and potassium (K), exchangeable sodium (Na), K, calcium (Ca) and magnesium (Mg) and carbon (C) content of soil sampled at different soil increments in the medium canopy cover orchards. Norms available for the different variables are indicated at the bottom of the table.

Orchard	**Depth increment (mm)**	**EC$_e$ (mS/m)**	**pH (KCl)**	**P Bray II (mg/kg)**	**K (mg/kg)**	**Exchangeable cations**				**C (%)**
						Na cmol(+)/kg	**K cmol(+)/kg**	**Ca cmol(+)/kg**	**Mg cmol(+)/kg**	
Lindeshof W04[1] (IBGR)	0-225	13	5.5	31	73	0.04	0.19	3.17	1.09	1.1
	225-450	16	5.6	19	49	0.05	0.12	2.58	1.00	0.7
	450-700	10	5.5	17	54	0.06	0.14	2.11	0.92	0.6
	700-900	7	5.5	10	55	0.05	0.14	1.65	0.79	0.5
Esperanto B15[1] (IBCP)	0-450	7	5.4	97	64	0.08	0.16	2.53	0.81	0.7
	450-700	4	6.2	11	24	0.16	0.06	2.07	0.56	0.3
	700-900	13	5.5	31	73	0.04	0.19	3.17	1.09	1.1
Vyeboom- Block B6[2] (IBGR)	0-300	43	5.1	104	85	0.11	0.22	3.85	0.74	1.6
	300-600	21	5.9	74	64	0.09	0.16	4.47	0.76	1.3
	600-800	17	5.8	40	66	0.11	0.17	4.55	0.98	1.2
Dennebos Block 13B[2] (IBCP)	0-300	28	5.1	103	81	0.11	0.21	7.24	1.31	2.6
	300-450	14	5.5	52	75	0.1	0.19	5.44	1.07	1.1
Low			<5.5	<25	<80	-	<0.21	<2.80	<0.60	<0.8
Acceptable			5.5-6.5	25-150	80-190		0.2-0.5	>2.80	0.60-1.2	0.8-1.5
Excessive			>6.5	>150	>190		>0.5		>1.5	>1.5

Sampled end August 2016 Sampled end November 2016

APPENDIX B. (Continues)

Table. B5 Texture class and particle size analysis for different soil depth increments of the soils sampled at the high canopy cover orchards.

Orchard	Depth increment (mm)	Texture class	Clay	Silt %	Sand	Stone (v/v)
Kromfontein KP07A	0-50	Sandy loam	10.2	4.0	85.8	11
Soil water balance	50-300	Sandy loam	12.2	4.0	83.8	18
(FBGD)	300-600	Sandy loam	14.2	2.0	83.9	20
	600-900	Sandy loam	14.2	2.0	83.8	19
	900-1100	Sandy loam	14.2	4.0	81.8	6
Kromfontein KP07B	0-50	Loamy sand	8.2	6.0	85.8	8
Eddy covariance	50-300	Loamy sand	8.2	4.0	87.8	12
(FGBD)	300-600	Loamy sand	8.2	4.0	87.8	12
	600-900	Loamy sand	8.2	4.0	87.8	8
	900-1100	Sandy loam	10.2	4.0	85.9	6
Kromfontein KP06	0-450	Sandy loam	12.2	4.0	83.80	11
(FBCP)	450-750	Sandy loam	14.2	4.0	81.82	20
	750-1050	Sandy loam	14.2	4.0	81.80	12
Southfield	0-300	Loamy sand	9.2	8	82.8	0.0
(FBGD)	300-600	Sandy loam	11.2	10	78.8	0.0
	600-900	Sandy loam	11.2	8	80.8	0.0
Radyn	0-450	Clay loam	39.2	26	34.8	36.6
(FBCP)	450-700	Clay loam	37.2	30	32.8	27.4
	700-900	Clay loam	35.2	32	32.8	0.0

Table. B6 The electrical conductivity of the saturated soil extract (ECe), pH, extractable phosphate (P Bray II) and potassium (K), exchangeable sodium (Na), K, calcium (Ca) and magnesium (Mg) and carbon (C) content of soil sampled at different soil increments in the high canopy cover orchards. Norms available for the different variables are indicated at the bottom of the table.

Orchard	**Depth (mm)**	**EC_e (mS/m)**	**pH (KCl)**	**P Bray II (mg/kg)**	**K (mg/kg)**	**Exchangeable cations Na cmol(+)/kg**	**K cmol(+)/kg**	**Ca cmol(+)/kg**	**Mg cmol(+)/kg**	**C (%)**
Kromfontein KP07A	0-50	23.6	6.5	128	120	0.12	0.31	9.15	2.23	2.52
Soil water balance	50-300	11.4	5.6	49	84	0.08	0.22	2.1	0.65	0.88
(FBGD)	300-600	8.7	5.4	52	52	0.09	0.13	1.62	0.55	0.73
	600-900	6.3	5.4	29	36	0.08	0.09	0.92	0.36	0.54
	900-1100	5.1	5.3	14	19	0.07	0.05	0.7	0.31	0.51
Kromfontein KP07B	0-50	15.5	5.9	44	63	0.12	0.16	5.25	1.2	1.63
Eddy Covariance	50-300	4.2	5.4	41	22	0.08	0.06	1.58	0.44	0.68
(FBGD)	300-600	4.5	5.6	48	14	0.07	0.04	1	0.35	0.66
	600-900	5.9	5.2	21	11	0.08	0.03	0.7	0.32	0.54
	900-1100	6.6	5.3	15	11	0.08	0.03	0.55	0.26	0.32
Kromfontein KP06	0-450	14.3	5.3	59	65	0.1	0.17	2.03	0.7	0.99
(FBCP)	450-750	7.7	5.3	40	50	0.08	0.13	1.29	0.53	0.68
	750-1050	6.1	6.8	14	28	0.07	0.07	0.76	0.35	0.51
Southfield	0-300	12.1	4.6	4.9	44.9	0.08	0.11	2.56	0.80	1.1
(FBGD)	300-600	7.4	4.6	17.0	26.7	0.10	0.07	1.95	0.85	0.9
	600-900	9.2	4.8	22.2	23.0	0.13	0.06	1.92	0.89	0.8
Radyn	0-450	24.2	5.2	22.1	58.5	0.26	0.15	5.75	1.60	1.3
(FBCP)	450-700	30.3	5.5	13.0	37.2	0.51	0.10	3.64	2.24	0.9
	700-900	36.0	4.4	3.8	30.6	0.57	0.08	3.48	4.77	0.8
Low			<5.5	<25	<80	-	<0.21	<2.80	<0.60	<0.8
Acceptable			5.5-6.5	25-150	80-190		0.2-0.5	>2.80	0.60-1.2	0.8-1.5
Excessive			>6.5	>150	>190		>0.5		>1.5	>1.5

Appendix C. Soil water retention statistics

Table. C1 Summary of soil water retention curve statistics for the soil in the low canopy cover orchards at Lindeshof, Paardekloof and Vyeboom Boerdery

Orchard	Depth	Mathematical model	Equation	Coefficient a	Coefficient b	$R^2_{adjusted}$ (%)	p-value	Standard error of the estimate	Soil matric potential range		N
									Min	Max	
Lindeshof (NBGR)	300	Multiplicative	Y = a*X^b	3.3745	-0.3714	92.75	<0.0001	0.1204	4	81	15
	600	Multiplicative	Y = a*X^b	3.3398	-0.3347	96.23	<0.0001	0.0838	4	80	14
	800	Multiplicative	Y = a*X^b	3.1844	-0.3019	91.22	<0.0001	0.1161	2	69	15
Paardekloof (NBRG)	300	Reciprocal-X	Y = a + b/X	5.0410	38.9713	74.85	<0.0001	0.9052	7	51	19
	600	Reciprocal-X	Y = a + b/X	4.6773	44.9566	71.78	<0.0001	0.8584	8	40	19
	900	Reciprocal-X	Y = a + b/X	2.8970	51.8335	42.80	<0.0001	1.0061	9	30	19
Vyeboom Block 14 (NBCR)	300	S-curve	Y = exp(a + b/X)	1.877	3.678	80.33	<0.0001	0.177	4	78	13
	600	S-curve	Y = exp(a + b/X)	1.667	6.017	80.68	<0.0001	0.221	4	64	17
	800	S-curve	Y = exp(a + b/X)	1.800	5.286	91.82	<0.0001	0.140	4	77	19

Table C2. Summary of soil water retention curve statistics for the soil in the medium canopy cover orchards at Lindeshof and Esperanto in the KBV and Vyeboom Boerdery in EGVV.

Orchard	**Depth**	**Mathematical model**	**Equation**	**Coefficient a**	**Coefficient b**	**$R^2_{adjusted}$ (%)**	**p-value**	**Standard error of the estimate**	**Soil matric potential range**		**N**
									Min	**Max**	
Lindeshof (IBGR)	300	Multiplicative	Y = a*X^b	3.173	-0.328	97.01	<0.0001	0.072	2	81	25
	600	Multiplicative	Y = a*X^b	3.07	-0.282	91.34	<0.0001	0.11	3	80	27
	800	Multiplicative	Y = a*X^b	3.151	-0.276	88.76	<0.0001	0.115	2	71	27
Esperanto (IBCP)	300	Reciprocal-X	Y = a + b/X	8.427	88.89	98.57	<0.0001	0.628	5	81	14
	600	Multiplicative	Y = a*X^b	3.639	-0.313	84.42	<0.0001	0.131	5	81	22
	800	Multiplicative	Y = a*X^b	4.187	-0.514	98.54	<0.0001	0.033	5	26	8
Vyeboom Block 6 (IBGR)	300	Multiplicative	Y = a*X^b	3.818	-0.261	92.05	<0.0001	0.063	8	84	23
	600	Reciprocal-X	Y = a + b/X	13.198	113.923	87.30	<0.0001	0.913	10	82	24

Table. C3 Summary of soil water retention curve statistics for the soil in the high canopy cover orchards at Kromfontein (KP06 and KP07) in the KBV and Southfield (Block 4) in EGVV.

Orchard	**Depth**	**Mathematical model**	**Equation**	**Coefficient a**	**Coefficient b**	**$R^2_{adjusted}$ (%)**	**p-value**	**Standard error of the estimate**	**Soil matric potential range**		**N**
									Min	**Max**	
KP06	300	Reciprocal-Y	Y = 1/(a + b*X)	0.0451	0.0049	83.39	0.0001	0.0085	2	14.5	11
(FBCP)	600	Reciprocal-Y	Y = 1/(a + b*X)	0.0458	0.0038	87.86	<0.0001	0.0049	4	17	13
	900	Reciprocal-Y	Y = 1/(a + b*X)	0.0384	0.0044	72.21	0.0023	0.0061	4	15	9
KP07	150	Reciprocal-X	Y = a + b/X	5.9275	42.0249	86.46	<0.0001	1.2403	4	70	18
(FBGD)	450	Reciprocal-Y logarithmic-X	Y = 1/(a + b*ln(X))	0.0271	0.0338	78.46	<0.0001	0.0138	4	76	19
	750	Reciprocal-Y logarithmic-X	Y = 1/(a + b*ln(X))	0.0300	0.0272	80.95	<0.0001	0.0122	2	65	21
Southfield	150	Multiplicative	$Y = (a + b/X)^2$	3.746	-0.446	85.28	<0.0001	0.197	2	87	15
Block 4	450	Multiplicative	Y = a*X^b	3.777	-0.462	91.22	<0.0001	0.174	4	90	21
(FBGD)	750	Multiplicative	Y = a*X^b	3.681	-0.403	94.03	<0.0001	0.131	2	88	26

Appendix D. Cs616 calibration statistics

Table. D1 Summary of linear regression statistics of gravimetrically sampled volumetric soil water content vs CS616 period of 30 CS616 sensors installed at four depths and in eight different positions relative to the tree at Lindeshof in 2014/15.

Position	Xcoeff	Intercept	R^2 (%)	p	Estimate SE	MAE	n	Period Range Min	Max
S150	0.035	-0.538	87.7	0.0006	0.0196	0.0138	8	17.6	21.2
N150[1]	0.041	-0.655	100.0	<0.0001	0.0010	0.0007	6	17.5	21.3
SE150[2]	0.049	-0.826	97.9	0.0002	0.0120	0.0090	6	18.0	21.7
SW150	0.051	-0.897	90.8	0.0003	0.0165	0.0109	8	18.8	21.7
NE150	0.034	-0.553	99.4	0.0002	0.0049	0.0034	5	18.0	21.7
NW150	0.029	-0.458	97.3	0.0019	0.0075	0.0051	5	18.0	21.4
WRE150	0.032	-0.547	98.3	<0.0001	0.0047	0.0034	8	18.3	21.1
WRW150	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	2	18.2	20.0
WR150	0.031	-0.522	97.6	<0.0001	0.0051	0.0035	10	18.2	21.1
S_N150	-0.518	0.033	91.2	<0.0001	0.0128	0.0097	13	17.5	21.3
SE_NE150	0.041	-0.691	94.4	<0.0001	0.0158	0.0097	11	18.0	21.7
ALL150	0.035	-0.580	78.4	<0.0001	0.0234	0.0191	47	17.5	21.7
S300	0.035	-0.557	98.2	<0.0001	0.0063	0.0044	7	18.1	21.5
N300[1]	0.052	-0.873	87.1	0.0021	0.0101	0.0149	7	18.1	21.8
SE300	0.028	-0.464	99.5	0.0026	0.0038	0.0021	4	18.3	21.5
SW300	0.027	-0.402	92.6	0.0001	0.0110	0.0080	8	17.9	21.6
NE300	0.051	-0.879	99.9	0.0007	0.0039	0.0023	4	18.3	21.7
NW300	0.026	-0.409	93.0	0.0001	0.0093	0.0067	8	18.7	22.1
WRE300	0.050	-0.855	98.7	<0.0001	0.0046	0.0027	7	18.0	20.0
WRW300	0.023	-0.380	98.9	<0.0001	0.0037	0.0025	6	18.4	21.9
S_N300	0.037	-0.585	87.1	<0.0001	0.0146	0.0100	14	18.1	21.8
ALL300	0.033	-0.534	74.7	<0.0001	0.0230	0.0184	51	17.9	22.1
S600	0.031	-0.494	85.1	0.0011	0.0172	0.0130	8	19.2	22.7
N600[1]	0.049	-0.919	83.6	0.0015	0.0166	0.0124	8	21.1	23.2
SE600	0.020	-0.301	83.0	0.0016	0.0139	0.0105	8	18.8	22.6
SW600	0.045	-0.739	97.3	<0.0001	0.0074	0.0049	7	18.5	20.8
NE600	0.048	-0.803	97.1	0.0021	0.0078	0.0050	5	18.6	20.4
NW600	0.023	-0.354	77.0	0.0042	0.0223	0.0173	8	18.7	23.2
WRW600	0.048	-0.849	98.1	<0.0001	0.0067	0.0040	8	18.6	21.3
WRE600	0.024	-0.383	98.7	<0.0001	0.0026	0.0019	7	18.1	20.4
S_N600	0.028	-0.447	82.0	<0.0001	0.0173	0.0138	13	19.2	23.2
ALL600	0.027	-0.438	73.7	<0.0001	0.0237	0.0193	59	18.1	23.2
N800	0.035	-0.589	88.3	0.0016	0.0157	0.0114	7	19.0	22.0
S800	0.033	-0.613	83.5	0.0860	0.0192	0.0121	4	22.5	24.8
SE800	0.036	-0.584	95.2	0.0009	0.0084	0.0058	5	18.1	20.4
SW800	0.026	-0.401	98.2	<0.0001	0.0051	0.0040	7	19.1	22.5
NE800	0.029	-0.474	53.7	0.0387	0.0215	0.0168	8	19.4	21.2
NW800	0.025	-0.343	95.9	0.0001	0.0089	0.0055	7	17.6	22.1
ALL800	0.018	-0.243	66.8	<0.0001	0.0223	0.0179	38	17.61	24.82
ALLDATA	0.027	-0.420	70.5	<0.0001	0.0248	0.0199	195	17.46	24.82

[1] Used N_S combined calibration to improve soil water content estimates for tree row N.

[2] Used SE_NE150 combined calibration to improve soil water content estimates for SE150.

Table D2 Summary of linear regression statistics of gravimetrically sampled volumetric soil water content vs CS616 period of 30 CS616 sensors installed at four depths and in eight different positions relative to the tree at Vyeboom Boerdery Block 14 in 2015/16.

Position	Xcoeff	Intercept	R^2 (%)	p	Estimate SE	MAE	n	Period Range Min	Max
TRE150[1]	0.068	-1.298	97.6	<0.0001	0.0136	0.0110	7	20.4	23.7
TRW150[1]	0.068	-1.298	97.6	<0.0001	0.0136	0.0110	7	20.4	23.7
WRSE150	0.025	-0.404	97.9	<0.0001	0.0076	0.0049	7	18.2	23.8
TRRSE150	0.026	-0.430	95.3	0.0008	0.0103	0.0067	5	19.3	23.8
SLSE150	0.023	-0.335	98.1	0.0001	0.0044	0.0031	6	18.5	22.2
WRSW150	0.041	-0.700	99.6	<0.0001	0.0037	0.0028	7	18.4	22.2
SLSW150	0.044	-0.699	97.6	0.0016	0.0088	0.0052	5	18.5	21.0
WRNE150	0.024	-0.379	88.6	0.0051	0.0127	0.0080	6	18.2	21.8
TRRNE150	0.035	-0.575	99.8	<0.0001	0.0032	0.0019	5	17.9	22.5
SLNE150	0.021	-0.314	94.5	0.0012	0.0094	0.0068	6	18.6	23.3
WRNW150	0.039	-0.642	97.2	0.0003	0.0112	0.0079	6	18.0	22.2
SLNW150	0.030	-0.520	98.2	<0.0001	0.0050	0.0027	7	19.7	23.1
TRE_W150	0.030	-0.46406	80.0	0.0001	0.0237	0.0194	12	18.4	23.7
D150All	0.029	-0.460	72.5	<0.0001	0.0282	0.0211	74	17.9	23.8
TRE300[1]	0.068	-1.298	97.6	<0.0001	0.0136	0.0110	7	20.4	23.7
TRW300[1]	0.068	-1.298	97.6	<0.0001	0.0136	0.0110	7	20.4	23.7
WRSE300	0.035	-0.569	98.4	<0.0001	0.0057	0.0041	7	18.4	21.9
SLSE300	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0	n.a.	n.a.
WRSW300	0.043	-0.706	85.1	0.0031	0.0235	0.0191	7	18.5	22.0
SLSW300	0.045	-0.757	89.2	0.0014	0.0134	0.0106	7	19.2	21.6
WRNE300	0.033	-0.551	98.3	0.0001	0.0066	0.0042	6	18.3	22.1
SLNE300	0.027	-0.431	96.2	0.0001	0.0056	0.0039	7	19.0	21.7
WRNW300	0.034	-0.570	99.3	<0.0001	0.0040	0.0028	7	18.9	22.6
SLNW300	0.027	-0.438	92.0	0.0006	0.0111	0.0089	7	19.0	22.8
TRE_W300	0.028	-0.438	84.5	0.0002	0.0163	0.0134	10	18.8	23.2
D300All	0.036	-0.593	79.0	<0.0001	0.0243	0.0189	59	18.3	23.2
TRE600[2]	0.062	-1.134	90.1	0.0508	0.0140	0.0089	4	20.6	22.1
TRW600	0.017	-0.190	84.0	0.0287	0.0090	0.0064	5	21.2	24.0
SLSE600	0.030	-0.498	88.3	0.0017	0.0122	0.0079	7	19.6	22.5
SLSW600	0.023	-0.313	97.7	<0.0001	0.0057	0.0040	7	18.8	23.3
SLNE600	0.040	-0.679	85.9	0.0027	0.0164	0.0116	7	19.0	21.5
SLNW600	0.037	-0.625	85.2	0.0087	0.0157	0.0114	6	19.6	22.1
TRESLSW	0.026	-0.372	93.6	<0.0001	0.0097	0.0066	12	18.8	23.3
D600All	0.028	-0.427	70.0	<0.0001	0.0223	0.0175	36	18.8	24.0
TRE800	0.018	-0.208	83.771	0.0847	0.0089	0.0049	4	19.9	22.0
TRW800	0.022	-0.324	81.748	0.0959	0.0126	0.0072	4	22.5	24.7
D800All	0.015	-0.160	78.584	0.0034	0.0111	0.0073	8	19.9	24.7
ALLDATA	0.030	-0.484	75.8	<0.0001	0.0258	0.0197	177	17.9	24.7

[1] Used relationship of combined dataset for TRE and TRW for soil water content estimates.

[2] Used combined dataset for TRE and SLSW for soil water content estimates.

Table. D3 Summary of linear regression statistics of gravimetrically sampled volumetric soil water content vs CS616 period of 30 CS616 sensors installed at four depths and in eight different positions relative to the tree at Lindeshof in 2016/17.

Position	Xcoeff	Intercept	R^2 (%)	p	Estimate SE	MAE	n	Period Range Min	Max
S150	0.038	-0.612	99.9	<0.0001	0.0013	0.0007	5	18.4	20.9
N150	0.032	-0.531	90.9	0.0120	0.0091	0.0054	5	19.6	21.6
SE150	0.035	-0.556	99.6	<0.0001	0.0034	0.0028	6	18.2	21.2
SW150	0.035	-0.554	96.5	0.0005	0.0086	0.0064	6	18.1	20.9
NE150	0.028	-0.465	98.0	0.0012	0.0080	0.0056	5	19.3	22.9
NW150	0.025	-0.367	87.9	0.0057	0.0081	0.0057	6	18.5	21.3
WRE150	0.028	-0.475	99.0	<0.0001	0.0056	0.0043	6	17.7	22.0
WRW150	0.037	-0.646	98.3	0.0001	0.0087	0.0059	6	18.5	21.8
WR150	0.033	-0.564	95.7	<0.0001	0.0120	0.0093	12	17.7	22.0
ALL150	0.032	-0.518	80.8	<0.0001	0.0214	0.0185	45	17.7	22.9
S300	0.030	-0.472	85.7	0.0080	0.0120	0.0092	6	18.5	21.0
N300	0.035	-0.586	98.3	0.0001	0.0045	0.0032	6	18.9	21.3
SE300	0.036	-0.597	98.2	0.0001	0.0057	0.0043	6	18.2	20.5
SW300	0.040	-0.651	97.6	0.0002	0.0076	0.0049	6	18.1	20.6
NE300	0.031	-0.487	97.3	0.0003	0.0081	0.0057	6	18.6	21.7
NW300	0.019	-0.278	82.0	0.0944	0.0113	0.0066	4	18.4	20.7
NE&NW300	0.029	-0.454	90.0	<0.0001	0.0124	0.0101	10	18.4	21.7
WRE300	0.035	-0.590	95.7	0.0001	0.0117	0.0087	7	18.1	21.1
WRW300	0.037	-0.619	95.3	0.0002	0.0101	0.0077	7	18.1	20.5
ALL300	0.035	-0.583	87.0	<0.0001	0.0159	0.0122	48	18.1	21.7
S600	0.028	-0.467	88.9	0.0571	0.0156	0.0088	4	19.2	21.8
N600	0.020	-0.289	96.9	0.0023	0.0069	0.0046	5	18.7	22.5
S&N600	0.023	-0.353	87.8	0.0001	0.0127	0.0094	10	18.7	22.5
SE600	0.036	-0.618	96.0	0.0001	0.0096	0.0067	7	18.6	21.3
SW600	0.041	-0.681	97.0	0.0003	0.0075	0.0040	6	18.2	20.3
NE600	0.029	-0.446	94.2	0.0013	0.0099	0.0071	6	18.1	21.1
NW600	0.019	-0.286	99.7	<0.0001	0.0021	0.0012	6	18.7	22.4
WRW600	0.038	-0.615	98.3	<0.0001	0.0063	0.0044	7	17.5	20.0
WRE600	0.039	-0.671	99.4	<0.0001	0.0035	0.0021	6	18.5	20.7
ALL600	0.024	-0.365	79.2	<0.0001	0.0177	0.0143	47	17.5	22.5
S800	0.029	-0.471	88.9	0.0048	0.0145	0.0114	6	19.0	22.4
N800	0.040	-0.643	88.8	0.0049	0.0135	0.0093	6	18.1	20.0
SE800	0.028	-0.454	91.3	0.0008	0.0111	0.0074	7	19.3	22.0
SW800	0.085	-1.524	90.4	0.0010	0.0147	0.0100	7	18.6	19.8
NE800	0.036	-0.588	99.1	<0.0001	0.0047	0.0032	6	18.7	21.5
NW800	0.044	-0.693	99.4	<0.0001	0.0032	0.0019	6	17.96	19.88
ALL800	0.020	-0.276	46.2	<0.0001	0.0291	0.0250	38	17.96	22.41
ALLDATA	0.028	-0.436	71.7	<0.0001	0.0231	0.0182	178	17.51	22.92

Table D4. Summary of linear regression statistics of gravimetrically sampled volumetric soil water content vs CS616 period of 30 CS616 sensors installed at four depths and in eight different positions relative to the tree at Esperanto Block 15 in 2016/17.

Position	Xcoeff	Intercept	R^2 (%)	p	Estimate SE	MAE	n	Period Range Min	Max
TRS150	0.011	-0.032	98.2	0.001	0.003	0.002	5	18.9	23.8
TRN150	0.048	-1.007	75.8	0.024	0.031	0.023	6	22.1	24.6
TRNRNW150	0.023	-0.364	90.0	0.000	0.015	0.011	9	20.1	25.2
RSW150	0.023	-0.324	84.8	0.003	0.017	0.013	7	20.8	25.7
RNW150	0.023	-0.363	95.9	0.001	0.011	0.007	6	20.1	25.2
SLSE150	0.021	-0.341	86.9	0.021	0.011	0.007	5	22.3	25.2
SLNE150	0.036	-0.715	95.9	0.001	0.013	0.008	6	22.0	25.9
SLSE&NE150	0.031	-0.577	85.5	<0.0001	0.018	0.014	11	22.0	25.9
TRTSE150	0.027	-0.459	98.2	0.000	0.006	0.004	6	22.6	26.3
TRTSW150	0.012	-0.125	98.5	0.000	0.003	0.002	6	18.5	23.9
CCSE150	0.010	-0.123	77.6	0.020	0.012	0.007	6	18.1	24.8
CCSW150	0.011	-0.146	88.6	0.005	0.012	0.009	6	18.6	27.1
ALL150	0.015	-0.186	35.1	<0.0001	0.042	0.034	59	18.1	27.1
TRS300	0.025	-0.353	100.0	0.0042	0.0002	0.0001	3	22.2	25.2
TRN300	0.024	-0.379	97.6	<0.0001	0.0064	0.0039	7	21.1	25.4
RSW300	0.032	-0.577	87.6	0.0019	0.0191	0.0135	7	21.1	25.1
RNW300	0.026	-0.423	82.9	0.0044	0.0195	0.0154	7	21.0	24.5
SLSE300	0.018	-0.222	95.2	0.0046	0.0046	0.0030	5	22.0	24.5
SLNE300	0.036	-0.654	95.8	0.0007	0.0104	0.0076	6	21.7	24.8
CCSE300	0.021	-0.351	99.0	<0.0001	0.0070	0.0047	6	19.3	28.2
CCSW300	0.045	-0.769	97.3	0.0003	0.0115	0.0090	6	18.0	22.0
ALL300	0.023	-0.349	71.2	<0.0001	0.0282	0.0203	47	18.0	28.2
TRS600	0.021	-0.278	89.7	0.0145	0.0112	0.0065	5	22.0	25.3
TRN600	0.021	-0.282	89.9	0.0040	0.0087	0.0056	6	22.7	25.6
RSW600	0.015	-0.230	93.2	0.0018	0.0113	0.0077	6	21.1	27.6
RNW600	0.023	-0.286	96.7	0.0165	0.0093	0.0061	4	19.3	25.2
SLSE600	0.041	-0.714	78.0	0.0197	0.0152	0.0113	6	20.1	21.9
SLNE600	0.020	-0.272	88.7	0.2186	0.0092	0.0044	3	20.9	23.0
SLNETRN600	0.022	-0.320	95.9	<0.0001	0.0078	0.0057	9	20.9	25.6
CCSE600	0.015	-0.172	92.4	0.0022	0.0071	0.0053	6	21.1	25.4
CCSW600	0.041	-0.818	95.1	0.0002	0.0125	0.0086	7	22.4	26.3
ALL600	0.010	-0.049	27.0	0.0004	0.0354	0.0281	43	19.3	27.6
TRS900	0.039	-0.697	89.7	0.0012	0.0102	0.0066	7	21.6	23.4
TRN900	0.040	-0.726	96.0	0.0006	0.0063	0.0045	6	21.7	23.5
RSW900	0.009	-0.125	61.0	0.0382	0.0183	0.0148	7	32.4	39.2
RNW900	0.030	-0.536	95.2	0.0009	0.0068	0.0046	6	22.0	24.2
ALL900[1]	0.028	-0.468	68.1	<0.0001	0.0159	0.0132	18	21.6	24.2
ALLDATA	0.016	-0.193	40.5	<0.0001	0.0372	0.0293	168	18.0	28.2

1 Excludes RSW900

Table D5. Summary of linear regression statistics of gravimetrically sampled volumetric soil water content vs CS616 period of 30 CS616 sensors installed at four depths and in eight different positions relative to the tree at Kromfontein KP07.

Position	Xcoeff	Intercept	R^2 (%)	p	Estimate SE	MAE	n	Period Range Min	Max
S150	0.062	-1.036	99.2	<0.0001	0.0065	0.0043	6	18.0	20.7
N150	0.030	-0.450	75.5	0.0051	0.0112	0.0089	8	17.3	19.1
SE150	0.007	-0.038	87.8	0.0188	0.0028	0.0017	5	17.3	19.6
SW150	0.044	-0.675	94.6	0.0011	0.0133	0.0091	6	17.9	21.0
NE150	0.038	-0.588	94.1	0.0301	0.0049	0.0029	4	16.8	19.2
NW150[1]	0.027	-0.390	91.2	0.0002	0.0114	0.0077	8	16.8	20.3
WRE150	0.056	-0.905	81.6	0.0021	0.0195	0.0144	8	17.2	19.6
WRW150	0.030	-0.509	97.0	<0.0001	0.0061	0.0051	8	18.4	22.1
ALL150	0.022	-0.300	48.4	<0.0001	0.0284	0.0198	48	16.8	22.1
S450	0.041	-0.625	99.5	0.0470	0.0060	0.0032	3	17.0	19.8
N450	0.057	-0.928	84.8	0.0092	0.0195	0.0140	6	17.2	19.3
SE450	0.027	-0.401	95.9	0.0207	0.0086	0.0050	4	17.1	20.0
SW450	0.083	-1.352	97.3	0.0134	0.0049	0.0032	4	17.0	19.1
NE450	0.059	-0.913	89.7	0.0012	0.0152	0.0115	7	16.8	18.7
NW450[2]	0.002	-0.405	97.5	<0.0001	0.0234	0.0167	7	14.0	20.1
WRE450	0.048	-0.744	86.8	0.0213	0.0144	0.0087	5	17.6	19.5
WRW450[3]	0.028	-0.402	90.1	0.0001	0.0153	0.0112	9	17.2	18.9
ALL450	0.031	-0.445	49.1	<0.0001	0.0259	0.0202	43	16.8	20.1
S750	0.033	-0.493	94.3	0.0012	0.0080	0.0052	6	16.9	19.2
N750	0.028	-0.401	79.3	0.0427	0.0137	0.0091	5	16.7	19.0
SE750[4]	0.056	-0.852	83.5	0.0040	0.0179	0.0126	7	16.5	18.5
SW750	0.029	-0.429	85.5	0.0246	0.0097	0.0066	5	17.1	20.2
NE750	0.064	-1.027	92.4	0.0001	0.0112	0.0081	8	17.2	19.3
NW750[2]	0.002	-0.420	97.1	0.0003	0.0287	0.0189	6	14.0	19.6
WRE750	0.039	-0.603	95.6	0.0221	0.0059	0.0034	4	18.1	19.7
WRW750	0.058	-0.899	91.2	0.0008	0.0164	0.0127	7	16.7	19.3
SESW750	0.02	-0.27	87.2	0.0001	0.0093	0.0071	10	16.5	20.2
ALL750	0.028	-0.392	53.6	<0.0001	0.0249	0.0182	47	16.5	20.2
S1050	0.059	-0.945	80.0	0.0162	0.0192	0.0129	6	17.1	18.9
N1050	0.057	-0.938	93.0	0.0019	0.0127	0.0089	6	17.7	19.5
SE1050	0.029	-0.419	97.6	0.0122	0.0043	0.0025	4	17.3	19.1
SW1050	0.031	-0.457	81.7	0.0021	0.0099	0.0082	8	17.5	19.5
NE1050	0.053	-0.849	92.4	0.0006	0.0078	0.0060	7	17.6	19.5
NW1050	0.030	-0.470	83.0	0.0016	0.0138	0.0098	8	18.2	20.7
ALL1050	0.025	-0.355	57.2	<0.0001	0.0197	0.0136	39	17.1	20.7
ALLDATA	0.023	-0.315	43.8	<0.0001	0.0268	0.0199	177	16.5	22.1

[1] Combined with NE150

[2] Square root-Y squared-X model: $Y = (a + b*X^2)^2$ –dataset included gravimetric soil water content (Y-variable) set equal to zero at a CS616 period (X-variable) of 14.

[3] Dataset included gravimetric soil water content set equal to zero at a CS616 period of 14.

[4] Used SE_SW750 combined calibration to improve water content estimates for SE750.

Table D6. Summary of linear regression statistics of gravimetrically sampled volumetric soil water content vs CS616 period of 30 CS616 sensors installed at four depths and in eight different positions relative to the tree at Southfield Block 4.

Position	Xcoeff	Intercept	R^2 (%)	P	Estimate SE	MAE	n	Period Range Min	Period Range Max
E150	0.023	-0.328	96.8	0.0004	0.0041	0.0030	6	20.4	23.0
W150	0.020	-0.274	94.3	0.0012	0.0070	0.0040	6	21.2	24.4
SE150	0.020	-0.227	86.3	0.0226	0.0064	0.0042	5	22.1	24.1
SW150	0.017	-0.184	95.6	0.0040	0.0066	0.0040	5	20.2	24.2
NE150	0.018	-0.228	81.6	0.0356	0.0081	0.0059	5	20.8	23.3
NW150	0.016	-0.172	76.7	0.0098	0.0067	0.0052	7	20.1	22.0
WRS150	0.033	-0.513	91.9	0.0025	0.0097	0.0070	6	19.2	21.9
WRN150	0.022	-0.304	77.4	0.0207	0.0097	0.0062	6	19.1	22.1
ALL150	0.019	-0.242	78.2	<0.0001	0.0135	0.0105	46	19.1	24.4
E450	0.045	-0.898	85.8	0.0003	0.0120	0.0073	9	22.3	24.1
W450	0.071	-1.452	96.0	<0.0001	0.0111	0.0087	8	21.9	24.9
SE450	0.031	-0.533	89.8	0.0012	0.0053	0.0032	7	22.1	23.6
SW450	0.052	-1.016	97.2	<0.0001	0.0063	0.0051	7	21.6	24.9
NE450	0.055	-1.089	87.3	0.0002	0.0113	0.0089	9	22.1	24.2
NW450	0.031	-0.545	97.8	0.0113	0.0032	0.0019	4	22.2	24.0
WRS450	0.039	-0.696	99.7	0.0001	0.0017	0.0010	5	21.2	22.9
WRN450	0.030	-0.526	84.1	0.0005	0.0153	0.0115	9	21.7	24.7
ALL450	0.034	-0.605	66.6	<0.0001	0.0186	0.0148	58	21.2	25.0
E750c[1]	0.044	-0.866	83.8	<0.0001	0.0106	0.0074	13	22.0	25.0
W750	0.048	-0.933	80.9	0.0146	0.0135	0.0088	6	22.2	24.4
W750c[1]	0.064	-1.295	91.1	<0.0001	0.0130	0.0102	14	21.9	24.9
SE750	0.059	-1.192	90.6	0.0001	0.0087	0.0067	9	22.4	24.0
SW750	0.031	-0.551	79.7	0.0005	0.0144	0.0120	10	21.8	24.6
NE750	0.024	-0.370	90.2	0.0011	0.0076	0.0056	7	22.0	24.5
NW750	0.026	-0.414	83.3	0.0041	0.0057	0.0045	7	21.9	23.2
WRS750	0.029	-0.488	96.0	0.0006	0.0048	0.0029	6	21.1	23.1
WRN750	0.015	-0.200	98.5	0.0076	0.0023	0.0016	4	20.6	23.5
WRN750c[1]	0.024	-0.398	83.0	<0.0001	0.0145	0.0103	13	20.6	24.7
ALL750	0.027	-0.448	67.3	<0.0001	0.0160	0.0132	53	20.6	24.6
E1100	0.064	-1.313	91.3	0.0008	0.0110	0.0086	7	23.1	24.4
W1100	0.054	-1.054	84.2	0.0280	0.0137	0.0095	5	22.2	23.5
E&W1100	0.054	-1.060	92.0	<0.0001	0.0119	0.0093	12	22.2	24.4
SE1100	0.056	-1.096	85.3	0.0085	0.0115	0.0083	6	23.0	24.2
SW1100	0.111	-2.403	94.6	0.0002	0.0069	0.0051	7	23.2	24.4
NE1100	0.019	-0.236	87.1	0.0066	0.0056	0.0041	6	22.3	24.1
NW1100	0.026	-0.401	82.3	0.0007	0.0054	0.0039	9	22.2	23.3
NE&NW1100	0.025	-0.369	88.3	<0.0001	0.0060	0.0044	15	22.2	24.1
ALL1100	0.043	-0.801	73.0	<0.0001	0.0162	0.0130	40	22.2	24.4
ALLDATA	0.023	-0.343	49.0	<0.0001	0.026	0.021	197	19.1	25.0

Appendix E. Calibration of the thermal dissipation sap flow method in potted apple trees

Apple trees were obtained from Caledon Nursery and potted in 50 L plastic containers in a mixture 1:2 (v/v) mixture of compost to sand in October 2016. These trees were grown in a glasshouse on the University of Pretoria’s Hatfield Experimental Farm (25° 44‟ 58.66‟‟ S, 28° 15‟ 31.65‟‟ E). The trees had attained a suitable stem diameter in December 2017 for the start of calibration experiments. A commercially available thermal dissipation probe (model TDP10, Dynamax Inc., Houston, TX, USA), which consisted of two 10 mm long 1.2 mm diameter stainless steel needles, was inserted radially into the stem, with one needle placed approximately 40 mm above the other. The probes were attached to a FLGS-TDP XM1000 sap velocity system from Dynamax, which consisted of a CR1000 logger, a AM16/32B multiplexer and an adjustable voltage regulator (AVRD). Voltage for the TDP10 probe was set at 2 V using the AVRD.

Transpiration volumes were calculated based on an empirical relationship in three species and artificial columns filled with synthetic fibre and sawdust (Granier 1985) and is expressed as:

$$SFD = 0.000119\left(\frac{\Delta T_o - \Delta T}{\Delta T}\right)^{1.231}$$

where ΔT_o is the temperature difference ΔT assessed during a period of zero flow (i.e. the maximum temperature difference between the two needles). The empirically determined coefficients (0.000119 and 1.231) do not apply under all conditions and in all species, which is one of the reasons why calibration is required.
Description and design / measurement protocol

A cantilever weighing lysimeter was used for the calibration of the sap flow system. The design of the lysimeters is given in Fig. E. The load cells used in the system have a range of 0 - 500 N which is equal to 0 - 51 kg with a sensitivity of 3.20789 mV V^{-1} (LC serial # 703370). Power was provided to the load cell via a 12 V battery and a voltage regulator to ensure a constant 12 V supply. The output signal from the two load cells was measured over a differential channel to increase the sensitivity of measurements on a CR10X data logger (Campbell Scientific Inc.) at a 1 s interval and then averaged over 15 min.

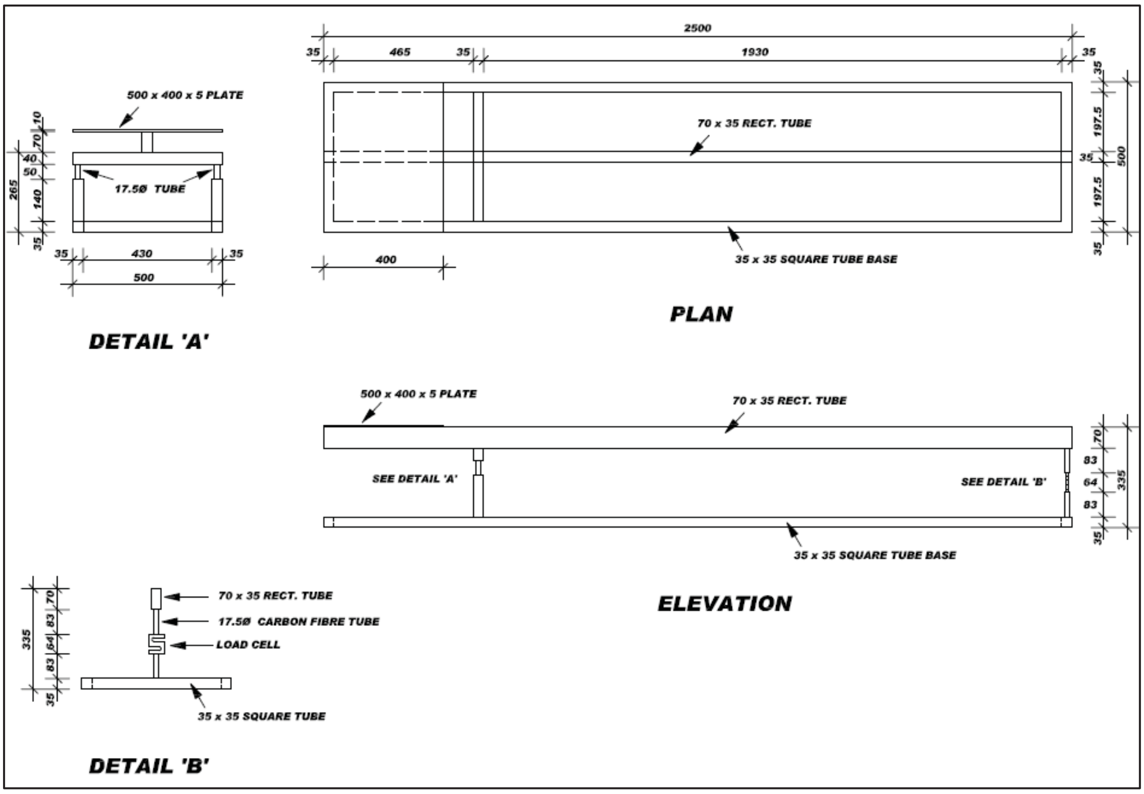

Fig. E1 Detailed sketch of the cantilever weighing lysimeters

Fig. E2: Weighing lysimeters in the glasshouse used for the calibration of the TDP sensors in apple trees

Calibration of the load cell on the weighing lysimeter

In order to determine the resolution of the load cell and convert the signal (mV$^-$) data into actual load or mass, calibration of a weighing lysimeter was required. The two weighing lysimeters were calibrated by adding various known masses on the lysimeter, using a set of 20 loads 0.1 kg, whilst the tree was on the lysimeter. It was reasoned that this would be the range in which measurements would be made. The two weighing lysimeter were calibrated by adding and removing the same mass to test for any hysteresis in the measurement.

The calibration results of lysimeter 1 and lysimeter 2 are shown in Fig E3. There was a strong linear relationship between the load cell output (mv) and the calibration mass (kg), with a 0.999 determination coefficient for both lysimeters. There was no evidence of hysteresis which would impact results.

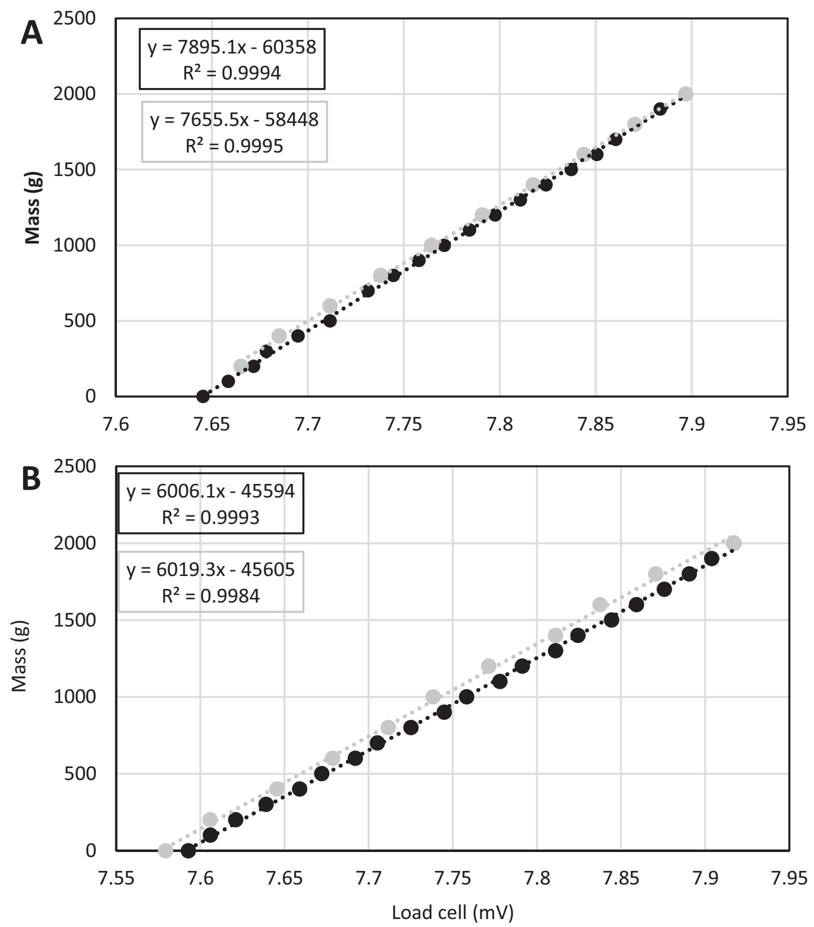

Fig. E3: Calibration of the lysimeters A) lysimeter 1 and B) lysimeter 2. The black line indicates the addition of mass and the grey line indicates the removal of mass.

Calibration of the sap flow techniques

Each pot was covered with black plastic to eliminate loss of water from the soil through evaporation and drainage of water from the bottom of the pot (*Fig. E*). Trees were irrigated five times during the night for 4 min, which equated to 1.12 L during each irrigation event (5.6 L in total) in order to ensure that the trees were not water stressed. Due to the low transpiration rates from the small apple trees, mass loss was determined at an hourly interval using the weighing lysimeter, whilst transpiration was determined on an hourly basis using the thermal dissipation method.

Two apple trees were used to calibrate sap flow (tree 1 circumference = 9.6 cm and tree 2 circumference = 9.2 cm). The calibration of tree 1 on lysimeter 1 will be discussed. Tree 2 demonstrated very low sap flow rates, with some interference with the lysimeter measurements as a result of air movement on the glasshouse. Due to the irrigation of trees at night, calibration was performed between 08:00 and 16:00, when the trees were actively transpiring. *Fig. E* illustrates the hourly comparison between transpiration determined by a weighing lysimeter and transpiration determined by the thermal dissipation method in a small potted apple tree.

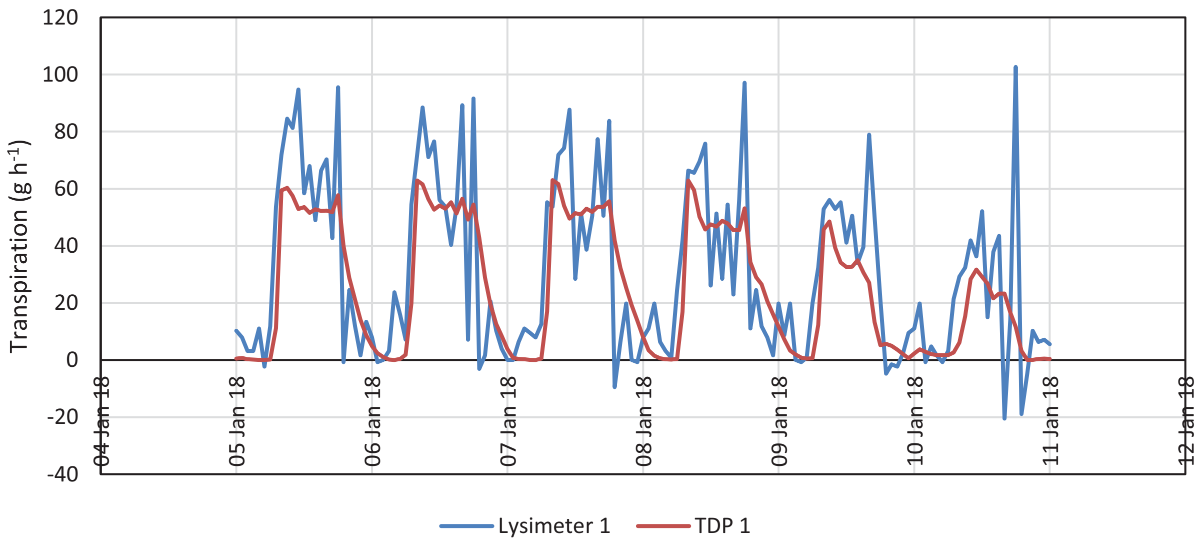

Fig. E4: Comparison of transpiration of an apple tree determined by a weighng lysimeter and the thermal dissipation method from 5 - 10 January 2018

Due to potential issues with lags between transpiration and sap flow calibration was performed by totally values between 08:00 and 16:00 (*Fig. E*). In addition, as zero mass loss from the lysimeter had to correlate with zero sap flow from the TDP system, the linear regression was forced through 0. The relationship between transpiration determined using the TDP system and that determined by the weighing lysimeter was fairly good with an R^2 value of 0.8638 and a regression equation of y=1.067x, indicating an almost 1:1 relationship. The TDP system was therefore able to accurately estimate transpiration of young apple trees on a daily basis.

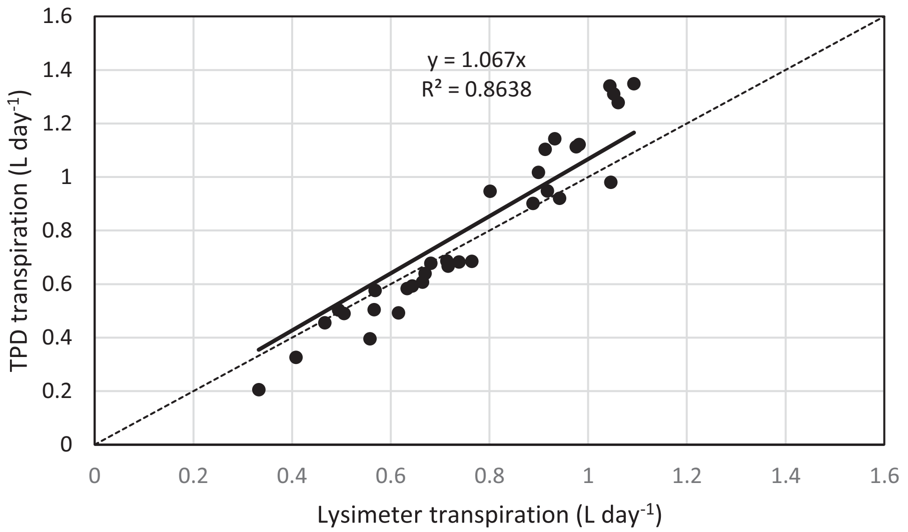

Fig. E5 Calibration of transpiration determined by the thermal dissipation method with transpiration determined using a weighing lysimeter. The 1:1 line is indicated by the dotted line.

Appendix F. Report on the field calibration of the li-cor lai-2000 plant canopy analyser

Introduction:

Researchers often rely on electronic instruments to measure various variables such as plant photosynthesis, crop water use and radiation interception. In many instances researchers are only interested in relative trends, but often want to know the absolute values. For this reason, it is important that these instruments are accurately calibrated. The LI-COR LAI-2000 plant canopy analyser is an instrument that is used to measure canopy interception of photosynthetically active radiation (PAR) and to calculate the leaf are index (LAI) non-destructively. This machine relies on a canopy extinction coefficient to do this calculation, which is very crop specific. This report provides a short summary of the methodology that was followed to check the calibration of the LI-COR LAI-2000 plant canopy analyser by comparing its calculations of LAI against destructively determined field measurements of LAI.

Material and Methods:

Three sites were selected to determine LAI destructively, namely Southfield, (Villiersdorp), Crookes Brothers (Vyeboom) and Oak Valley (Grabouw). These sites were selected such as to represent trees with large, medium and small canopies respectively. At each site four trees were selected randomly. Canopy height was measured vertically from the soil surface up to the tip of the highest branch and the canopy width (in the direction of the inter-row) horizontally from the tip of the lowest branch on one side of the tree up to the branch tip on the other side of the tree. Inter-tree as well as inter-row spacing was also recorded (middle of stem to middle of stem). Details describing the canopy dimensions and tree sizes selected at the three measurement sites are provided in Fig F1 and Table F1.

The LI-Cor LAI-2000 plant canopy analyser was used to measure radiation interception underneath the canopy of each tree at five different positions around the tree. Each set of new readings were preceded by a set of above canopy readings, taken outside the orchard. To force leaf drop, trees were subsequently sprayed with a 10% copper sulphate solution using a small portable mist blower. Each tree was then fully enclosed within a 20% white shade net (supplied by Allnet) enclosure in order to collect all the tree leafs as they were shed. Leaves were collected 10 days after spaying (picking off the few leafs that were still on branches) and the shade net enclosures removed. The leaf area (m^2) of each of the 12 leaf samples were meticulously determined with a LI-Cor–3100 leaf area meter. Before and during measurement, the calibration of this machine was checked with the supplied calibration discs and found to be accurate. Leaf area was converted to LAI by dividing by the canopy footprint area (m^2), calculated as the inter-tree spacing times the canopy width.

Fig. F1. Apple trees covered in shade net at Southfield, Villiersdorp (Large) - Top, Crookes Brothers, Vyeboom (Medium) - Middle and Oak Valley, Grabouw (Small) – Bottom.

Table. F1 Canopy dimensions and tree spacing arrangements of the selected apple trees at three measurement sites.

Location	Canopy Size	Variety	Replication	Tree nr	Canopy Height (m)	Canopy Width (m)	Inter Tree (m)	Inter Row (m)
Southfield (Villiersdorp)	Large	Golden Delicious	1	R4T1	4.45	2.40	1.84	4.0
			2	R4T4	4.33	2.60	1.80	4.0
			3	R4T5	4.10	2.35	1.80	4.0
			4	R5T6	4.33	2.99	2.06	4.0
Crookes Brothers (Vyeboom)	Medium*	Golden Reindeers	1	1	3.20	2.45	1.98	4.0
			2	2	3.59	2.30	1.98	4.0
			3	3	3.0	2.20	1.95	4.0
			4	4	2.95	1.70	1.95	4.0
Oak Valley (Grabouw)	Small	Golden Delicious	1	1	2.95	1.0	0.90	4.0
			2	2	2.73	0.90	0.85	4.0
			3	3	2.75	0.90	0.85	4.0
			4	4	2.76	0.90	0.88	4.0

*Medium - Trees were pruned a few days before the measurement and had also begun shedding leaves.

Results:

Leaf area index comparisons between the destructive measurements and those calculated by the LI-Cor LAI-2000 plant canopy analyser are presented in Table. F2 and the regression analysis are shown in Fig. F2 (all replication points) and 3 (average values).

Table. F2. Comparison between LI-Cor LAI-2000 plant canopy analyser and destructive measurement (LI-Cor–3100 leaf area meter) of leaf area index (LAI).

Location	Canopy Size	Variety	Replication	Tree nr	LAI (m^2m^2)	
					LiCor Canopy analyser	Destructive measurement
Southfield (Villiersdorp)	Large	Golden Delicious	1	R4T1	1.40	0.87
			2	R4T4	2.30	1.11
			3	R4T5	1.72	0.80
			4	R5T6	1.87	0.52
			Average		**1.82**	**0.82**
Crookes Brothers (Vyeboom)	Medium*	Golden Reindeers	1	1	0.64	0.09
			2	2	0.53	0.05
			3	3	0.35	0.08
			4	4	0.73	0.06
			Average		**0.56**	**0.07**
Oak Valley (Grabow)	Small	Golden Delicious	1	1	0.75	0.33
			2	2	0.97	0.41
			3	3	0.65	0.28

			4	4	0.72	0.29
			Average		**0.77**	**0.32**

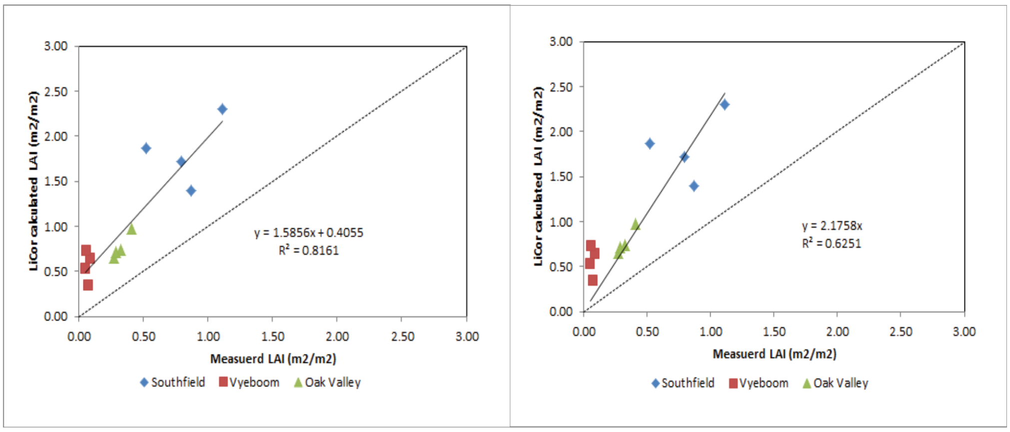

Fig. F2. Regression analysis of measured (LI-Cor–3100 leaf area meter) vs. calculated (LI-Cor LAI-2000 plant canopy analyser) leaf are index (LAI) for all measurement points. In the top graph the linear regression was forced through the origin.

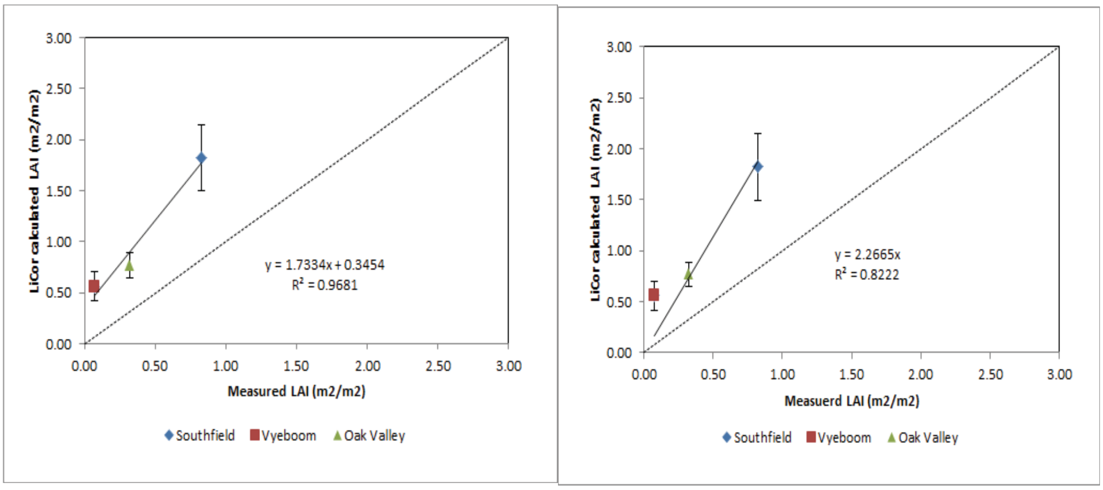

Fig. F3 Regression analysis of measured (LI-Cor–3100 leaf area meter) vs. calculated (LI-Cor LAI-2000 plant canopy analyser) average leaf are index (LAI) – average of four replications. In the top graph the linear regression was forced through the origin. Error bars present one standard deviation.

Results show that the LI-Cor LAI-2000 plant canopy analyser is currently overestimating the LAI of apple trees, especially for the larger trees. Therefor the extinction coefficient ("canopy factor") currently in use in the instrument is not suitable for this tree crop and/or the current apple varieties. Medium sized trees at Vyeboom had a smaller LAI than the youngest trees that were measured at Oak Valley. This might indicate sensitivity to cultivar differences as the Vyeboom site cultivar was Golden Reindeers which was different to that of the other two sites (Golden Delicious). This anomaly could also be explained by the fact that these trees were pruned a few days before the field measurements were made.

Conclusions and Recommendations:

The LI-Cor LAI-2000 plant canopy analyser is currently overestimating the LAI of apple trees by a factor of almost two, at the three measurement sites and requires adjustment/ calibration in order to accurately reflect in-field LAI values.

The following corrections are required:

Correct the extinction coefficient/ canopy factor currently in use in the LI-Cor LAI-2000 plant canopy analyser.

Apply corrections to historic measurements of LAI at these sites by making use of the regression equations supplied above.

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