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The influence of canopy cover and cultivar on rates of water use in apple orchards in the Western Cape Province, South Africa

By

Nompumelelo Thelma Mobe

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Supervisors:

Prof. D. Mazvimavi
Dr. S. Dzikiti

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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations

BGR	Bearing Golden Delicious Reinders®
BCP	Bearing Cripps' Pink
DOS1	Dark Object Subtraction
EC	Eddy Covariance
EGVV	Elgin/Grabouw/Vyeboom/Villiersdorp
E_L	Transpiration per unit leaf area
ET	Evapotranspiration
FAO-56	Food and Agriculture Organization, paper no 56
FBGD	Full-bearing Golden Delicious
FBCP	Full-bearing Cripps' Pink
FC	Field capacity
HPV	Heat Pulse Velocity
HRM	Heat Ratio Method
IAA	Indole-3-acetic acid
IPAR	Intercepted Photosynthetically Active Radiation
IRGA	Infrared Gas Analyzer
KBV	Koue Bokkeveld
LAI	Leaf Area Index
LAI_c	Leaf Area Index of the Cover Crop
MAE	Mean Absolute Error
NBGR	Non-Bearing Golden Delicious Reinders®
NBCR	Non-bearing Cripps' Red
NBRG	Non-bearing Rosy Glow
NDVI	Normalized Difference Vegetation Index
NIR	Near Infrared
NSE	Nash-Sutcliffe Efficiency
PAR	Photosynthetically Active Radiation
PT-JPL	Priestley and Taylor Jet Propulsion Laboratory
REW	Readily Evaporable Water
RMSE	Root Mean Square Error
SAI	Sapwood Area Index

SCP	Semi-Automated Classification
SFD	Sap Flux Density
SMAP	Soil Moisture Active Passive Mission
SWIR	Shortwave Infrared
TAW	Total Available Water
TDP	Thermal Dissipation Probe
TEW	Total Evaporable Water
USGS	United States Geological Survey
WP	Wilting Point

Symbols

Cl	Percentage fraction of clay in soil (%)
D_r	Daily root zone depletion (mm)
λE	Latent heat flux (W m^{-2})
λEc	Energy for canopy transpiration (W m^{-2})
λEs	Energy for soil evaporation (W m^{-2})
E_s	Soil evaporation (mm d^{-1})
e_s	Saturation vapour pressure (kPa)
e_a	Actual vapour pressure (kPa)
E_{so}	Potential rate of evaporation from a wet soil surface (mm d^{-1})
ET	Actual evapotranspiration (mm d^{-1})
f_{PAR}	Fraction of the photosynthetically active radiation absorbed by canopy (-)
f_c	Fraction of the ground surface covered by vegetation at midday (-)
f_{ceff}	Effective vegetation cover (-)
f_{IPAR}	Fraction of the photosynthetically active radiation intercepted by canopy (-)
f_g	Green canopy stress factor (-)
f_{SM}	Soil moisture stress factor (-)
F_r	Stomatal sensitivity adjustment factor (-)
f_T	Plant temperature stress factor (-)
f_{VPD}	Vapour pressure deficit stress factor (-)

f_w	Fraction of the orchard floor wetted by irrigation or rain (-)
G	Soil heat flux (W m^{-2})
h	Tree height (m)
K_c	Crop coefficient (-)
K_{cfull}	Crop coefficient from a fully covered soil (-)
K_{cb}	Basal crop coefficient (-)
$K_{cbcover}$	Basal crop coefficient due to the cover crop (-)
K_{cbfull}	Basal crop coefficient of a mature well-watered orchard (-)
$K_{cbfullc}$	Maximum cover crop basal crop coefficient (-)
K_{cmin}	Minimum basal coefficient for bare soil (-)
K_{cmax}	Maximum crop coefficient for the surface under full vegetation (-)
K_d	Density coefficient (-)
K_{dc}	Density coefficient for the cover crops (-)
K_{edry}	Evaporation coefficient from dry portion of the soil (-)
K_{ewet}	Evaporation coefficient from wet portions of the soil (-)
k_{PAR}	Extinction coefficient for photosynthetically active radiation (-)
k_{Rn}	Extinction coefficient for net radiation (-)
K_s	Transpiration reduction coefficient (-)
K_{sf}	Plant-based transpiration reduction coefficient (-)
K_{soil}	Average soil evaporation coefficient (-)
K_t	Transpiration coefficient (-)
k_{vpd}	Parameter for the vapour pressure deficit stress factor (-)
M_L	Empirical parameter imposing an upper limit on transpiration (-)
p	Soil depletion coefficient (-)
RH_{min}	Minimum relative humidity (%)
r_l	Mean leaf resistance (s m^{-1})
R_n	Net radiation on a horizontal surface (W m^{-2})
R_{ns}	Net radiation absorbed by the soil surface (W m^{-2})
Sa	Percentage fraction of sand in soil (%)
SAI	Sapwood area index (m^2 m^{-2})
SFi	Sap flow rate (cm^3 h^{-1})
SWC	Volumetric soil water content (cm^3 cm^{-3})
SWC_{min}	Volumetric soil water content at the permanent wilting point (cm^3 cm^{-3})

SWC_{max}	Volumetric soil water content at the field capacity (cm^3 cm^{-3})
T	Orchard level transpiration (mm d^{-1})
T_c	Cover crop transpiration (mm d^{-1})
T_a	Air 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_w	Average time between independent wetting events (days)
T_p	Potential transpiration (mm d^{-1})
U_2	Mean wind speed at 2 m height (m s^{-1})
VPD	Vapour pressure deficit of the air (kPa)
Z_e	Effective depth of soil evaporation (m)
Z_r	Effective rooting depth (m)

Greek symbols

β	Bowen ratio (-)
α	Priestley and Taylor coefficient (-)
α_c	Priestley and Taylor coefficient for canopy transpiration (-)
α_s	Priestley and Taylor coefficient for soil evaporation (-)
τ	Fraction of net radiation transmission reaching the soil or water surface (-)
Δ	Slope of saturation vapour pressure vs air temperature curve (kPa K^{-1})
γ	Psychrometric constant (kPa K^{-1})
ψ_x	Midday xylem water potential (MPa)
λ	Latent heat of vaporization (J kg^{-1})

ABSTRACT

The influence of canopy cover and cultivar on rates of water use in apple orchards in the Western Cape Province, South Africa

NT Mobe

PhD. Environmental and Water Science Thesis, Department of Earth Sciences, University of the Western Cape

Water availability and climate related issues are some of the greatest crop production risks to irrigated agriculture in arid regions. In South Africa, for example, the increasing frequency and severity of droughts related to climate change and the growing competition for limited water resources among different users threaten the sustainability and growth of irrigated agriculture, especially the water-intensive fruit industry. Major fruit such as apples (*Malus domestica* Borkh) are produced entirely under irrigation in South Africa. As a result, there has been considerable research to accurately quantify the water requirements of fruit tree orchards in order to maximize water productivity. However, the actual rates of water use and its drivers, by apple orchards across different age groups and cultivars is not well known, not only in South Africa, but in other apple growing regions too. This paucity of data may cause irrigation and water allocation decisions to be inaccurate leading to inefficient water use. This study therefore aimed to close these important knowledge gaps by: 1) establishing how apple orchard water use is influenced by canopy cover from planting until the trees reach full-bearing age; 2) investigating whether or not the water use rates varied with cultivar, and 3) identifying and improving appropriate evapotranspiration (ET) models that estimate water use across different orchard age groups in major apple growing regions in South Africa. To address these aims, the study was split into two parts. The first part involved a pot trial where the transpiration dynamics and water status of young apple trees of major cultivars planted in South African orchards i.e. the Golden Delicious and Cripps' Red were compared. The pot trial provided detailed insights on how the transpiration rates of the two cultivars were influenced by soil and climatic factors under controlled conditions. This experiment was conducted outdoors in an open space at Stellenbosch University, Welgevallen experimental farm with the trees subjected to

similar irrigation levels and climatic conditions. Findings from the pot trials showed that the sap flux density did not differ significantly between the two cultivars ($p>0.05$). Similarly, plant water status indices i.e. leaf and stem water potentials and stomatal conductance were not significantly different between Golden Delicious and Cripps' Red cultivar. The second part of the study was done under field conditions in twelve commercial apple orchards of different age groups and cultivars under micro-sprinkler irrigation. The study was carried out in two prime apple producing regions namely the Koue Bokkeveld (KBV) and Elgin/Grabouw/Vyeboom/Villiersdorp (EGVV) in the Western Cape Province, South Africa over three growing seasons (2014/15, 2015/16 and 2016/17). Tree transpiration rates were measured using the heat ratio method of monitoring sap flow in the mature high yielding orchards (with high effective fraction of ground covered exceeded 60%) and medium canopy cover orchards (with 30–44% fractional cover). Transpiration in young non-bearing trees with less than 20% canopy cover was measured using Granier probes due to the small size of the stems (< 30 mm). Orchard evapotranspiration (ET) was measured using open path eddy covariance systems which were deployed during selected periods. Detailed eco-physiological i.e. leaf gas exchange and leaf and stem water potential and soils data e.g. soil physical properties were also collected to determine how environmental factors and management practices influenced key processes that govern tree transpiration. Ancillary data which included the orchard microclimate and the volumetric soil water content were also collected. The field results showed that canopy cover rather than cultivar had the largest effect on transpiration per unit leaf area and the sap flux density for all orchards. The sap flux density was greater in the medium cover orchards than the other orchard age groups likely because of the larger fruit to leaf area ratio. As expected, whole tree transpiration rates were highest in the high canopy cover orchards, followed by the medium canopy orchards, and lastly the low canopy cover orchards. Peak seasonal (October to June) total transpiration was highest for the mature Golden Delicious orchards at about 790 mm compared to about 630 mm for the Cripps' Pink orchards. These differences in seasonal total transpiration were attributed to the variations in canopy size due to the different canopy management practices for these two cultivars. Golden Delicious fruit are susceptible to sunburn damage, so dense foliage is allowed on the trees to reduce sunburn damage which costs the apple industry in South Africa large amounts of money each year. On the other hand, the Cripps' Pink trees tend to have

smaller, more open canopies to allow light penetration for the development of the red fruit color. This study showed that the canopy management practices for Cripps' Pink orchards also have water saving benefits as a result of the reduced transpiring leaf area. Given the need for accurate information for irrigation management in apple orchards, the field measured data were then used to improve an algorithm for estimating orchard crop coefficients using readily available data. For this purpose, the algorithm developed by Allen and Pereira (2009) (A&P) was adopted and improved using the actual measured water use and environment data from 12 apple orchards. A key finding of this study is that applying the A&P parameters for apple orchards as published caused significant errors in the estimated crop coefficients (about 103% for young orchards), and hence orchard water use. However, significant improvements were achieved by reformulating the resistance ratios in the stomatal sensitivity function of the A&P method, replacing the resistance of an annual crop (~ 100 s m^{-1}) with a crop-specific canopy resistance. Finally, given the wide variation in the canopy cover of the orchards studied, the last part of this study investigated the partitioning of evapotranspiration in the orchards in order to identify opportunities to reduce orchard floor evaporative losses. This task was achieved by modifying and applying the Priestley and Taylor Jet Propulsion Laboratory (PT-JPL) ET model which partitions ET into its constituent components namely tree transpiration and soil evaporation. The model was calibrated using data collected from the EGVV orchards and validated with data from KBV for orchards with varying canopy covers. This study showed that the improved PT-JPL model has the potential to accurately estimate ET and its components in irrigated apple orchards.

KEYWORDS

- Apple (*Malus Domestica* Borkh)
- Canopy Cover
- Crop Coefficients
- Evapotranspiration
- Heat ratio method
- Leaf Resistance
- Water Use Modelling
- Plant Water Status
- Sap Flow
- Water Resources Management

DECLARATION

I, Nompumelelo Thelma Mobe, Student number 3764716 declare that the thesis titled ***“The influence of canopy cover and cultivar on rates of water use in apple orchards in the Western Cape Province, South Africa”*** is my own work and it has not been submitted before for any other degree at any other University. Where secondary material is used, this has been indicated and duly acknowledged by means of complete references.

Signature: N.T MOBE Date: 2020/12/14

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CHAPTER 1: GENERAL INTRODUCTION

1.1 STUDY BACKGROUND

In South Africa, the deciduous fruit industry is well-established and primarily aimed at supplying apples (*Malus domestica* Borkh) to the export market. The deciduous fruit industry makes a significant contribution to the country's annual GDP with a turnover of about R10.28 billion (Hortgro, 2019). South Africa produces mainly for export a wide range of deciduous fruits that include apples, pears, apricots, nectarines, peaches, plums and cherries. Within the deciduous fruit sector, apples are the largest export fruit by volume, comprising 45% of the total planted area. Globally, South Africa is ranked as the 6th largest exporter of fresh apples. According to Hortgro (2019), more than 894 306 tons of apples are produced annually in South Africa and about 44% is exported mainly to the United Kingdom, Europe, Russia, Asia, and Africa. About 25% of the apples produced are sold in the local markets while 31% are processed into various products. During the 2017/18 production season, apples contributed about R 1.2 billion in terms of gross value of production and the industry employed 30 213 people directly on the farms. These farm workers supported 120 853 dependents (Hortgro, 2019). The sector is a very important source of employment with many more people employed in downstream industries involved with the handling, processing and export of apples.

The main production regions for apples in South Africa are the Western Cape and Eastern Cape Provinces. Small production areas occur along the Orange River in the Free State, in Mpumalanga and Limpopo Provinces (DAFF, 2012). The Western Cape Province accounts for about 79% of all the apples produced in South Africa. Like most commercial fruits produced in South Africa, the production of apples is mainly reliant on irrigation.

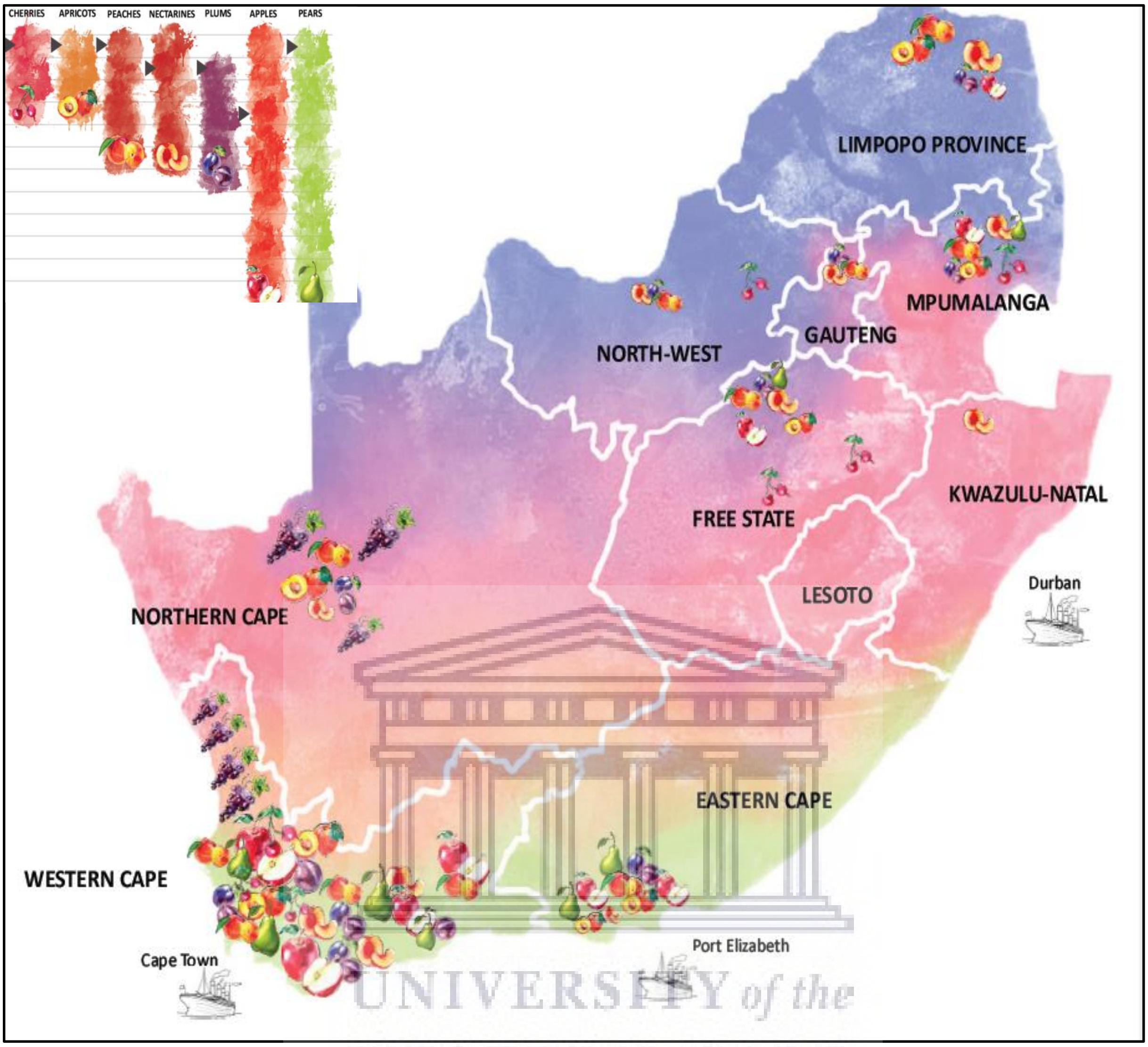

Fig. 1.1: The deciduous fruit production areas in provinces in South Africa (Hortgro, 2018).

The variability of adequate water is the most important risk to sustainable fruit production in South Africa given the potential for increased frequency and severity of droughts in key production regions such as the Western Cape (Western Cape Government, 2017). The occurrences of past droughts have been linked to climate change in the western parts of the country (Zwane, 2019). The rapid expansion of urban areas (e.g. the Cape Town Metropolitan), growing competition for water between irrigated agriculture, and commercial and industrial uses are increasing pressure on already limited water resources (Midgley and Lötze, 2011; Dzikiti et al, 2018b). It is therefore imperative that the fruit industry has tools and information to optimise water use while maintaining or increasing yields.

Recent studies show that parts of the Western Cape region, which is a prime apple producing area in South Africa, will become drier in the next 30-40 years due to climate change (Zwane, 2019, Ziervogel et al., 2014). The average temperatures are expected to increase by 2-3 °C (Midgley et al., 2005) together with reduced rainfall amounts, shorter rainfall seasons and increased evaporative losses (Midgley et al., 2007; Midgley and Lötze, 2011). An increase in evapotranspiration in the range 5-15% is also projected throughout the region by 2050 (Midgley et al., 2007) and this will inevitably increase the net water requirements of fruit trees. Therefore, to ensure the long-term growth and sustainability of the fruit industry, there is need for farmers to adopt practices that increase the water productivity (defined in this study as yield per unit volume of water consumed) of the orchards (Gush et al., 2019). This can be achieved either by improving the genetic performance of fruit trees and horticultural practices to produce higher yields or by improving irrigation scheduling to reduce water wastage (Naor et al., 2008; Naschitz and Naor, 2005).

According to the latest National Water Resources Strategy for South Africa (NWRS2, 2013), irrigated agriculture is one of the most inefficient water users in the country. Between 30% and 45% of the water allocated to this sector is wasted either through leakages, poor irrigation scheduling, and/or other non-beneficial uses. Although, the country is facing increasing water scarcity, Volschenk et al. (2003) have reported substantial over irrigation in the deciduous fruit industry, mainly due to poor irrigation scheduling. Poor irrigation scheduling results from lack of information and tools to determine accurate crop water requirements. Therefore, there is a need to develop reliable guidelines for optimum irrigation water planning and management for sustainable fruit production, and supporting livelihoods (Chartzoulakisa and Bertaki, 2015). In arid and semi-arid regions including South Africa, apple orchards are irrigated from planting until they reach full-bearing age. Although, a number of studies have determined the water requirements of apple orchards (e.g., Cohen and Naor, 2002; Green et al., 2003; Volschenk et al., 2003; Gush and Taylor, 2014; Gush et al., 2019), few of these have focused on how apple orchard water use vary with canopy cover under Mediterranean climates (Dzikiti et al., 2018b). Informal discussions with apple farmers in South Africa revealed that there are greater uncertainties in the water requirements of younger orchards given the paucity of actual measured water use data in these orchards. Little has also been published on the effects of cultivar on the water requirements of apple orchards. There are more than eleven apple cultivars in commercial production in South Africa, and yet no comparative studies have been done to establish whether or not the cultivars have different water requirements. This study therefore, seeks to address these knowledge gaps to improve water use efficiency and increase the resilience to climate change which is expected to have considerable effects on commercial fruit production.

Numerous methods and approaches have been developed over the years for estimating crop water use of fruit tree crops, and these vary in their complexity, accuracy and affordability (Allen et al., 1998; Wilson et al., 2001; Zhang et al., 2002). The methods include soil water balance, sap flow methods, weighing lysimeters, and micrometeorological methods (e.g. the Bowen ratio systems, eddy covariance systems, scintillometry and surface renewal systems). These methods, however, provide point or near point measurements that may not fully represent the water use from a larger population of fields other than where the measurement was conducted (Reyes-González et al., 2018). Therefore, they cannot be used for routine evapotranspiration (ET) estimation in fruit orchards over wide areas.

For these reasons, the development of ET estimation procedures and models is critical to accurately determine orchard water use and facilitate the scaling up of results from specific study sites to other fruit growing regions. The crop coefficient approach first published by Doorenbos and Pruitt (1977), and later refined by Allen et al. (1998), has been extensively applied for estimating crop water requirements world-wide. According to this method, crop evapotranspiration is estimated as the product of the reference evapotranspiration (ET_o) and the crop coefficient (K_c). The reference evapotranspiration can be calculated either for a short or tall grass reference depending on the crop type (Allen et al., 1998). However, published crop coefficients require adjustments to suit local conditions because water use in commercial orchards varies due to a range of factors (Allen and Pereira, 2009). These include the fractional vegetation cover, size of the wetted area, orchard management practices, e.g. cover crops, mulching etc. (Naor et al., 2008).

Acknowledging the need for crop coefficients to be transferable between locations, Allen and Pereira (2009) improved the FAO-56 approach by developing a method for estimating the crop coefficients from readily available data. Their approach involved the use of a canopy density function (K_d) computed from the fraction of ground cover (f_c) and plant height (h). This also takes into consideration crop stomatal control through an adjustment factor (F_r) that varies with crop type. Such an approach can be used by irrigators to derive accurate coefficients in water scarce countries like South Africa where there are few reliable tools for making accurate irrigation decisions. The extensive actual water use and environmental data collected in this study provided an opportunity to validate and improve this method for apple orchards under semi-arid Mediterranean climatic conditions.

Given the heterogeneous surface of orchards which comprise tree rows, bare ground in between the rows, cover crops, etc. there is a need to understand how ET is partitioned into the constituent components in order to identify opportunities to reduce non-beneficial water losses (e.g. the orchard floor evaporation fluxes). Of particular interest is how this partitioning varies in orchards with different canopy cover from planting until maturity. According to Bastidas-Obando et al. (2017) and Liu et al (2014), the estimation of ET can be improved by modelling tree canopy transpiration and soil evaporation separately since transpiration is disconnected from the soil physical conditions related to soil evaporation. So dual or in some cases multiple source ET models have been developed and tested (e.g. Shuttleworth-Wallace, FAO dual K_c, Two Source Energy Balance, Energy and Water Balance, etc). However, these models are not without their own problems and some of these difficulties are detailed in Ward (1971); Dickinson et al. (1991); Sellers et al. (1997); Rana and Katerji (2000). Apart from challenges arising from the data-demanding nature of the models, the values of parameters needed may be difficult to determine or require local calibration. In cases where data and parameters are available, extrapolating the point scale estimates to larger spatial scales remains highly uncertain. The present study presents an opportunity to identify, improve, and validate multiple source models in orchards whose trees have a range of canopy cover from young to fully-grown orchards. These models can be used for estimating the water requirements of apple orchards in areas where measured actual water use data in apple orchards does not exist.

1.2 AIM OF THE STUDY

The primary aim of this study was to investigate how the water use of apple orchards planted to different cultivars varies with canopy cover from planting until the trees reach full-bearing age. The second aim was to identify and improve tools for estimating apple orchard water requirements in data scarce growing regions, using measured data.

1.3 THESIS OBJECTIVES

The specific objectives of this thesis were to:

1) Quantify the transpiration and evapotranspiration dynamics in apple orchards of different age groups under semi-arid Mediterranean climatic conditions;
2) Establish how drivers such as canopy cover, cultivar, and microclimate influence orchard water use;
3) Use measured orchard water use and environmental data to improve methods for determining orchard crop coefficients using readily available data;
4) Validate a dual source water use model for apple orchards that can be used to extrapolate the research results to other fruit growing regions.

1.4 HYPOTHESES

The philosophy behind this study is based on the following hypotheses:

1) Different apple cultivars on similar rootstocks respond differently to environmental factors causing variations in water use and productivity;
2) Crop coefficients for apple orchards of all age groups and cultivars can be estimated from readily available data;
3) Dual source water use models can accurately predict ET and its partitioning in both young (low canopy cover) and mature (high canopy cover) orchards.

1.5 STUDY APPROACH

To address these hypotheses, the approach to this thesis involved first a detailed study with young potted apples trees in order to gain insights on how tree water use and water status varied for different cultivars subjected to similar environmental conditions. The next phase of the study involved detailed data collection in 12 commercial orchards planted to two different cultivars with trees of different age groups, and hence different fractional canopy cover. The first cultivar studied was Golden Delicious which is the most widely planted cultivar in South Africa accounting for about 22% of the area under apples (Hortgro, 2019). The Golden Delicious is a high yielding early season variety commonly harvested in February-March in South Africa. In some instances the Golden Delicious Reinders® cultivar, which is in the same family as the Golden Delicious, was used when appropriate orchards under the later cultivar could not be found. The second cultivar studied was the blushed Cripps' Pink cultivar which is a high value, high yielding and long season cultivar. Cripps' Pink fruit are commonly marketed as 'Pink Lady' if they meet the fruit colour requirements. Although the area under this cultivar in South Africa is still relatively low (about 12%), the annual expansion in the area under this cultivar is fairly high because of the high returns. In some orchards cultivars in the Cripps' Pink family e.g., Rosy Glow and Cripps' Red, were used given difficulties in identifying study sites with the right attributes. The approach followed in this study was quantitative with the following measured variables over a period of three years from 2014 to 2017: 1) site microclimates, 2) orchard transpiration rates (sap flow), 3) orchard evapotranspiration rates, 4) tree growth (canopy dimensions and leaf area index), 5) soil properties and root zone soil water content, and 6) irrigation volumes.

1.6 THESIS OUTLINE

It is against the background above that this thesis is structured as follows:

Chapter 2 provides a critical review of existing literature on apple production in South Africa, water availability in the apple growing regions, previous measurement and modeling of water use studies in apple orchards. The review incudes relevant observations made in studies in other countries.

Chapter 3 evaluates the transpiration dynamics and water relations of two apple cultivars grown under controlled conditions in pots. The potted trial was conducted outdoors on young Golden Delicious and Cripps' Red cultivars at the University of Stellenbosch, Welgevallen experimental farm.

Chapter 4 assesses the effect of cultivar and canopy cover on the water use dynamics for field grown trees comprised of different cultivars and age groups. This investigation was done in 12 commercial orchards with varying canopy cover and cultivars spread across two key apple producing regions in the Western Cape Province, South Africa.

Chapter 5 uses the data collected and presented in Chapter 4 to evaluate and improve an approach for estimating apple orchard crop coefficients using readily available data. In order to accurately estimate orchard evapotranspiration (ET) and its components, simple but robust operational models for estimating water use are required. Hence Chapter 6 focused on the adoption and modification of a dual source Priestley and Taylor Jet Propulsion Laboratory (PT JPL) model using a combination of in situ and remote sensing data to determine ET in apple orchards of different age groups. This model has mostly been used in natural ecosystems. For the first time, we will apply the model to irrigated fruit trees with varying canopy cover in this study.

Chapter 7 summarizes the main findings from the study; recommendations for future research are made.

CHAPTER 2: LITERATURE REVIEW

2.1 PRODUCTION TRENDS AND APPLE CULTIVARS IN SOUTH AFRICA

The deciduous fruit industry in South Africa is well-established and primarily aimed at supplying fresh apples, pears, peaches, nectarines, plums and apricots to the export market (Tharaga, 2016). South Africa is the second largest apple (*Malus domestica* Borkh) exporter in the southern hemisphere (Chile is the first) and sixth in the world. About 44% of apples produced in South Africa are exported, with the Far East & Asia being the largest importers, accounting for about 32%, followed by the African market (31%), the United Kingdom (UK) (17%), the Middle East (7%), Europe (6%), Russia (4%), Indian Ocean Islands (3%), the United States of America (USA) and Canada (<1%) (Fig 2.1). About 25% of the apples produced are sold in the local markets while 31% are processed into various products (Hortgro, 2019). During the 2018/19 season, apples contributed approximately 28.2% (R5.8 billion) of the total gross value for deciduous fruits (R10.28 billion) in South Africa (Hortgro, 2019).

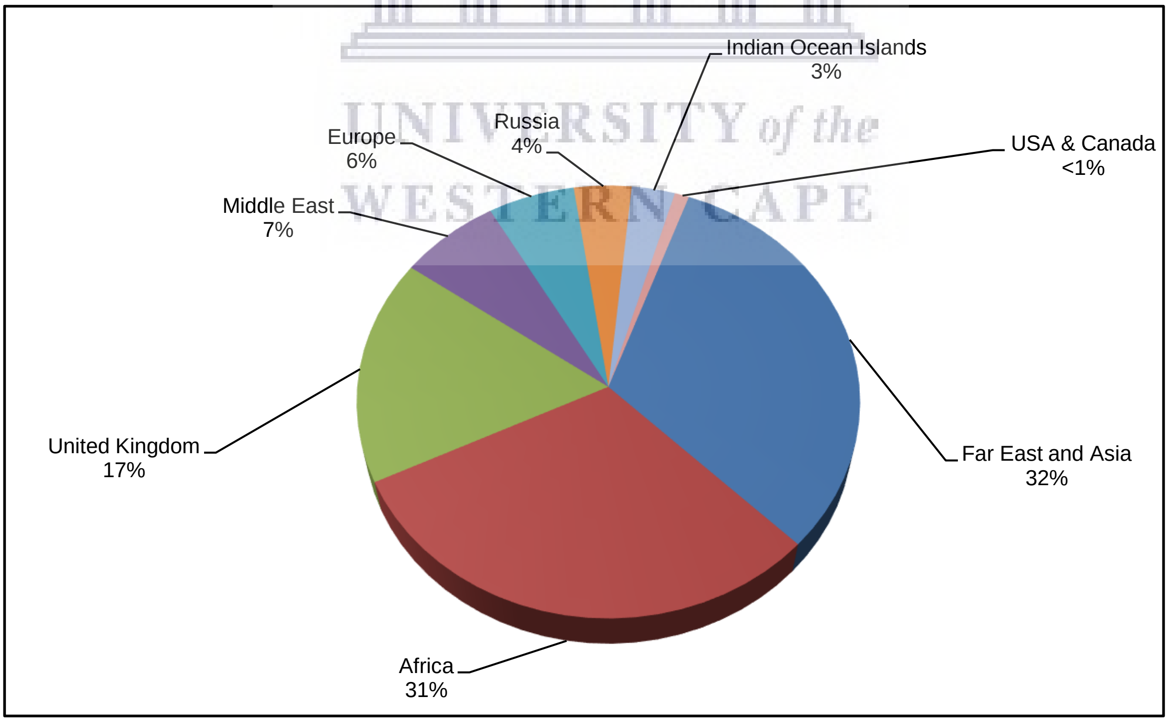

Fig. 2.1: South African apple exports per market destination (Source: Hortgro, 2019).

In South Africa, most apples are grown in the Western Cape Province, followed by the Eastern Cape Province. Smaller production areas are found along the Orange River in the Free State, Mpumalanga and Limpopo Provinces as shown in Fig. 1.1. The Western Cape Province accounts for more than half of the country's apple production. The main producing areas are in the Koue Bokkeveld near Ceres, and in Groenland (Elgin/Grabouw/Villersdorp/Vyeboom) (Fig. 1.1). Annual reports show that the area under cultivation has steadily increased from 22 167 ha in 2012 to 24 971 ha in 2019 with about 35 110 937 trees planted (Hortgro, 2019). In key production areas in the Western Cape, irrigation is vital to meet the water requirements of the trees given that most rain falls during the winter months (May to August) and very little precipitation is received during the fruit growing season (September to April). The main apple cultivars planted in South Africa are the Golden Delicious which accounts for about 22% of the total area planted, followed by the Royal Gala cultivar at 17%. Other cultivars whose planted area has been growing steadily are Granny smith (14%), Cripps' Pink (12 %) and Fuji (9 %), among others (Fig 2.2).

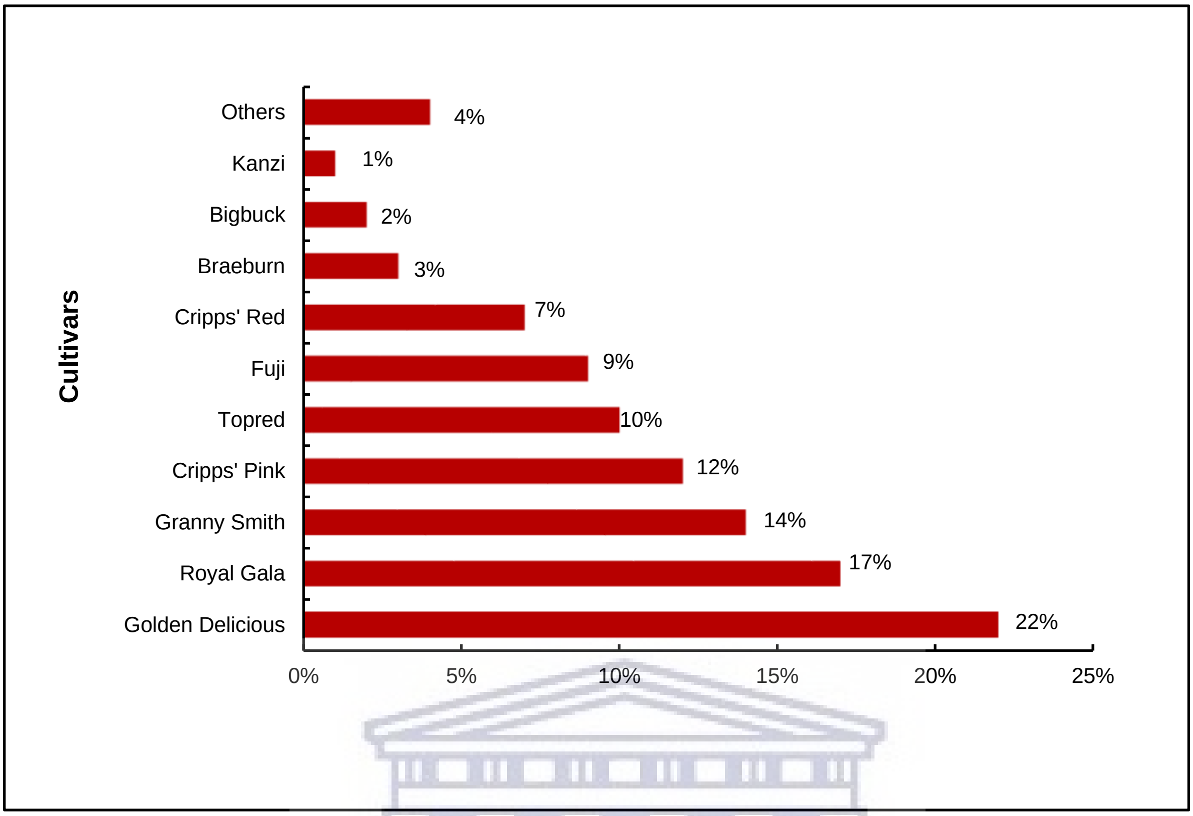

Fig. 2.2: Area planted to different cultivars in South Africa as a percentage of the total area under apple cultivation in 2019 (Source: Hortgro, 2019).

2.2 ENVIRONMENTAL REQUIREMENTS FOR APPLE PRODUCTION

2.2.1 CLIMATE AND SOILS

Apples are the most important deciduous fruits grown in various countries worldwide (Fig. 2.3). They grow in a variety of climates from temperate to semi-arid, subtropical and even tropical environments with ample water supply (Musacchi and Serra, 2018). In South Africa, apples grow best in environments with cool winter temperatures and warm summers. Cold winter temperatures are essential for meeting the chilling requirements of most apple cultivars in order to induce a phase of rest/dormancy (Melke, 2015). The average summer temperature for growth should be between 21 and 24°C (Tharaga, 2016). Well-distributed rainfall in the range 1 000 to 1 250 mm throughout the growing season is most favourable for optimum growth and yields (Janick et al., 1996; Chuine and Cour, 1999). Apple trees are also known to grow well in deep well-drained sandy and loamy soils, although they can tolerate a wide variety of soils due to the incredible number of rootstocks available (Taylor and

Gush, 2014). Soils with poor aeration and prolonged water logging are not ideal as this increases the incidence of crown rot (*Phytophtora cactorum*). The trees perform better to soil pH in the range of 6.0 – 7.0. Too low or high soil pH affects the availability of nutrients to the trees (Dzikiti et al., 2018b).

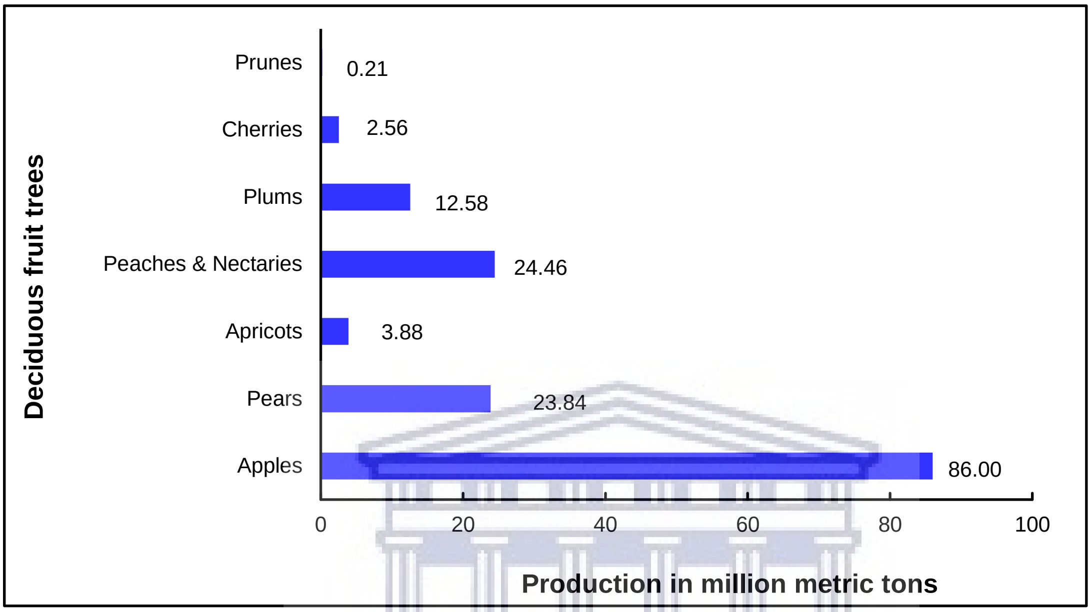

Fig. 2.3: Global production of deciduous fruit trees (in million metric tons) (Source: Hortgro, 2019).

Apple and other temperate deciduous fruit trees such as pear, plums, peach that originated from cold-winter climates fall dormant in winter, which enables them to tolerate freezing temperatures in their native habitats (Luedeling, 2012). To survive this period of low temperature stress, apple trees have developed a mechanism that delays bud-break and anthesis called 'dormancy' (Atkinson et al., 2013). The term 'dormancy' is associated with temporary suspension of visible growth. Although the bud dormancy cycle is regulated simultaneously by numerous internal and external factors, low temperature has been reported as the most important environmental factor that induces and maintains dormancy until the end of the winter (Cooke et al., 2012; Inamaharo, 2020). During this period, buds remain dormant until they have accumulated sufficient chilling of cold weather. When enough chilling accumulates, the buds are ready to reactivate in response to warm temperatures during spring for trees to produce leaves, flowers and ultimately bear fruit. It is commonly assumed that the dormancy period is composed of three phases; namely 1) para-dormancy; 2) endo-dormancy, and; 3) eco-dormancy (Cesaraccio et al., 2004; Rea and Eccel, 2006). The para-dormancy phase occurs when factors outside the bud, but within the plant, affect growth and determine activity (Lang, 1987). This type of dormancy is seen during apical dominance, where auxin (IAA) synthesised in the terminal bud inhibits the growth of subtending buds (Bangerth et al., 2000). At the end of autumn, buds progress into a state of endo-dormancy, often referred to as true, deep or winter dormancy where the inhibition of growth is by internal bud signals (Saure, 1985; Lang et al., 1987; Faust et al., 1993). During endo-dormancy, growth is not possible even under favourable environmental conditions, as buds have not received sufficient exposure to chilling (Fadón et al., 2020). This is crucial for plant survival at low temperatures. During the eco-dormancy phase, growth inhibition is determined by the unfavorable environmental conditions outside of the plant (Lang et al., 1987). Therefore, apple trees that do not fulfil their normal annual dormancy process will remain dormant even when the environmental conditions are favorable (Lang et al., 1987). This phase is overcome by a certain amount of accumulated warmth. Therefore, the understanding of the dormancy phenomenon and its relationship to environmental factors is crucial to adapt new cultivars to future scenarios of temperature increase.

2.2.2 CHILLING REQUIREMENTS FOR VARIOUS APPLE CULTIVARS

Under natural conditions, temperate fruit tree species requires a specific amount of chilling to induce dormancy (Naor et al., 2003; Rohde and Bhalerao, 2007). This critical minimum amount of chill is referred to as ‘chilling requirement’ and it is needed for deciduous fruit trees like apples to perform optimally. Chilling requirements are defined as the amount of cold needed by a plant to resume normal spring growth following the winter dormancy (Melke, 2015). The chilling requirements vary not only among plants but also among fruit type, cultivar and location. The fulfilment of the chilling requirement results in the synchronisation of bud development, deep dormancy, dormancy release, flowering, fruit set and subsequently high yield (Fuchigami and Nee, 1987). Consequently, if the chilling requirements of a plant are not met, bud-break becomes delayed and dormancy is prolonged (Fadón et al., 2020). Anthesis extension and reduced vegetative growth may also occur resulting in erratic and poor flowering, which is responsible for poor fruit set and often reduced yields (Sunley et al., 2006; Jones et al., 2013; Melke, 2015). For these reasons, it is important that estimates of chilling requirement thresholds for different species are reliable and accurate.

Most apple production areas in South Africa are characterized by warm climates with insufficient winter colds needed to break full dormancy (Sagredo, 2008). The degree of coldness is described using the concept of chill units, which is defined as the cumulative number of hours below a specific temperature threshold to ensure that the enzymatic changes needed to stimulate bud break occur (Sagredo, 2008; Melke, 2015). Compared to other deciduous fruit trees, apples require sufficient low temperatures in winter to terminate rest (Tharaga, 2016). The most effective range of chilling temperatures are from 0.6 °C to 16.5 °C and the optimum temperature is 7.2 °C (Shaltout and Unrath, 1983), depending on the type of cultivar. Temperatures below or above these ranges do not seem to contribute to chill accumulation. Few authors have documented different values of chill units under different conditions for apple trees in general and for individual cultivars in South Africa as indicated in Table 2.1.

Table 2.1: Chilling requirements (accumulated positive chill units) of selected apple cultivars that are grown in South Africa. High, medium, and low chilling requirements denote >1000, 600 – 1000 and <600 daily positive Utah chill units (PUC), respectively.

Fruit type	Cultivar	Chilling requirement	PUCs	Source
Apples	Golden Delicious	High	800-1000+	Sheard, 2001; Tharaga, 2016
	Granny Smith	Medium to low	<800 600	Costa et al., 2004; Tharaga, 2016 Sheard, 2001
	Royal Gala	High	800-1000+	Sheard, 2001; Tharaga, 2016
	Cripps' Pink	Medium	450-800	Tharaga, 2016
	Cripps' Red	Medium	450-800	Tharaga, 2016
	Top Red/ Starking	High	800-1000+	Tharaga, 2016
	Fuji	High	800-1000+	Tharaga, 2016
	Braeburn	High	800-1000+ 800	Tharaga, 2016 Sheard, 2001

On average, apple trees need between 1 000 and 1 200 chill units (Utah model) to meet the chill requirement of apple buds (Cook, 2010). If these chill units are not experienced, bud burst is delayed and flowering will occur over a longer period and consequently yield will be reduced, a condition commonly referred to as 'delayed foliation' (Tharaga, 2016; Schmitz et al., 2015; Melke, 2015). Due to insufficient winter chilling in most apple production regions in South Africa, growers resort to the application of artificial rest-breaking agents to promote bud-break and manipulate flowering of apple trees (Mohamed, 2008). The effect of these chemical agents depends on the local conditions and type of chemical used. Over the last decade, a number of chemicals have been tested and found to promote bud-break (e.g. hydrogen cyanimide, DNOC winter oils, potassium nitrate, thiourea and growth regulators). But only a few have been effective for field treatments and used in commercial apple orchards. For instance, hydrogen cyanimide (Dormex®) in combination with mineral oils has become the leading rest breaking chemical (Jaldo et al., 2009; Campoy et al., 2011a; Mujahid et al., 2020). The benefit of using these products is that they increase crop productivity. Sagredo et al. (2008) evaluated the effect of combining Dormex® and mineral oils in South African apple orchards. Their results showed that a combination of these two rest-breaking agents was sufficient to break dormancy in most apple cultivars. Although these chemicals are able to promote dormancy, their drawback is that they can be harmful to the buds and may result in phytotoxic damage if not applied optimally (Mujahid et al., 2020). Therefore, a good understanding of the dormancy status of the buds is valuable and necessary to mitigate this risk.

2.3 CLIMATE CHANGE IMPACTS ON DORMANCY, CHILL UNITS AND PRODUCTION

Like many other countries elsewhere, South Africa is already affected by climate change which is posing significant threat to the water resources and agricultural production (Luedeling et al., 2011). High population growth will put further strain on already scarce water resources and food security (Midgley and Lötze, 2011). It is anticipated that the mean temperatures for the South Western fruit production areas of South Africa will increase by an average of 1.5°C around the coast, to 3°C in the interior by 2050 (African Climate and Development Initiative, 2016), with a doubling of these figures to 3°C and 6°C by the end of the century. These conditions may also be accompanied by less autumn and winter rainfall and a much shorter winter season in terms of temperature (Hewitson et al., 2005). The occurrences of both cold and warm days are expected to change with a marked decrease in cold day frequency and an increase in warm day frequency by the end of the century. One aspect of tree physiology which will be influenced by climate change is the accumulation of winter chills, and this will have a major impact on fruit species with chilling requirements like apples (Luedeling et al. 2011). If winter chill reduction occurs because of the changing climate, production restraints are expected to set in and most fruit trees might not fulfil their chilling requirement to break dormancy (Baldocchi and Wong, 2008).

Climate change can be defined as, "*a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades* *or longer* (IPCC, 2014b). The main driver of climate change at present is anthropogenic emission of greenhouse gases (mainly CO_2) into the atmosphere leading to global warming. The concentration of atmospheric CO_2 has risen from pre-industrial revolution concentrations of about 270 ppm to 410 ppm in 2019 (WMO, 2020). It has been predicted that by 2050 atmospheric CO_2 concentration will surpass 500 ppm depending on the emission scenario (IPCC, 2014a). The major threats of climate change to agriculture are temperature increase and the decrease in precipitation (Kang et al., 2009). Thus, if the world continues on this trajectory, the Intergovernmental Panel on Climate Change (IPCC) projects that global mean surface temperatures are likely to increase by 3. 7 °C to 4.8 °C in 2100 compared to pre-industrial levels (IPCC, 2014b), while precipitation is expected to decrease in some areas and increase in others. Furthermore, the occurrence of extreme events like droughts, floods, frost days and heat waves is also expected to rise (Lipper et al., 2014).

Many apple fruit production regions in South Africa are barely fulfilling their chilling requirements under current climate conditions. Therefore it is expected that the risk of insufficient chill accumulation in these areas will worsen in the near future due to increasing temperatures (Lobell et al., 2007). A shift in the areas suitable for the production of apples in the country is expected. With growing competition for lucrative markets for apples, producers will need to adapt to changes in climate for sustainability (Midgley et al., 2005). For example, the growing of extra-low chill cultivars together with the use of correct rest-breaking agents could be a successful production strategy oriented to fresh, early market fruits in moderately warm areas. However, this situation might differ in sub-tropical areas where low-chill cultivars are already being grown and rest-breaking agents are needed.

2.4 WATER USE OF APPLE ORCHARDS

2.4.1 Water availability in the apple growing regions in South Africa

Water resources in South Africa are generally scarce, and irrigation uses more than 60% of the available resources (Backeberg, 2005). The water situation in key fruit producing catchments such as the Oliphants, Breede-Gourits in the Western Cape and the Inkomati-Usuthu in Mpumalanga is so critical that the water is either already fully allocated or almost fully allocated. Yet irrigation practices in most sectors are inefficient, characterized by over-irrigation. This not only causes wastage of water, but it also leads to the contamination of water courses and groundwater by agrochemicals and it raises the production costs through increased pumping. The expansion of the area under irrigation in these catchments e.g. to increase the food security and to create jobs, can only be achieved by using the existing water allocations and this requires significant increases in the water use efficiencies (Gush and Taylor, 2014; Gush et al., 2019).

One of the major reasons for the inefficient irrigation is the lack of knowledge on crop water requirements due to a lack of appropriate user-friendly tools (Volschenk et al., 2003). As a result, most farmers tend to over-irrigate their crops to minimize the negative impacts of water deficits on yields (Jones, 2008). According to the national water policy (DWAF, 2008), inefficient water use, especially in commercial irrigation, requires to be urgently addressed in order to prevent severe water stress and ensure economic yields in water scarce regions. The recommended actions include: 1) the provision of accurate quantitative information on crop water use under different production practices, and 2) the adoption of precision irrigation technologies. Irrigation infrastructure in the South African apple industry is already modernized. Most fruit is produced under high pressure irrigation systems, mainly drip and microsprinkler. In addition, water saving practices such as mulching are the norm in the deciduous fruit industry (Trevor Abrahams, pers. comm.[1]), while some growers acquire water saving benefits through the use of shade nets.

According to Ferreres et al (2012), the challenges that most fruit farmers face to maximize productivity require: i) knowledge of the irrigation requirements to meet the full tree water 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 the irrigation schedule to their own conditions and monitoring the tree response to the water applied, and; iv) knowledge of 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

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[1] Trevor Abrahams, personal communication, apple farmer.

remain competitive. Currently, a knowledge gap exists on where these thresholds lie for apple orchards at different stages of growth not only in South Africa, but also elsewhere in the Mediterranean climatic regions where most apples are grown.

2.4.2 Irrigation scheduling in apple orchards

Fruit trees are usually irrigated throughout the growing season, therefore their growth and production heavily depends on water availability, especially in arid and semi-arid zones (Chartzoulakisa and Bertaki, 2015; Nikolaou et al., 2020). It is expected that within the next decade the availability of water for irrigation will decrease drastically in these regions. For this reason, decision-making tools, especially for irrigation scheduling, i.e., deciding when to irrigate and with how much water, are needed to optimize water efficiency in order to maintain sufficient levels of crop productivity and quality.

2.4.2.1 Using climate data for irrigation scheduling

The FAO-56 Penman-Monteith approach, described by Allen et al. (1998) is currently accepted worldwide as the standard method for estimating crop water requirements due to its simplicity and robustness. In this approach crop evapotranspiration (ET) is estimated as the product of the reference evapotranspiration (ET_0) and crop coefficient (K_c). Use of this technique in the deciduous fruit industry in South Africa is being aided by the large network of automatic weather stations which provide data on an hourly or daily basis. The ET_0 is basically a measure of the atmospheric evaporative demand of a given environment. If the crop coefficient (K_c) is known then the actual water use by the orchard (ET) can be estimated as:

$$ET = K_c \times ET_0 \qquad (2.1)$$

The FAO-56 Penman-Monteith approach also provides the option of differentiating transpiration from soil evaporation using a dual crop coefficient approach in which;

$$ET = (K_e + K_{cb}) \times ET_O \qquad (2.2)$$

where K_{cb} is a transpiration or basal coefficient and K_e is a soil evaporation coefficient. The dual approach seems to be more applicable to estimate ET in orchards, because, in general, fruit orchards have a significant area of bare soil in between the rows of trees, which means that the soil evaporation is an important parameter in the estimation of ET. Whilst these approaches have been proven to be 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). Typical K_c values for a range of irrigated fruit trees, using both FAO-56 Penman-Monteith single and dual K_c methods, have been tabulated by Allen et al. (1998). For standardization, tabulated values refer to a sub-humid climate with minimum relative humidity (RH_{min}) averaging 45% and moderate wind speed, averaging 2 m s^{-1} (Lakso, 2003; Ferreira et al., 2012). Therefore, specific adjustment of crop coefficients for local climatic conditions is required, as documented K_c values produce substantial error in the estimation of actual orchard water requirements. Several studies compared the results obtained using the FAO-56 Penman-Monteith approaches with actual evapotranspiration measured using various traditional techniques (Casa et al., 2000; Allen, 2000; Lascano, 2000; Dragoni et al., 2005; Paço et al., 2006; Volschenk, 2017). The results demonstrate the need to adjust the tabulated crop coefficient to suit actual conditions because water use in commercial orchards varies due to many site-specific factors (Naor et al., 2008).

2.4.2.2 Soil moisture based irrigation scheduling

Soil water status methods for assessing water stress are based on the direct measurement of soil water content or soil water potential. Soil water content represents the amount of water in the soil, while soil water potential measures the energy status of water in the soil (Dasguptaa et al., 2015). Several researchers have estimated the threshold values of total available water during water stress using a wide range of sensors in commercial fruit tree orchards. These include sensors that measure soil water content such as neutron probes (Ebel et al., 2001; Al-Yahyai, 2012), dieletric sensors such as time domain reflectometers (Green and Clothier, 1999; Sisson, 2009), and those that measure the soil water status such as tensiometers (Cohen and Naor, 2002; Al-Yahyai, 2012). The objective of assessing water stress with soil sensors is to monitor soil water at one or more depths until a threshold that indicates the need for irrigation is reached. Therefore, knowing the amount of water in the soil at any given time can prevent severe stress conditions that could irreversibly damage crops or crop yields. A major disadvantage of almost all soil based sensors is the limited sampling of soil heterogeneity, which can be substantial as it is a function of varying soil types over a field, rooting depth (Jones, 2008) and size of wetted versus dry areas in micro-irrigated orchards. Large sensor arrays are necessary to get good representative readings of soil water content/status, and this tends to be limited by cost.

Consequently, current research emphasis is on the possibility of exploring plant-based methods for scheduling irrigation in fruit tree orchards (Fernández and Cuevas, 2010; Fernández, 2017). Broadly these methods can be separated into those indices that depend directly or indirectly on leaf or shoot water status (e.g., visual wilting, leaf water potential, stem or xylem water potential, leaf relative water content, leaf turgor pressure, leaf thickness, and stem or fruit shrinkage), and those that detect other physiological responses (e.g., xylem cavitation, growth, sap flow, stomatal conductance and photosynthesis rate) to changes in plant water status (Jones, 2008). Selected plant stress indicators for scheduling irrigation in orchards are discussed below. A detailed review was done by Jones (2004, 2008) and also by Fernández (2017) including their advantages and disadvantages.

2.4.2.3 Using leaf or xylem water potential for irrigation scheduling

Since the advent of the pressure chamber (Scholander et al., 1965), the most common used method for determining plant water status is by measuring the water potential. Plant water potential is a measure of the free energy status of the sap solution in a plant relative to that of a pure water sample (Taiz et al., 2006). This technique, originally referred to as ‘sap pressure’, uses a pressurized chamber to force sap back through a cut leaf petiole or stem. The energy required to move a unit volume of water (energy per unit volume = pressure) through the hydraulic system is equivalent to the water potential of the system, often measured in MPa and with negative units.

The three common methods of assessing water potential are leaf, pre-dawn leaf and midday stem or xylem water potential. Leaf water potential is the simplest measure, usually taken on a well-exposed healthy adult leaf. The drawback of this method is that it is sensitive to rapid changes in environmental conditions (i.e. passing of clouds) making it not a reliable indicator (Jones, 2004; Dzikiti et al., 2010). Literature, however, suggests that taking the leaf water potential at pre-dawn gives a more reliable indicator of tree water status when the water potential of the transpiration stream is in equilibrium with that of the soil (when transpiration is zero). However, there are practical limitations that constrain the use of this method e.g. collecting the data in the dark which is not safe at remote sites. Another widely used indicator is the stem or xylem water potential which has been shown to be reliable, practical and strongly correlated with the atmospheric evaporative demand (Shackel, 2011). A study conducted by Doltra et al. (2007), on Golden Delicious orchards in Spain noted a higher sensitivity to water stress with the midday stem water potential than the predawn leaf water potential. The stem water potential indicates the water status of the stem's xylem while the pre-dawn leaf water potential reflects the average soil water status in the tree's root zone. Despite the accuracy of these methods, their utilization in commercial orchards remains very limited. Some of the reasons for the limited use include the fact that they are destructive, slow, and require skilled manpower for reliable information.

2.5 FACTORS INFLUENCING GROWTH, PHYSIOLOGY AND WATER USE OF APPLE TREES

2.5.1 Canopy cover and rootstock

Canopy size/cover is one of the most important factors influencing orchard water requirements as this determines the amount of energy intercepted by the tree and the transpiration rates. However, no studies have directly quantified the transpiration rates of apple orchards over a range of canopy covers from planting to full-bearing age (Williams et al., 2003). Canopy size is extremely variable in the field and it is a direct cause of the large variability in water use from tree to tree in the same orchard, and from orchard to orchard. In this context, water requirements of young orchards with sparse canopies will be different from those of mature trees with dense canopies. For mature trees planted to different cultivars, it is not clear whether this will induce differences in water use rates, which may require different water management approaches. Studies by Dzikiti et al (2017 and 2018a) demonstrate that growers should carefully manage the canopies of mature apple trees to reduce orchard water use. This can be done by preventing excessive vigour in cultivars that are less susceptible to sunburn damage e.g., by using dwarfing rootstocks or through shoot thinning or spraying shoot growth retardants such as Regalis® (active ingredient: Prohexadione-calcium). Alternatively, producers can consider growing sunburn-susceptible cultivars under shade nets where they are maintained with less dense open canopies on dwarfing rootstocks.

Rootstocks are other highly important factors influencing orchard productivity as they affect tree growth and vigour, leaf nutrition, yield and fruit quality. They differ in resistance to soil-borne pathogens and tolerance to environmental factors (Fallahi et al., 2002; Tworkoski and Miller, 2007; Kosina, 2010). The selection of a rootstock is usually based on its ability to promote vegetative growth from the scion 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). Therefore, the selection of appropriate rootstocks is critical to ensure early returns on investment, given the high costs associated with establishing high density orchards and controlling excessive vigour. In this regard, rootstocks that produce the desired growth habit (dwarfing or semi-dwarfing) of the trees and promote high yields early in the orchard's life are ideal.

2.5.2 Environmental factors

While some apple cultivars and rootstocks are susceptible to cold injury (frost), excessive radiation, high air temperature and precipitation are the other common environmental factors negatively affecting apple production worldwide. The impacts of these factors must be understood if economic returns from commercial orchards are to be maximized. In apples, constant high temperatures cause an array of changes in plant growth and development, and may lead to a drastic reduction in economic yield (Wahid et al., 2007). In addition, when temperatures are above the optimum for photosynthesis, a strong decline in net gas exchange for the whole tree due to the simultaneous decline in carbon fixation and increase in respiration occurs (Marais, 2005). Furthermore, high temperatures (>36-40 °C) can reduce photosynthesis by up to 70%, thus reducing both the quality and quantity of the yield (Gindaba and Wand, 2007). The increase in temperature also contributes to an increase in evapotranspiration which will result in a large increase in crop water demand.

Soil water deficit is another major limiting environmental factor to plant physiological processes and functions and its effect is expected to intensify with the changing climatic conditions (Galeano et al., 2019; Bhusal et al., 2020). Water stress is known to trigger a wide variety of plant responses, ranging from cellular metabolism to crop growth rates leading to reduced biomass, yield, and quality of crops (Rossini et al., 2013; Yang et al., 2016; Kumari and Thakur, 2019). In fruit trees, water stress induces stomatal closure, reduces evaporative cooling and increases leaf temperature (Gonzalez-Dugo et al., 2014). Stomatal closure is one of the first responses to water deficit that allows plants to limit photosynthetic activity, which in turn has an adverse effect on transpiration (Flexas and Medrano, 2002). Carbon dioxide (CO_2) assimilation is also affected, restricting leaf metabolism and crop growth (Galeano et al., 2019). Fernández et al. (2020) has reported that in apple trees, early season water stress can reduce fruit set, resulting in less fruit per cluster and interfering with flower bud morphogenesis. Naor et al. (2008) on the other hand has reported that water stress can decrease yield of apple trees by affecting fruit growth due to reduction in cell turgor and carbohydrate availability owing to a decrease in photosynthetic rate. As a result, water stress needs to be quantified in order to develop effective strategies for irrigation scheduling that optimize agricultural water use without affecting crop yield especially in water-limited environments.

2.7 MEASUREMENT OF WATER USE IN ORCHARDS

Water use in orchards can be measured using a range of methods. These include hydrological approaches (lysimetry and soil water balance based methods), micrometeorological approaches (Bowen ratio, eddy covariance and surface renewal method), remote sensing (remote sensing energy balance and satellite-based crop ET using vegetation indexes) and plant physiology approaches (sap flow methods and chamber systems). These methods are subject to varying degrees of uncertainty, complexity and may require substantial experimental care (Monteith and Unsworth, 1990; Allen et al., 2011). In addition, most of these techniques, e.g. micrometeorological approaches are generally expensive, time consuming and requires trained personnel (Allen et al., 2011). Despite these limitations, these approaches have provided useful information on the water requirements of apple orchards in South Africa and elsewhere in the world (Volschenk et al., 2003; Dragoni et al., 2005; Gush and Taylor, 2014).

2.7.2 Measuring tree transpiration rates in orchards

Due to the importance of transpiration in plants, several techniques have been used to directly estimate transpiration of trees in general, including fruit trees (Rana and Katerji, 2000; Allen et al., 2011). These include weighing lysimeters, large tree potometers, stable isotopes, gas exchange chambers and a range of sap flow measurements. The most accurate and accepted method is the weighing lysimeters and as such it has been used in a number of studies in orchards (Ferreira et al., 1996; Ayars et al., 2003; Payero and Irmak, 2008). However this technique is expensive to install in existing orchards and it is not easy to maintain (Rana and Katerji, 2000). Due to these limitations, thermometric sap flow measurements have shown considerable promise for the estimation of tree transpiration in orchards (Green et al., 2003; Gush and Taylor, 2014). These sensors offer several advantages which include the measurements of the water stream inside the plant, a potentially high number of replicates, continuous and long monitoring of transpiration (Dragoni et al., 2005). The three most widely used methods are the: i) heat pulse velocity (HPV) (Green and Clothier, 1988; Burgess et al., 2001), ii) thermal dissipation (TDPs) (Granier, 1985), and iii) heat balance method (Sakuratani, 1981). All of these approaches are easily automated and have been shown to be robust and reliable enough for operation in the field over extended periods of time (Dragoni et al., 2005). The technical details and the specific advantages and disadvantages of each of the above mentioned techniques will be discussed in detail in the next section.

2.7.2.1 Stem heat balance

The heat balance method is normally used on stem sizes in the range 2 to 125 mm in diameter. This technique comprises a partially flexible heater which is wrapped around a tree stem. A known constant power, P_{in}, is applied to the entire circumference of the stem encircled by a heater, typically a few centimeters in width where sap flow is to be measured (Smith and Allan, 1996). The power is applied continuously. The energy balance equation for that segment is then solved for the amount of energy taken up by the moving sap stream under steady state conditions. The energy carried by the sap stream (in W) is subsequently converted to the mass flow of sap (in kg h^{-1}).

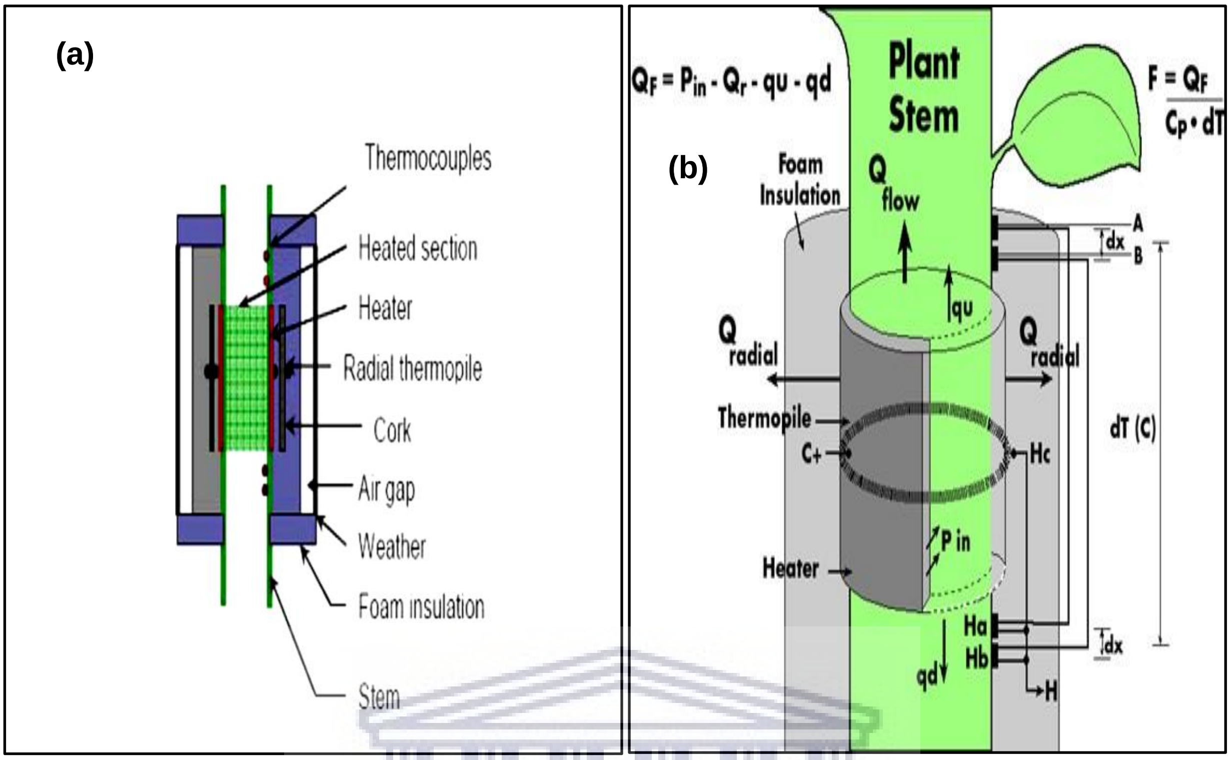

Fig. 2.4: Schematic representation of the heat balance sap flow gauge (Dynamax, Houston,TX, USA). (a) Vertical section through the stem heat balance sap flow gauge. (b) Energy balance components of the heat balance sap flow sensor connected to a plant stem.

Given the need for steady state conditions, it is essential that the heater is the sole source of energy. Thus substantial insulation of the gauge and parts of the plant stem section above and below the heater are critical to eliminate energy inputs from the environment. This is usually achieved by using a radiation shield and aluminium foil to ensure steady state conditions around the gauge are achieved. Suppose the heater power input to the stem in Fig 2.3b is P_{in} then the heat balance of the stem according to Sakuratani (1981) and Baker and van Bavel (1987) can be written as:

$$P_{in} = q_v + q_r + q_f \qquad (2.3)$$

where q_v is the rate of axial heat conduction along the stem, q_r is radial heat loss by conduction through the gauge, and q_f is the energy taken up by the moving sap stream. The value of q_f is obtained by subtracting q_v and q_r from P_{in} in Equation (2.3) given that the other energy terms can be measured. If ΔT_a and ΔT_b are the temperature gradients measured by the axial thermocouples on the upper and lower portions of the heater and ΔT_r is the radial temperature gradient, then applying Fourier's law for one-dimensional heat flow can be estimated as:

$$q_v = A_{st}K_{st}\left(\frac{\Delta T_a - \Delta T_b}{X}\right) \qquad (2.4)$$

where A_{st} is the cross sectional area of the heated section, K_{st} is the thermal conductivity and X is the distance between the two thermocouple junctions on each side of the heater.

The radial component of the stem heat balance, q_r , is determined from ΔT_r using:

$$q_r = K_{sh}\Delta T_r \qquad (2.5)$$

where K_{sh} is the effective thermal conductance of the sheath of materials surrounding the heater. The value of K_{sh} is unknown and depends on the thermal conductivity of the insulating sheath material and stem size. So Equation (2.3) has two unknowns i.e. q_f and K_{sh}. The value of $\mathrm{K_{sh}}$ is determined from the energy balance equation during periods when q_f is zero and this condition is approached at predawn.

Sources of error in sap flow measurements using the heat balance technique include the influence of changes in the heat stored in the gauged section of the plant which is often neglected, errors in determining K_{sh}, non-constant K_{sh} values (sensor theory assumes K_{sh} is constant throughout the day), influence of naturally occurring temperature gradients, insufficient heater power (leading to very low differential temperature signals), and the non-steady state conditions around the gauge, among others.

2.7.2.2 Thermal dissipation probes

The thermal dissipation probe (TDP) method has been extensively used for sap flow measurement worldwide due to its simplicity, high accuracy and reliability, and relative low cost (Steppe et al., 2010). This method was quantified by Granier (1985) based on the work of Viewegh and Ziegler (1960). It is based on the detection of convective heat transport (heat carried with the sap stream) (Fernández et al., 2017). Using the TDP method, transpiration rates are determined based on the temperature difference between a constant heated probe and an unheated probe installed in the hydro-active xylem of a tree (Fig. 2.5). These sensors are spaced 40 mm apart and measure changes in heat dissipation caused by the movement of sap up the stem of the plant.

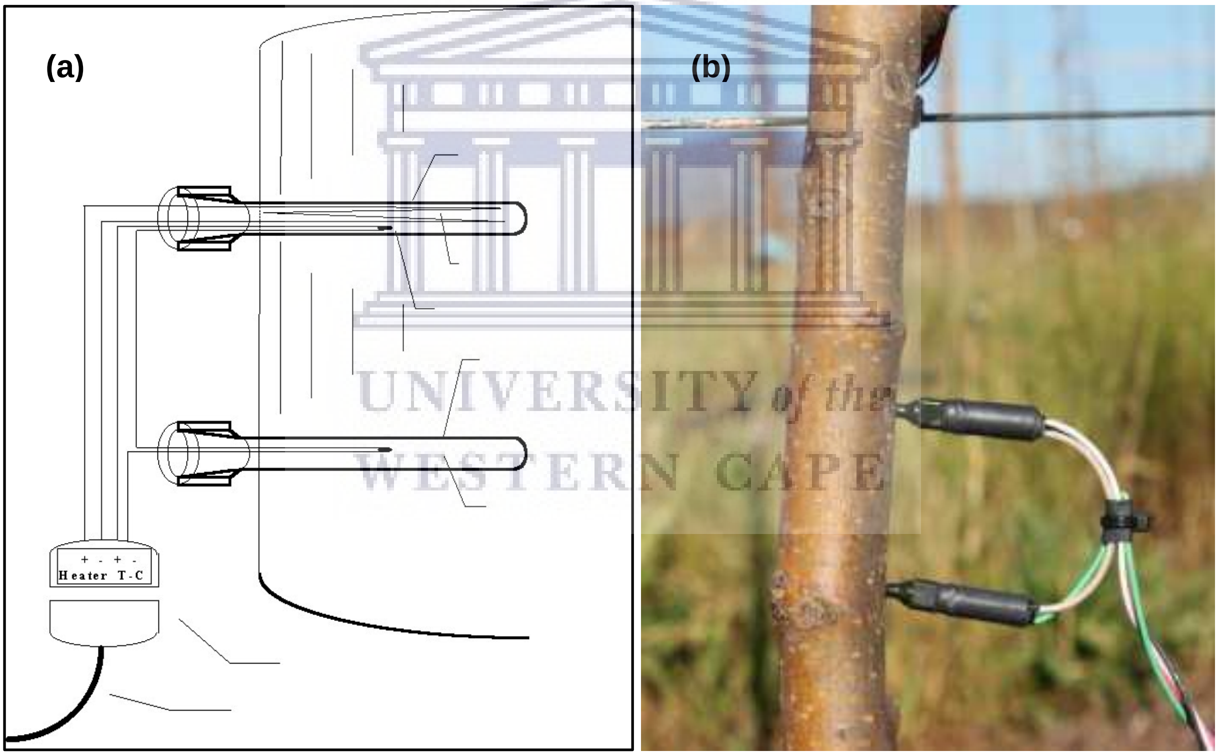

Fig. 2.5*:* (a) Diagram of the thermal dissipation probe (TDP) sap flow gauge showing technical details of the sensor. (b) A TDP installed on the stem of young non-bearing apple tree in Vyeboom orchard.

From Granier (1987) average sap flow velocity V (cm s^{-1}) may be empirically determined by the exponential expression:

$$V = 0.0119 * K^{1.231} \tag{2.6}$$

where the parameter K is defined as:

$$K = (dTM - dT)/dT \tag{2.7}$$

where dT is the measured difference in temperature between that of the heated needle and the lower non-heated needle. The parameter dTM is the value of dT when there is no sap flow (zero set value) (Dynamax, 1997). The TDP method requires the physical dimensions of the sapwood to be known in order to convert velocity to a sap flow rate as follows:

$$F_s = A_s * V * 3600 \tag{2.8}$$

where F_s is the sap flux density (cm^3 hr^{-1}), A_s is the cross-sectional area of sapwood, V is sap flow velocity, and the multiplier of 3600 is used to convert to hourly values (Dynamax, 1997).

Sources of errors associated with this technique include: the effect of the ambient thermal gradient (errors caused by the cold junction in thermocouples), the underestimation of the night-time sap flow, and the deficient thermal contact between the probe and tree body.

2.7.2.3 Heat ratio method

The heat ratio method (HRM) of the heat pulse velocity (HPV) technique is underlain by the theory of thermal conductance (i.e., diffusivity/conductivity) and convection (i.e., sap movement or flow). The HRM method consists of a line heater and two temperature sensors (thermocouples) inserted radially into the xylem to determine the heat pulse velocity. Heat pulses are used as a tracer, carried by the flow of sap up the stem. This allows the velocity of individual heat pulses to be determined by measuring temperature difference at defined locations around the heater.

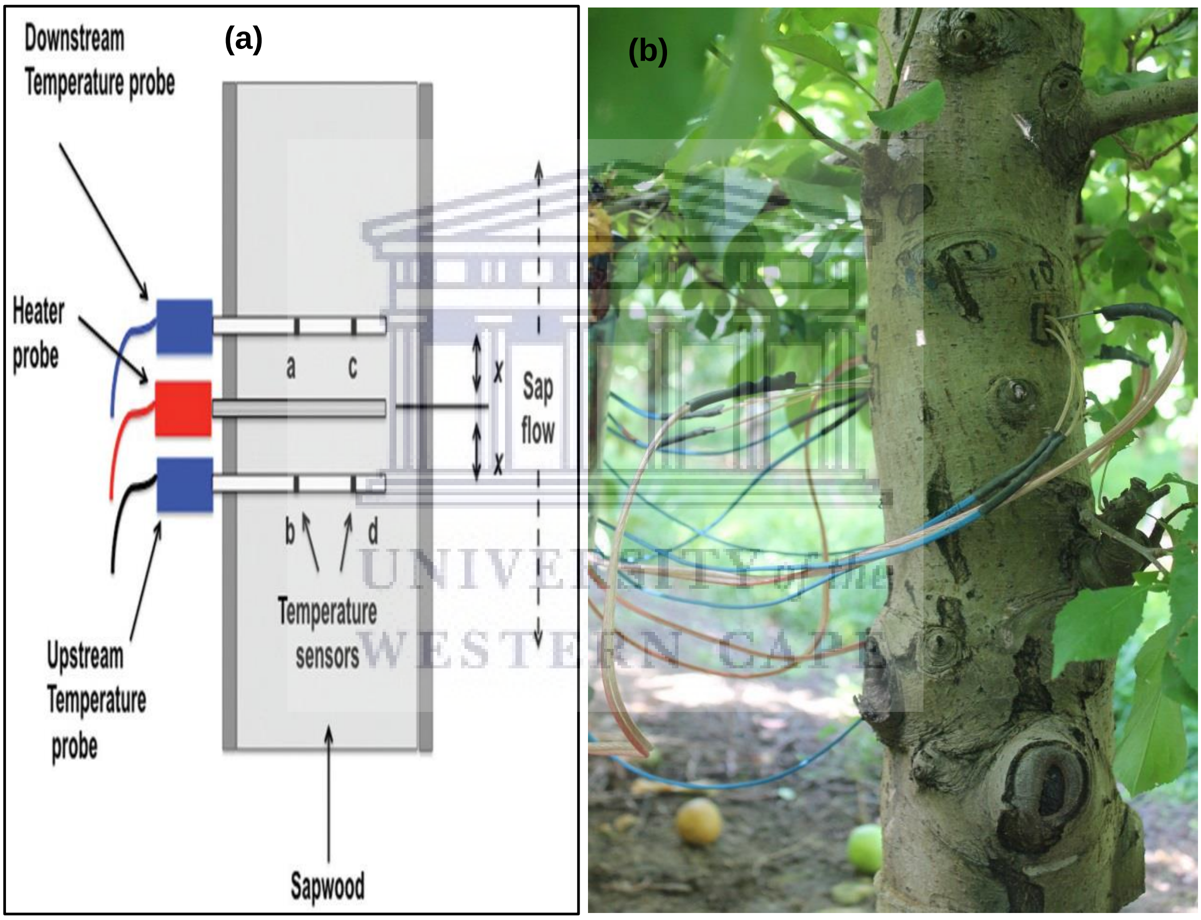

Fig. 2.6: (a) Schematic diagram of the heat-pulse probe configuration in a tree stem, which can be applied for both CHPM and HRM, depending on the distances at which temperature probes are installed away from the heater. (b) HPV installed on the stem of mature full-bearing apple tree in Southfield orchard.

The heat pulse velocity is then calculated according to Marshall (1958) as:

$$V_h = \frac{k}{x}\ln(v_1/v_2)\,3600 \qquad (2.9)$$

where, V_h is the heat pulse velocity (cm h^{-1}), k is thermal diffusivity of the wood, x is distance (cm) between the heater and either temperature probe, and v_1 and v_2 are increases in temperature (from initial temperatures) at equidistant points downstream and upstream, respectively.

The heat pulse velocity in Equation (2.9) needs to be corrected for sensor misalignment and tree wounding effects created by the drill which can affect the sap flow measurements. Burgess et al. (2001) modified the empirical model of Swanson and Whitfield (1981) for the correction of wounding, since their method did not pass through the origin and the resulting corrections yield a poor approximation of low and reverse flow rates of sap flow. According to Burgess et al. (2001), wounding can be corrected as follows:

$$V_c = bV_h + cV_h^2 + dV_h^3 \qquad (2.10)$$

where, V_c is the corrected heat pulse velocity, V_h is the heat pulse velocity and b, c and d are the correction coefficients to adjust for wound width (cm).

The HRM technique is popular for sap flow measurements due to its relatively low costs, low power requirements, and low maintenance (Forster, 2017). Furthermore, many sensors can be deployed across multiple species types or across the growth stages of herbaceous crops saving the time and expense of laborious calibrations (Miner et al., 2017). The main disadvantage of this method includes substantial errors that can arise from wounding and density corrections. Great care is therefore required when installing the probes, and when implementing these corrections. Moreover, instrumented trees must be representative of the tree size distribution in the orchard because scaling up sap flow rates from individual trees to orchard level transpiration can also introduce substantial errors.

2.7.1 Estimation of evapotranspiration in fruit orchards

Over the land surface, evapotranspiration (ET) accounts for approximately 60% of the total precipitation that is returned to the atmosphere, while in arid and semi-arid environments this can be as high as 90% (Fisher et al., 2008; García et al., 2013; Kool et al., 2014; Ershadi, 2014). Evapotranspiration is defined as the process whereby water is lost from the soil surface by evaporation and from the crop by transpiration (Allen et al., 1998). Irrigation is, therefore, critical to supplement 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. This fact makes accurate ET estimates vital for accurately and properly managing limited water resources (Moorhead et al., 2017). Currently, several traditional techniques are used to determine actual water use or evapotranspiration. Unfortunately, in orchards these methods are generally difficult to install and operate. They require homogenous soil surfaces and constant technical management, (Rana et al., 2005). These techniques include soil water balance approaches using soil water measurements (Rallo et al., 2014; Rallo et al., 2017; Volschenk, 2017); micrometeorological techniques such as eddy covariance net flux measurements (Gush and Taylor, 2014; Dzikiti et al., 2017), scintillometry, Bowen ratio and surface energy balance methods (Cammalleri et al., 2010; Consoli and Papa, 2013), and others. A brief review of the various methods is provided below.

2.7.1.1 Soil water balance method

The soil water balance method has been used together with the soil water content data measured using automated capacitance probes to estimate evapotranspiration (ET) since the 1980s (Jovanovic and Israel, 2012; Masango, 2014; Nyathi et al., 2016). This approach estimates ET as the residual of a soil water balance for measured soil water fluxes:

$$ET = I + P + CR - DP - RO \pm \Delta S \qquad (2.11)$$

where, I is irrigation, P is precipitation, CR is the capillary rise from the groundwater table, DP is deep percolation through the bottom of the root zone, RO is the runoff from the soil surface and ∆S is change in soil storage (all in mm d^{-1}).

The soil water balance is performed considering the soil is divided into two zones: the upper one where roots are, the depth of which increases with time until the mid-season when maximum root depth is attained, and the underlying layer that develops from the actual root depth to the maximum one, which behaves like a reservoir where soil water becomes available for the crop as the roots grow. This approach takes into account inputs of water into the orchard (e.g. irrigation and rainfall) and losses (e.g. evapotranspiration, runoff and drainage) from the orchard. Components such as deep percolation and surface runoff are often ignored when using the water balance method, due to the fact that they are difficult to determine. However, ignoring these components often results in inaccurate estimation of the crop ET (Rana and Katerji, 2000). Therefore, Allen et al. (2007) suggested appropriate algorithms needed to estimate runoff, deep percolation and capillary rise to obtain better accuracy of ET, especially in arid and semi-arid regions. Another drawback of the soil water balance method is that high spatial variability of soil properties and soil moisture conditions can be problematic especially when extrapolating the results to larger scales (Taylor and Gush, 2014). Considering all the limitations with the use of the soil water balance approach, calibration of the soil water content sensors is often required to account for the soil type, density and depth to reduce errors in ET calculations

Although this approach presents limitations for estimation of water use, Fares and Alva (2000) reported that continuous monitoring of soil moisture content within and below the active root zones in irrigated agriculture can facilitate optimal irrigation scheduling aimed at minimizing both the effects of water stress on the plants as well as assessing the impact of changing environmental conditions on crop evapotranspiration and yield.

2.7.1.2 Micrometeorological techniques

2.7.1.2.1 Eddy covariance

The eddy covariance (EC) system is considered one of the most reliable micrometeorological techniques for estimating field–scale evapotranspiration (Gush and Taylor, 2014; Rana and Katerji, 2005). The technique is based on the theory that, as wind moves, it does not move uni-directionally but rather in the form of turbulent eddies (Moorhead et al., 2017) which can be resolved into a net vector (flux) if the eddies are measured. As the air moves, it carries molecules of water vapor and other gases such as carbon dioxide and methane (Moorhead et al., 2017). These fluxes can be determined by measuring air temperature (T_a) and vertical wind speed (ω) at high frequencies, typically 10-20 Hz, and by estimating the covariance between them:

$$H = \rho C_p \, \Sigma \, (\omega - \overline{\omega})(T_a - \overline{T_a}) \qquad (2.12)$$

where, H is the sensible heat flux (i.e. energy used to warm up the air), ρ is the density of air, C_p is the specific heat capacity of air at constant pressure and T_a is the air temperature. The wind speed ω and T_a are measured using sonic anemometers and there are various types that are available commercially. The latent heat flux (λE), which is the energy equivalent of evapotranspiration (ET), can be calculated in two ways. First as a residual of the surface energy balance equation if all other terms are measured

$$R_n - G = H + \lambda E \qquad (2.13)$$

where, all terms are usually expressed in Wm^{-2}. The R_n term is the net radiation which is the algebraic sum of the net shortwave and net longwave radiation components at the Earth's surface. The G term represents the soil heat flux transferred into or out of the Earth's surface and it usually accounts for 5-32% of the energy balance (Monteith, 1973; Kustas and Daughtry, 1989) and R_n-G represents the available energy. Use of Eq. 2.13 assumes surface energy balance closure (Burba and Anderson, 2010), which is not always achieved in practice. So secondly, direct measurement of ET using the eddy covariance method can also be done through the covariance of the vertical wind speed and the atmospheric water vapour concentration (e) measured using an infrared gas analyser (IRGA) as:

$$\lambda E = \lambda \frac{M_w / M_a}{P_a} \rho_a \overline{\omega' e'} \qquad (2.14)$$

where, M_w and M_a are the molar masses of water vapour and air (g mol^{-1}), P_a is the atmospheric pressure (kPa), ω' is the instantaneous deviation of the vertical wind speed, and e' is the air's vapour pressure. Main sources of error with the eddy covariance method include time lags in sensor responses, spikes and noise, un-levelled instrumentation, and air density fluctuations, among others. Post-processing of the data is therefore critical to correct for these errors.

The general advantage of using the eddy covariance method in estimating crop water requirements is that it is arguably the most direct and accurate method of measuring ET provided the equipment is used properly and the data correctly processed and interpreted (Burba and Anderson, 2010). The main disadvantage of this system is that it requires highly skilled manpower to apply post processing corrections, favorable wind directions, careful sensor positioning and alignments. Moreover, the sensors are expensive and require significant care and well-trained personnel in setting up (Burba and Anderson, 2008). The other drawback of the eddy covariance technique is that it provides local-scale observations, which cannot adequately represent the spatial variability of the underlying surface. Also, the eddy covariance system suffers from a lack of energy balance closure, which can be as much as 10-30%, where the sum of turbulent latent and sensible heat flux are usually smaller than the available energy which comprise the sum of net radiation and ground heat flux. The underlying cause of the energy imbalance is not well known. But possible causes include measurement errors, an incompletely considered storage term, mismatches between the scales of the energy balance components, and the contribution of large eddies (with low frequency) to the energy transport not captured by eddy covariance.

2.7.1.2.2 Bowen ratio–energy balance method

The Bowen ratio-energy balance method (BREB) is a widely used micrometeorological method to estimate sensible and latent energy fluxes for various crops, land surfaces, and ecosystems (Mastrorilli et al., 1998; Mengistu, 2008). This method has been used mainly because of its relative simplicity and precision for vertical water vapor flux estimation. The BREB determines the latent heat and sensible heat fluxes based on the rearrangement of the simplified surface energy balance equation given in Equation (2.13).

The ratio of the sensible heat flux to the latent heat flux is called the Bowen ratio (β). Substituting the Bowen ratio into Equation (2.13) and re-arranging the equation gives the latent heat flux as:

$$\lambda \mathrm{E} = \frac{R_n - G}{1 + \beta} \qquad (2.15)$$

The value of β is estimated based on the direct measurements of vertical gradients of temperature and relative humidity (Rana and Katerji, 2000) as:

$$\beta = \gamma \frac{\Delta T_a}{\Delta e_a} \qquad (2.16)$$

where γ is the psychrometric constant in kPa $°C^{-1}$, ΔT_a is air temperature difference between two heights in °C and Δe_a is the air vapour pressure difference, measured at two height in kPa. Then, using measurements for R_n and G, together with the estimated the Bowen ratio, $\lambda \mathrm{E}$ is then determined using Equation (2.15). Like other energy balance methods, the BREB is an indirect method to estimate $\lambda \mathrm{E}$. Only the temperature and humidity are measured directly to determine the ratio H/$\lambda \mathrm{E}$. Consequently, accurate measurement of R_n, G and β are needed to properly estimate the latent heat flux (Angus and Watts, 1984; Perez et al., 1999; Allen et al., 2011). The main advantage of this method is its ability to measure crop ET from vegetation surfaces which are not well-watered. Also this method requires simple instruments, and provides continuous measurements over large areas and at time scales of less than an hour (Rosenberg et al., 1983).

On the other hand, the disadvantages of the BREB method include sensitivity of the instrument bias for gradient and energy balance measurements (Moorhead et al., 2017). Another drawback is that it assumes that field surfaces are horizontally homogeneous, resulting in only vertical energy transport (Mengistu, 2008). However, heterogeneous surfaces are common in fruit tree orchards, which make the application of the BREB difficult, and this may lead to significant errors. In addition, the BREB method requires an adequate elevation above the canopy to collect the required meteorological data (Perez et al., 1999; Yunusa et al., 2004). The M-BREB method, however, is still in its developing stages, and requires further testing and adaptation under varying environmental conditions before the approach can be more broadly adopted (Holland et al., 2013).

2.7.1.3 Remote sensing approaches

Over the past few decades, numerous remote sensing-based techniques, varying in complexity, have been developed and are currently used to quantify spatio-temporal variability of water requirements for a wide range of vegetation types (Kalma et al., 2008; Cammalleri et al., 2010; Consoli and Papa, 2013) with the surface energy balance algorithms being one of the most widely used approach (Liou and Kar, 2014). These algorithms provide robust, economical, and efficient tool for ET estimations at field and regional scales, in contrast to conventional ground-based ET measurement techniques such as eddy covariance, surface renewal and Bowen ratio, which are limited to relatively small, homogeneous footprints. To map actual ET from satellite imagery, remote sensing surface energy balance algorithms use the satellite-based data in combination with ground-based meteorological measurements. Thus, daily actual ET can be computed as a residual from the surface energy balance equation at the time of the satellite overpass as:

$$ET = R_n - G - H \tag{2.17}$$

where, the Rn, G and H terms are estimated using surface reflectance and radiometric surface temperature from satellite platforms such as MODIS, Landsat (7 ETM+ and 8 OLI) and etc.

The use of satellite based energy balance models has some advantages over the traditional methods. The main advantage of this technique lies in the fact that it can provide more affordable estimates of actual ET over large areas where the applicability of traditional methods could be limited (Mkhwanazi et al., 2012). The other advantage of this approach includes its ability to handle heterogeneity and various spatial-temporal scales. Although several surface energy balance models have shown reasonable accuracy for predicting ET in different parts of the world, these methods still requires some ground truth data to validate their performance (Hoedjes et al., 2007; Mkhwanazi et al., 2012). Another limitation of these algorithms is that the instantaneous ET obtained at the time of the satellite pass has to be extrapolated to daily values in order to be useful, both for irrigation scheduling purposes at farm level and for general water resource management (de la Fuente-Sáiz et al., 2017). Furthermore, input parameters such surface temperature have been reported to be difficult to estimate and this will lead to model errors.

2.8 REVIEW OF WATER USE MEASUREMENTS IN APPLE ORCHARDS

The amount of fresh water available for agricultural use worldwide is decreasing drastically and this has led to an emphasis on accurate assessment of crop water use. Although no clear guidelines on the water requirements of apple orchards with varying canopy cover are available, a few reports in literature have presented results of water uptake (transpiration) by field grown apple trees in South Africa and elsewhere in the world (Volschenk et al., 2003; Green et al., 2003; Dragoni et al., 2005; Gush et al., 2019). In this section a summary of studies done in South Africa will be provided and next we summarize studies done internationally.

In South Africa, Gush and Taylor (2014) conducted a study in the Koue Bokkeveld region of the Western Cape, near Ceres to measure the transpiration rates of a 12 year old Cripps' Pink ('Pink Lady') apple orchard on M793 rootstock. Water use measurements were conducted in the same orchard over a period of two years between May 2008 and July 2010. Tree density was 2 000 trees per hectare, and sap flow (transpiration) rates were measured on an hourly basis for the entire period on four trees, using the Heat Ratio Method (HRM) of monitoring sap flow. In addition, short-term seasonal measurements of ET were measured periodically, using an open path eddy covariance system. Distinct seasonal trends in water use were observed. On average, Cripps' Pink apple trees transpired about 4 000 L tree^{-1} per season, with mid-summer peak daily transpiration volumes of up to 58 L tree^{-1} day^{-1}. Maximum leaf area index of individual trees was around 3.5 with the average leaf area of each tree being approximately 15.8 m^{2}. Orchard leaf area index was about 2.74. The pollinators used a mere 1 100 L tree^{-1} year^{-1}, with maximum daily transpiration volumes of just 15 L tree^{-1} day^{-1} due to their small canopy sizes. Seasonal total orchard transpiration equated to 680 mm, while ET amounted to 950 mm.

Volschenk et al. (2003) on the other hand measured transpiration rates of three apple orchards with varying fractional cover in two production regions in the Western Cape, South Africa. One study was conducted at Molteno Glen farm in Elgin in a young four-year-old orchard planted to ‘Golden Delicious’ trees. The second trial was conducted at Grabouw and Oak Valley in Elgin Farms on 8-10 yr. old full-bearing orchards also planted to ‘Golden Delicious’ trees. A seasonal transpiration rate of about 174 mm was recorded on the young ‘Golden Delicious’ orchard. The seasonal total transpiration rates of between 356 mm and 422 mm were reported for full-bearing orchards at Grabouw and Oak Valley, respectively. These results show that differences in the transpiration rates are attributed to difference in canopy size and microclimatic conditions. Therefore orchards with varying fractional cover might have different water requirement.

In another study Volschenk (2017) used the soil water balance method to quantifying orchard evapotranspiration (ET) in the Koue Bokkeveld region, Western Cape. In this study, the ET of thirteen-year-old full bearing ‘Golden Delicious’ apple trees on Merton 793 rootstock was determined. The experiment was conducted for a period of three consecutive growing seasons from 2005/06 to 2007/08 in a 1.1 ha orchard. Tree spacing was 1.5 m x 4.5 m with 1 481 trees. The results from the study showed that on average daily ET rates increased about threefold from October to January, i.e. from 1.9 to 5.9 mm d^{-1} over the three growing seasons. Mean seasonal ET on the other hand was about 914 ± 33 mm, 799 ± 21 mm and 894 ± 8 mm in 2005/06, 2006/07 and 2007/08, respectively.

In New Zealand, Green et al. (2003) successfully estimated the transpiration rates of two mature trees planted to ‘Splendour’ cultivar on a vigorous MM106 rootstock at a tree spacing of 4 m x 4.5 m in summer and autumn. The trees had a large canopy size of about 45 m^2. Transpiration rates were measured on an hourly basis using the compensation heat pulse velocity sap flow method. Measured mid-summer transpiration rates on warm sunny days of about 60-70 L day^{-1} $tree^{-1}$ with hourly peaks of 6-7 L tree-1 h^{-1} were recorded. In mid-autumn, the peak hourly and daily sap flow rates halved to just 2-3 L tree-1 h^{-1} and 20-30 L tree-1 day^{-1}, respectively. It was concluded from this study that the reduced transpiration rates in mid-autumn were due to a decline in evaporative demand.

Dragoni et al. (2005) on the other used a combination of a whole tree gas exchange system and the compensation heat pulse velocity sap flow system to quantify transpirations rates of mature, dwarf 'Royal Empire' apple trees on M9 rootstock in a humid climate at Cornell University's New York State agricultural experiment station in Geneva over a period of 10 weeks. The orchard rows were north-south oriented, and the spacing between rows and trees were about 4.28 m and 1.83 m, respectively, giving 1280 tree ha^{-1}. Four trees were selected to be representative of the average tree size in the orchard. Average daily water use rates per tree ranged between 40-50 L for each individual tree with maximum canopy area of approximately 14 m^{2}. Transpiration rates normalized using the leaf area peaked at about 2.5 L day^{-1} m^{-2} but generally averaged about 2 L day^{-1} m^{-2}.

In another study, Gong et al. (2007) conducted field experiments to investigate the effects of leaf area index and soil moisture content on evapotranspiration and its components in an apple orchard in northwest China for two years. The experiment was conducted from April to October in 2002 and 2003 growing seasons. Evapotranspiration rates were estimated using two approaches: 1) the soil water balance method based on tube-type time-domain reflection measurements, and 2) combination of compensation heat pulse sap-flow technique plus micro-lysimeter methods. The two methods were in good agreement, with differences usually less than 10%. The average daily measured ET during the 2002 and 2003 growing seasons were about 2.27 mm day^{-1} and 2.25 mm day^{-1}, respectively. The maximum daily estimated ET were 6.14 mm day^{-1} during 2002 and 6.53 mm day^{-1} during 2003. It was observed from the study that the soil evaporation component of ET fell to very small values during the course of the study and the evapotranspiration of the orchard was mainly composed of the tree transpiration.

2.9 CROP WATER USE MODELLING

Although information on orchard water requirements can be obtained through various field measurement techniques, their practical application is subject to varying degrees of uncertainty and substantial experimental care (Allen et al., 2011). Therefore, evapotranspiration (ET) simulations models provide a cost-effective approach for estimating crop water requirements for irrigation management (Kang et al., 2003). These models estimate ET from readily available meteorological data for a variety of species and some are able to distinguish between beneficial (transpiration) and non-beneficial water use (evaporation losses). Examples include simple, empirical approaches and complex, mechanistic approaches. Simple, empirical approaches are more easily parameterized, but they are often site-specific, whilst mechanistic approaches can be more widely transferred, provided that the required input parameters are well determined (Leenhardt et al., 1995; Skaggs et al., 2004). To ensure these models are adoptable by growers, input data requirements should be kept to minimum and simple procedures should be available to determine the necessary input variables.

2.9.1 Penman-Monteith approach

The advent of the Penman-Monteith (P-M) combination or “Big leaf” approach in the 1960s (Monteith, 1965) received sustained interest in water use modelling studies (Rana et al., 2005; Oguntunde et al., 2007). P-M model describes the ET process and its influencing factors by considering meteorological and vegetation physiological characteristics (Monteith, 1965). This model estimates ET as water vapor diffusing from the canopy surface based on the aerodynamics and boundary layer canopy resistances (Monteith and Unsworth, 2013). The main advantage of the P-M method is that it does not require local calibrations, provided there are complete input data. The P-M equation also does not have any wind function; rather, it has aerodynamic and surface resistance terms. Thus, the P-M equation is given by:

$$ET = \frac{s(R_n - G) + \rho c_p g_b [e_s(T_a) - e_a]}{\lambda\left[s + \gamma\left(1 + \frac{r_c}{r_b}\right)\right]} \qquad (2.18)$$

where, λ is the latent heat of vaporization of water (J kg^{-1}), s is the slope of the saturation vapour pressure against temperature curve (Pa °C^{-1}), ρ is the density of air (kg m^{-3}), c_p is the specific heat of air at constant pressure (J kg^{-1} °C $^{-1}$), $e_s(T_a) - e_a$ is the vapour pressure deficit (VPD) of the air (Pa), γ is the psychrometric constant (Pa °C $^{-1}$), r_b and r_c are the aerodynamic and canopy resistance (s m^{-1}), respectively. For a well-watered reference crop (height ~ 0.12 m) that completely covers the ground, the ET (in mm d^{-1}) can be derived from standard meteorological data using a simplified P-M equation according to Allen et al (1998) as:

$$ETo = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T_a + 273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \qquad (2.19)$$

where, U_2 is the mean wind speed at 2m height (m s^{-1}), Δ is the slope of the saturation vapour pressure-temperature curve (kPa K^{-1}), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa). This approach is widely used for estimating the reference evapotranspiration (ET$_\text{o}$).

Although the P-M equation is probably the most widely used and robust method for estimating ET, it has several shortcomings (Allen et al., 1998; Subedi and Chavez, 2015). The main limitation of this approach is that it was derived for horizontally homogeneous soil or vegetation surfaces (Monteith, 1965), therefore, it fails to accurately estimate ET from sparse canopies and to partition fluxes associated with the soil and plant components. It also ignores the estimation of appropriate surface resistance, which is very important for estimating the rate at which water is lost through the stomata (Subedi and Chavez, 2015). The exclusion of surface temperature while deriving the P-M equation can induce errors, especially in areas where surface temperature and air temperature are significantly different (Subedi and Chavez, 2015). In addition, the Penman-Monteith model often requires parameters that are difficult to characterize globally such as aerodynamic resistance, stomatal resistance, and wind speed (Cleverly et al., 2013).

2.9.2 Priestley and Taylor approach

Despite the fact that P-M approach has proven to be remarkably accurate and robust for estimating potential ET in a wide range of conditions, its application is limited due to the frequent unavailability of meteorological variables. Priestley and Taylor (1972) then proposed a simplified version of the model for calculating ET$_\text{o}$, using less input data, i.e. available energy and air temperature. In addition, the model takes does not consider aerodynamic properties and physiological behavior of the surface and is given by:

$$\lambda E = \alpha \frac{\Delta}{\Delta + \gamma}(R_n - G) \tag{2.20}$$

where, λE is actual evapotranspiration, α is a model coefficient (which Priestley and Taylor allowed to vary for different degrees of dryness), Δ is the slope of the saturation vapor density curve (kPa K^{-1}), γ is the psychrometric constant (Pa °C^{-1}), R_n is net radiation (W m^{-2}), and G (W m^{-2}) is soil heat flux.

The accuracy of the Priestley and Taylor (P-T) model mainly relies on the accurate determination of the empirical parameter, (α, P-T coefficient), which represents the effect of temperature, soil moisture and vegetation cover on evapotranspiration. In general, the P-T coefficient can range from 0 (dry surfaces) to 1.26 for (wet surfaces) (Priestley and Taylor, 1972; Ai and Yang, 2016). Recent studies based on *in situ* global data sets have reported a good robustness of the Priestley-Taylor modelling approach over a variety of biomes (Ershadi et al., 2014). Nevertheless, various theoretical and experimental studies have stressed that the P-T coefficient is variable under different surface and atmospheric conditions (Fisher et al., 2008), and this might lead to ET underestimation or overestimation. Therefore, accurate quantification of this parameter is required and that will lead to good estimates of ET.

2.9.3 Multiple source models

Acknowledging the weaknesses of the simple, empirical approaches, multiple source ET models were developed to estimate ET for heterogeneous or sparse vegetation (i.e. orchards) (Shuttleworth and Wallace, 1985; Li et al., 2010). Multiple source models do not assume complete uniformity throughout the entire orchard but rather account for the heterogeneity in surface characteristics (e.g., Shuttleworth and Wallace, 1985; Choudhury and Monteith, 1988). This is crucial, especially if one is evaluating irrigation management regimes, as soil evaporation always contributes a large portion of water use in crops with sparse canopies. Examples of multiple source models applied to orchards can be found in Oguntunde et al (2007), Villalobos et al (2009), Li et al (2010), Ding et al (2013), and among others. The Shuttleworth and Wallace (S-W) model is by far considered the most accurate model.

The S-W model is a two-source model that is based on two Penman-Monteith models, one for the soil surface (i.e. soil evaporation) and the other for the plant surface (i.e. transpiration) (Dolman, 1993). This model provides the possibility to partition ET into plant and soil components through the use of surface resistances to regulate the transfer of energy from plants (r_s^c) and soil (r_s^s). Aerodynamic resistances (r_a^a, r_a^c, r_a^s) are also required to regulate the transfer of energy between the surfaces and atmosphere (Farahani and Bausch, 1995). Evapotranspiration (λE, in W m^{-2}) is then estimated as the algebraic sum of the fluxes from transpiration and soil evaporation as:

$$\lambda E = \lambda E_c + \lambda E_s \qquad (2.21)$$

where, λE_c is the latent heat flux from tree canopies (transpiration) and λE_s is evaporation from the orchard floor, both in (W m^{-2}). The fluxes are estimated at a reference height (x) above the canopy and the transpiration and soil evaporation components are given by:

$$\lambda E_c = C_c \frac{\Delta A + \left\{\frac{\rho c_p D - \Delta r_a^c A_s}{r_a^a + r_a^c}\right\}}{\Delta + \gamma\{1 + r_s^c/(r_a^a + r_a^c)\}} \qquad (2.22)$$

$$\lambda E_s = C_s \frac{\Delta A + \frac{\{\rho c_p D - \Delta r_a^S (A - A_S)\}}{r_a^a + r_a^S}}{\Delta + \gamma\{1 + r_s^S/(r_a^a + r_a^c)\}} \tag{2.23}$$

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}, D is the vapour pressure deficit of the air at the reference height (kPa), 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.

Despite the fact that the S-W model has been tested extensively in different parts of the world with positive results for natural ecosystems (Fisher et al., 2005), its practical application is somewhat limited by the large number of input parameters and measurements required. This results in a complex structure, which will require more parameters that are not always easily obtained from conventional meteorological data (Kool et al., 2014). The lack of accurate quantitative knowledge of the resistance terms that control the latent heat fluxes at the canopy and soil surface also limits the use of this model.

In summary, all models described above vary in structural complexity, parameterization and number of input data required to run them. Hence, their performance in estimating evapotranspiration is expected to differ over various land surface types and conditions. As such, there is a need for adopting model(s) that requires readily available input data and is not difficult to parameterize.

CHAPTER 3: CULTIVAR EFFECTS ON THE TRANSPIRATION AND WATER STATUS OF GOLDEN DELICIOUS AND CRIPPS' RED APPLE TREES: RESULTS FROM A POT TRIAL

In preparation for publication as:

***Nompumelelo T Mobe**, Sebinasi Dzikiti, Dominic Mazvimavi, Zanele Ntshidi. Water use and hydraulic properties of young Golden Delicious and Cripps' Red apple cultivars*

Summary

Many apple cultivars are planted in orchards globally for various reasons. In South Africa, the high yielding Golden Delicious and the high value Cripps' Pink/Red are widely planted. While many trials have focused on the productivity and fruit quality attributes of these cultivars, little is known about whether or not there are differences in their water use characteristics. The goal of this study was therefore to investigate, in detail, the transpiration responses of these two cultivars and to establish their key drivers under controlled conditions. Data were collected on six young Golden Delicious and Cripps' Red trees, respectively, grown in 20 liter pots at Stellenbosch University, Welgevallen experimental farm from 12 April to 06 May 2018. The young trees, all of them on the M793 industry standard rootstock, were well-watered using drip irrigation system. Transpiration rates of the two cultivars were quantified using sap flow sensors installed on two trees per cultivar at the stem and branch levels. Differences in tree water status in response to changes in microclimatic conditions were quantified by monitoring the plant water potential (stem and leaf water potential) and the stomatal conductance on selected clear days. An additional indicator of the efficiency of the hydraulic systems of the two cultivars was the percentage utilization of the internally stored water. This variable is a function of the imbalance between the root water uptake and the transpirational losses. Results suggest that there were no significant differences in the peak sap flux density (SFD) of the two cultivars on clear days averaging 15.48 ± 1.29 and 15.07 ± 0.97 $cm^3\ cm^{-2}\ h^{-1}$ for the Golden Delicious and Cripps' Red cultivar, respectively. The leaf and stem water potentials were slightly higher for the Golden Delicious compared to the Cripps' Red cultivar, but these differences can be explained by the mild water stress in the Cripps' Red pots at some point during the campaigns. Differences in the stomatal conductance were non-significant. Use of internally stored water was up to 28 and 25% of the daily total transpiration for the Golden Delicious and Cripps' Red cultivars, respectively on typical clear days. This study suggests that there are insignificant differences in the water use characteristics of the young potted Golden Delicious and Cripps' Red cultivars studied here.

3.1 INTRODUCTION

There are more than 7 500 apple cultivars planted globally and only a small number of them are grown commercially in South Africa (Afzadi, 2012). Several studies have investigated the production potential and yield quality attributes of various apple cultivars (Blažek and Hlušičková, 2007; Oliveira et al., 2017; Uzun et al., 2019). However, an important information gap exists on whether or not there are differences in the transpiration dynamics of different apple cultivars at the whole tree level. Massonnet et al. (2007) observed differences in the leaf water status and gas exchange between the Braeburn and Fuji apple cultivars while Liu et al. (2012) made similar observations on 31 different cultivars. In these studies, the plant water status data were collected from spot measurements. It is not clear whether these spot measurements translate to whole tree and indeed orchard level differences in water use.

Differences in the whole tree level transpiration can arise from multiple factors. These include variations in stomatal density, stomatal aperture, the type and makeup of the water conducting vessels (i.e. whether predominantly vessel elements or tracheids), and the diameter of the xylem vessels which affect the hydraulic conductance of the plant (Sellin et al., 2008; Rockwell and Holbrook, 2017). The wood anatomy, either ring porous or diffuse also plays a part in the efficiency of water transport through the trees although apples are predominantly ring porous (Lambers et al., 2008). Numerous studies have shown that canopy size has a significant effect on the transpiration dynamics of apple trees (e.g. Dragon et al., 2005; Dzikiti et al., 2018b; Gush et al., 2019).

In countries with high radiation levels such as South Africa, and indeed elsewhere in the Mediterranean climatic regions, apple cultivars that produce green fruit such as the Golden Delicious, Golden Delicious/Reinders®, Granny Smith etc. maintain large amounts of foliage. The dense canopies have the advantage of shading the fruit thereby reducing losses due to sunburn damage. In South Africa, sunburn damage losses in apple orchards is substantial accounting for as much as 29% of the total production (Gindaba and Wand, 2007; Makeredza et al., 2013). On the other hand, trees that bear blushed fruit such as the Cripps' Pink, Cripps' Red, Rosy Glow, Royal Gala etc. are maintained with more open canopies. This is to maximize the amount of radiation that penetrates into the canopy to facilitate the development of the red pigmentation through anthocyanin activities. Recent studies in South Africa e.g. Dzikiti et al., (2018a, b) show that while the small canopies of the red cultivars produce high quality fruit, they also have significant water saving benefits.

The goal of this study was to determine in detail whether, besides canopy cover, do the physiological differences between the Golden Delicious and Cripps' Red cultivars translate to differences in the tree water use rates? This study investigated young trees growing under similar environmental conditions in pots in an attempt to establish whether physiological differences between the cultivars also induce differences in transpiration responses. In the next Chapter field trial was used to validate this potted plant experiment is up scaled to field level trials with trees of these two cultivars (or their close relatives) of different age groups.

The specific objectives of this potted plant experiment were to:

(i) Quantify water use rates in the two cultivars at the whole tree level based on normalized indicators of water use such as the sap flux density (SFD);

(ii) Compare the hydraulic properties of the transpiration streams of the two cultivars by deriving the hydraulic conductance in different parts of the trees e.g. soil-to-stem and stem-to-leaf and the extent of reliance of each cultivar on the internally stored water;

(iii) Attempt to explain any differences in water use characteristics using leaf level measurements of leaf and stem water potential and stomatal conductance.

3.2 MATERIALS AND METHODS

3.2.1 Experimental set up and plant material

Twelve young trees, six of each cultivar were grown outdoors in 20 litre pots at the University of Stellenbosch, Welgevallen experimental farm (33° 94'.24"S, 018° 86' 64"E, 157 m mean height above sea level) (Fig 3.1). The average tree height and stem circumference (~ 50 cm from the soil surface) at the beginning of the experiment in 12 April 2018 were 142.67 cm and 6.08 cm for Golden Delicious, and 159.50 cm and 7.52 cm for Cripps' Red cultivar, respectively. The Cripps' Red trees were slightly taller and had thicker stems, so the results presented here are normalized to remove bias due to plant size differences.

The pot mixture used as a growing medium comprised well-drained compost and sand potting mix. The trees were maintained on a standard fertilizer regime wherein five grams of compound fertilizer (N:P:K = 2:3:2) were applied to each pot every week to provide the nutrients throughout the experiment. Water was supplied by a drip irrigation system using one drip line per pot and the trees were irrigated daily to ensure adequate water availability. Four healthy and actively growing trees were instrumented with 10 mm Granier sap flow sensors (TDPs) to investigate the transpiration dynamics in detail. The TDPs were installed in the sapwood of the trees and we assumed that the young trees had not yet developed heartwood. All the twelve trees could not be instrumented with the sap flow sensors due to equipment limitations.

To quantify the dynamics of water uptake and loss, an additional sap flow sensor of the stem heat balance type (Model SGA 3: Dynamax Houston, USA) was installed on the branch of two TDP instrumented trees, one per cultivar. The stem heat balance sensors were installed according to the manufacturers' recommendations (van Bavel and van Bavel, 1987). Because of the proximity of the branch sap flow sensors to the leaves, we assumed that the branch sap flow in fact approximated the tree transpiration (i.e. tree water loss). The volumetric soil water content (SWC) was monitored in each pot with sap flow instrumented trees using time domain water content reflectometer probes (Model CS616- Campbell Sci. Inc., Logan, UT, USA) (Fig 3.2a).

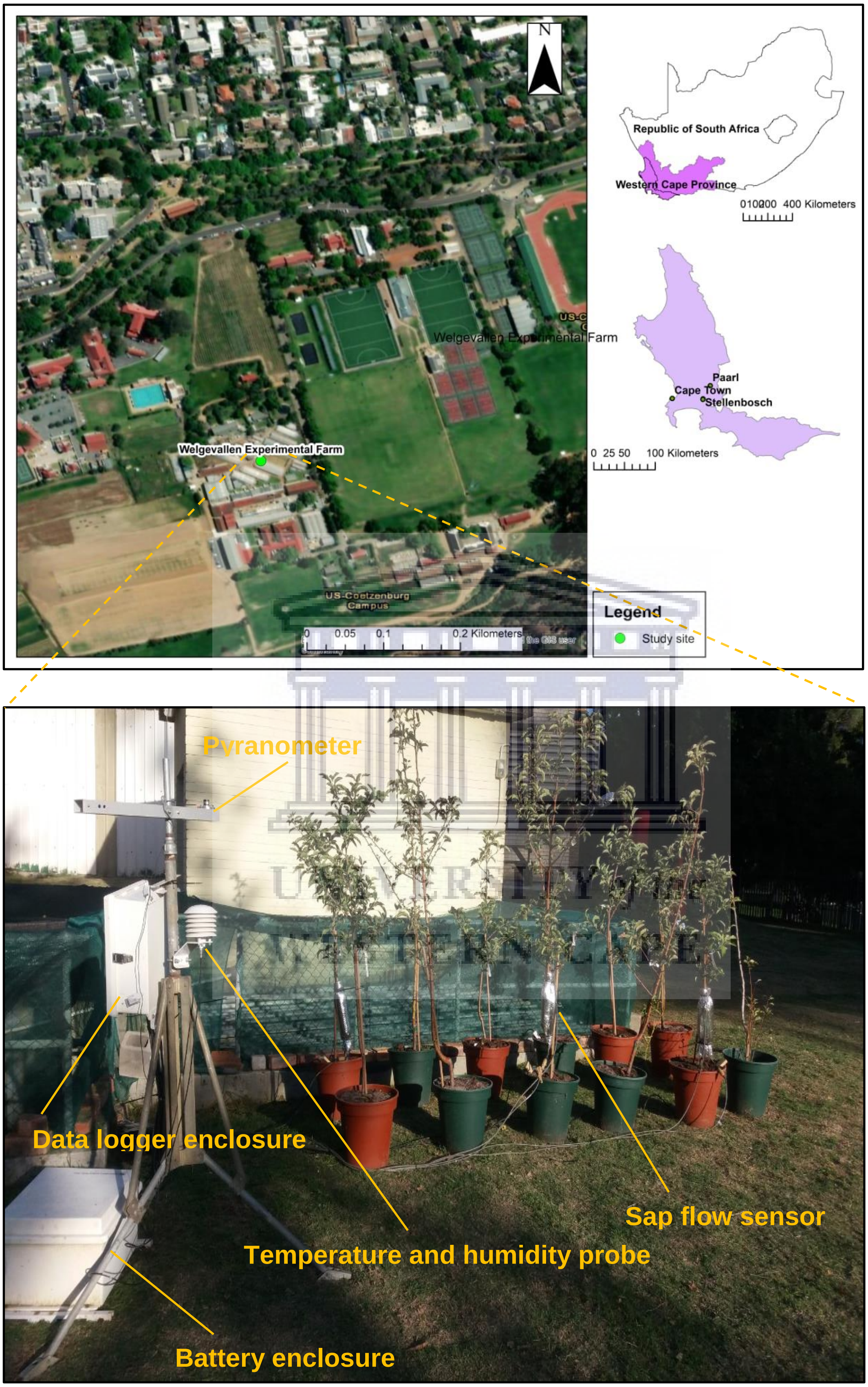

Fig. 3.1: Experimental set-up to compare the water use characteristics of the Golden Delicious and Cripps' Red apple cultivars.

3.2.2 Weather data

The microclimate data were monitored using an automatic weather station for the duration of the experiment (12 April to 06 May 2018) (Fig 3.1). The equipment comprised a pyranometer (Model: LI 200R Apogee Instruments, Inc., Logan UT, USA) which measured the solar irradiance, installed on a horizontal levelling fixture mounted on a north-facing cross bar to avoid self-shading. Air temperature and relative humidity were measured using a Vaisala HMP60 temperature and humidity probe (Vaisala, Vantaa, Finland). The vapour pressure deficit (VPD) was calculated based on measurements of air temperature and relative humidity, as the difference between the air's potential saturated vapour pressure value (es) and actual value (ea) (Jones, 1992). All the sensors were connected to a data logger (Model: CR1000, Campbell Scientific, Inc., Logan UT, USA) that was programmed to store data at 10 minutes intervals. A 12 - volts rechargeable sealed lead-acid battery was used to power the station. Data were downloaded using a SC-USB cable connected to the data logger and a laptop.

3.2.3. Transpiration and use of internally stored water

Sap flow was measured on the main stem using commercially available Granier probes (Model: TDP 10, Dynamax Inc., Houston USA) (Granier, 1987). These sensors are 10 mm long of which about 8-9 mm was situated in the sapwood of the trees given that the average bark thickness was approximately 1-2 mm. Two healthy and actively growing trees per cultivar were instrumented as shown in Fig 3.2a. The sensors were installed at least 50 cm above the growing medium surface to minimize errors due to thermal gradients especially early in the morning. Thermal dissipation probes (TDPs) measure temperature changes in a heated probe implanted in the sapwood and an unheated reference probe below the heated probe. These probes are spaced 40 mm apart and the temperature difference between the sets of probes is related to the sap velocity by empirical equations detailed in Chapter 2. Reflective aluminium foil was wrapped around the plant section on which the Granier sap flow gauges were installed to minimize the effects of exogenous heating on the sap temperature signals. The TDPs were connected to CR1000 data logger programmed with a scan interval of 5 seconds and the signals were averaged at 10 minutes intervals throughout the study period. The mean stem diameters of instrumented trees at the sap flow installation positions were between 4.8 and 7.5 cm for the Golden Delicious and 6.1 and 8.1 cm for the Cripps' Red cultivar. Because the TDPs are known to underestimate sap flow (Steppe et al., 2010), calibration corrections developed for young apple trees using a weighing lysimeter detailed by Dzikiti et al., (2018b) were used. Analysis of the sap flow data in this chapter is based on measurements collected from 12 April to 06 May 2018 (day of year (DOY) 102 to 126) when good quality continuous data was available for both treatments.

Differences in the water use characteristics of the two cultivars can be related to differences in stomatal density, stomatal dimensions and hydraulic properties such as the hydraulic resistances and water storage (often represented by the capacitance) (Jones, 1990). The variations in stomatal properties can be captured by differences in the stomatal conductance which will be described shortly. Estimates of the whole tree hydraulic conductance will also be described in section 3.2.6. However, to quantify the reliance of each cultivar on internally stored water, which is a proxy of the efficiency of the hydraulic system, additional sap flow data were collected at the branch level of the two sap flow instrumented trees. The branch sap flow rates were measured using miniature stem heat balance sap flow gauges (Model: SGA3, Dynamax, Houston, USA) and the sensors were located close to the leaves so that the branch sap flow approximated tree transpiration (Fig 3.2b). Only two trees were instrumented, one per cultivar and the miniature stem heat balance sap flow sensors were installed according to the manufacturer's recommendations. The diameter at the branch installation points were 1.4 cm and 1.5 cm for Cripps' Red and Golden Delicious cultivars, respectively. A strip of thin plastic was wound around the plant section where the sap flow gauges were installed to ensure that possible stem/branch transpiration did not affect the signals. Double layer of aluminum foil was then wrapped around the gauge to keep out the sun and to maintain steady state conditions around the gauged areas (Fig 3.2b).

Fig. 3.2: Measurement of (a) stem sap flow (Granier probe), (b) branch sap flow (miniature stem heat balance sap flow gauges)

3.2.4 Plant water status measurements

The diurnal dynamics in the water potential gradients within the trees were determined from simultaneous measurements of the leaf water potential (LWP) and stem water potential (SWP) at approximately hourly intervals on three consecutive clear days. The selected days were 15 April (DOY 105), 16 April (DOY 106) and 17 April (DOY 107) 2018 from 09:00 to 18:00. Data were collected on healthy, mature and fully expanded leaves on the adjacent trees with no sap flow sensors. Stem water potential was measured on two leaves located close to the trunk in each tree. Leaves were enclosed the day prior to data collection 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 the water potential in the stem's xylem. Enclosed leaves were cut at the petiole with a razor blade and stem water potential was measured using a pressure chamber (model 615, PMS Instrument Company, Albany, OR, USA).

In order to compare differences in the stomatal characteristics of the two cultivars, the leaf stomatal conductance (g_s) was measured using a diffusion porometer (Model AP4: Delta-T Devices, Cambridge, UK). Data were collected on two tagged healthy young leaves as they are at maximal physiology on two trees per cultivar giving an average of four measurements per cultivar. Measurements were taken on an hourly basis on sun-exposed leaves in the morning from 09:00 to 11:00 and in the afternoon from 12:00 to 14:00 on three clear days (15 -17 April 2018) when the water potentials were measured.

3.2.5 Tree hydraulic properties

Given that the stem sap flow rate is driven by the water potential gradient between the soil and the leaves, the whole plant hydraulic resistance to water flow can be determined by applying Ohm's law, following the method of Jones (1992). Simultaneous measurements of leaf water potential and soil water potential gradient are used to estimate the integrated hydraulic resistance of the soil-to-stem pathway (R_x [MPa h g^{-1}]) using the water potential difference (MPa) and the prevailing stem sap flow rate as shown in Equation (3.1):

$$R_x = \frac{\Psi_s - \Psi_L}{SF} \tag{3.1}$$

where, (Ψ_L, [MPa]) is the leaf water potential, (Ψ_s [MPa]) is the soil water potential and *SF* (g h^{-1}) is the stem sap flow rate at the time when leaf water potential measurements were conducted. The soil water potential in this study was assumed to be zero as the trees were well-watered during the course of the experiment.

The hydraulic resistance downstream of the stem i.e. between the stem and the leaves (R_{sx} in MPa h g^{-1}) on the other hand was determined from the water potential difference between the stem's xylem and the leaf water potential divided by the prevailing stem SF rate (g h^{-1}) as given in Equation (3.2):

$$R_{sx} = \frac{\Psi_x - \Psi_L}{SF} \tag{3.2}$$

where, (Ψ_X, [MPa]) is the stem water potential which was measured hourly using a pressure chamber.

The dynamics of the sap flow rate near the base of the stem (*F*) as affected by the changes in the transpiration rate of the whole crown (*E*) can be described using a simple water balance model. The rate of change in the water stored in the tissues (*W*) of the tree is determined from the differences between water uptake, represented by stem sap flow (*F*) measurements and water loss via transpiration (*E*) determined from branch sap flow scaled up to the tree level estimated as:

$$f = \frac{dW}{dt} = F - E \tag{3.3}$$

Equation (3.3) assumes that there is a negligible capacitance in the roots such that the stem sap flow rate (*F*) equals the root water uptake. To estimate the total transpiration (*E*), branch sap flow was scaled up to the whole-canopy level using the approach by Meinzer et al. (2004). In this method, the scaling factor is estimated as the ratio of the daily total sap flow at stem level to that at the branch level since over a whole day time scale total tree transpiration is numerically equal to the stem sap flow since capacitance is negligible over longer time scales. So multiplying the branch sap flow rate by this factor gives an estimate of the whole-canopy transpiration rate (E).

3.2.7 Data analysis

Student's t test analysis was used to establish significant differences in the sap flux density and plant water status between Golden Delicious and Cripps' Pink cultivars at P = 0.05 level of significance. All data were analyzed using the Statistix v. 10.0 statistical package.

3.2 RESULTS

3.2.1 Weather Conditions

The hourly global solar radiation (R_s, W m^{-2}), vapour pressure deficit (VPD, kPa) of the air, air temperature (Ta, °C) and relative humidity (RH, %) recorded during the study (15-17 April 2018) are presented in Figure 3.3a & b. For demonstration purposes, data for three clear days (DOY 105 (15 April), DOY 106 (16 April) and DOY 107 (17 April) 2018) coinciding with plant water status measurements are presented. The hourly air temperature ranged from 11.4 °C to 29.7 °C, 13.5 °C to 33.4 °C and 16.1 °C to 27.5 °C in DOY 105, 106 and 107, respectively. Hourly relative humidity (RH) reached 92% and solar radiation exceeded 706.8 W m^{-2} on DOY 105. Vapour pressure deficit reached a daytime maximum of 2.81 kPa, 3.78 kPa and 2.31 kPa on DOY 105, DOY 106 and DOY 107, respectively. During this April period weather conditions were changing from summer to winter in the Southern Hemisphere and the atmospheric evaporative demand was on a declining trend. During the peak summer period (December to February), maximum air temperatures reach up to 40 °C with the relative humidity dropping to less than 10% on very dry days. Because the trees were located between buildings, the wind speed was assumed to be negligible in this study.

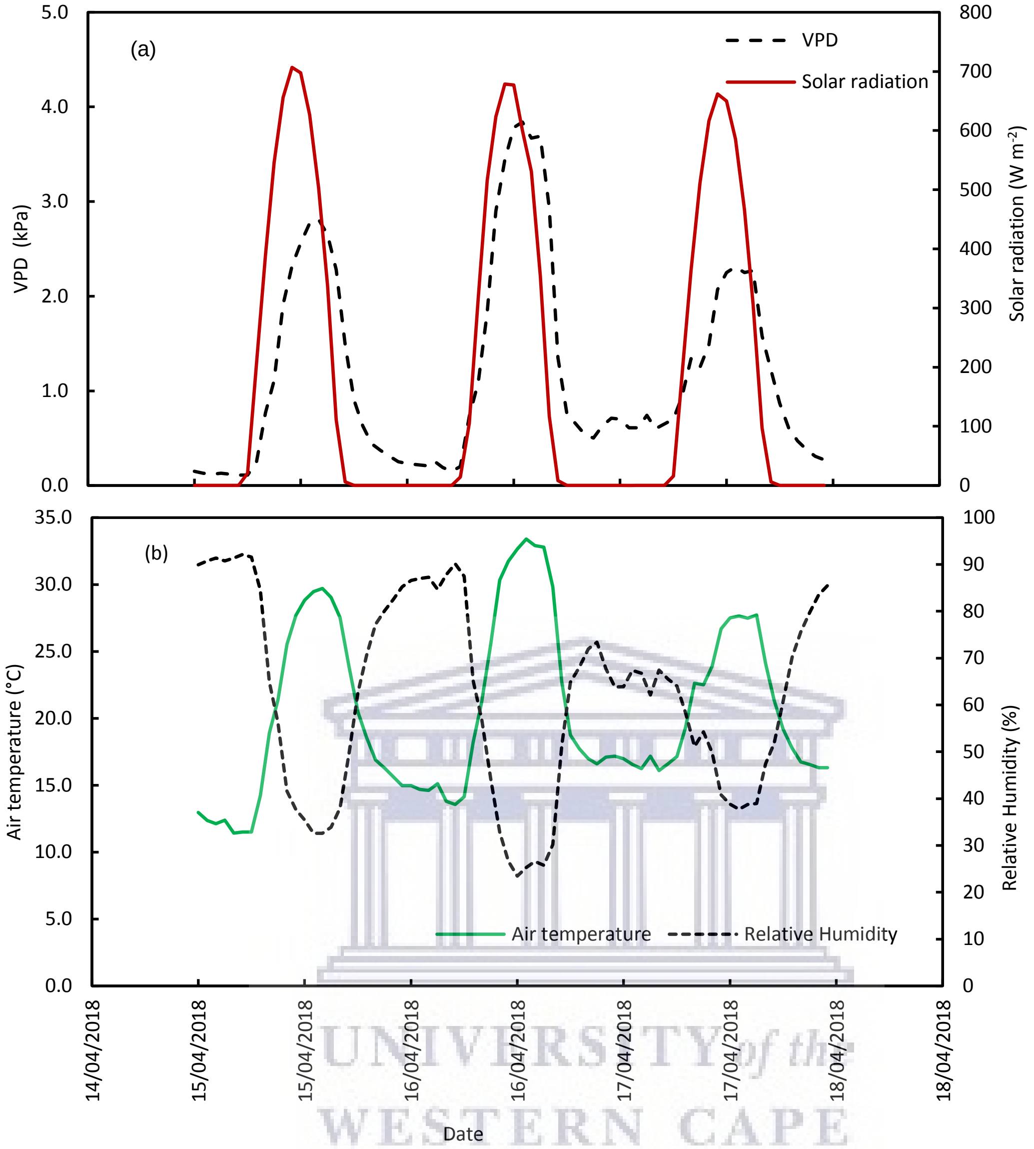

Fig 3.3: Typical variations of weather elements; (a) vapour pressure deficit of the air and solar radiation, (b) air temperature and relative humidity from day 105 to 107 (15 – 17 April 2018).

3.2.2 Effects of cultivar on sap flux density and transpiration per unit leaf area

The typical diurnal variations of sap flux density for three clear hot days from (15 April to 17 April 2018) are shown in Figure. 3.4 a & b for Cripps' Red and Golden Delicious cultivars, respectively. The sap flux density increased after dawn and peaked typically between 12:00 and 13:00 for the Cripps' Red cultivar and between 13:00 and 14:00 for the Golden Delicious cultivar coinciding with increasing solar radiation and VPD. Sap flux density declined sharply in the evening since stomata was almost closed in the dark; therefore very little transpiration was expected (Figure. 3.4a & b). For the Golden Delicious cultivar, the hourly sap flux density peaked at 17.3, 16.4 and 14.0 cm^3 cm^{-2} h^{-1} for DOY 105, DOY 106 and DOY 107, respectively. For the Cripps' Red cultivar, peak hourly sap flux density was 14.3, 17.5 and 15.0 cm^3 cm^{-2} h^{-1} for DOY 105, DOY 106 and DOY 107, respectively. Average daily total transpiration recorded was 2.21 L d^{-1} for Cripps' Red and 2.03 L d^{-1} for Golden Delicious.

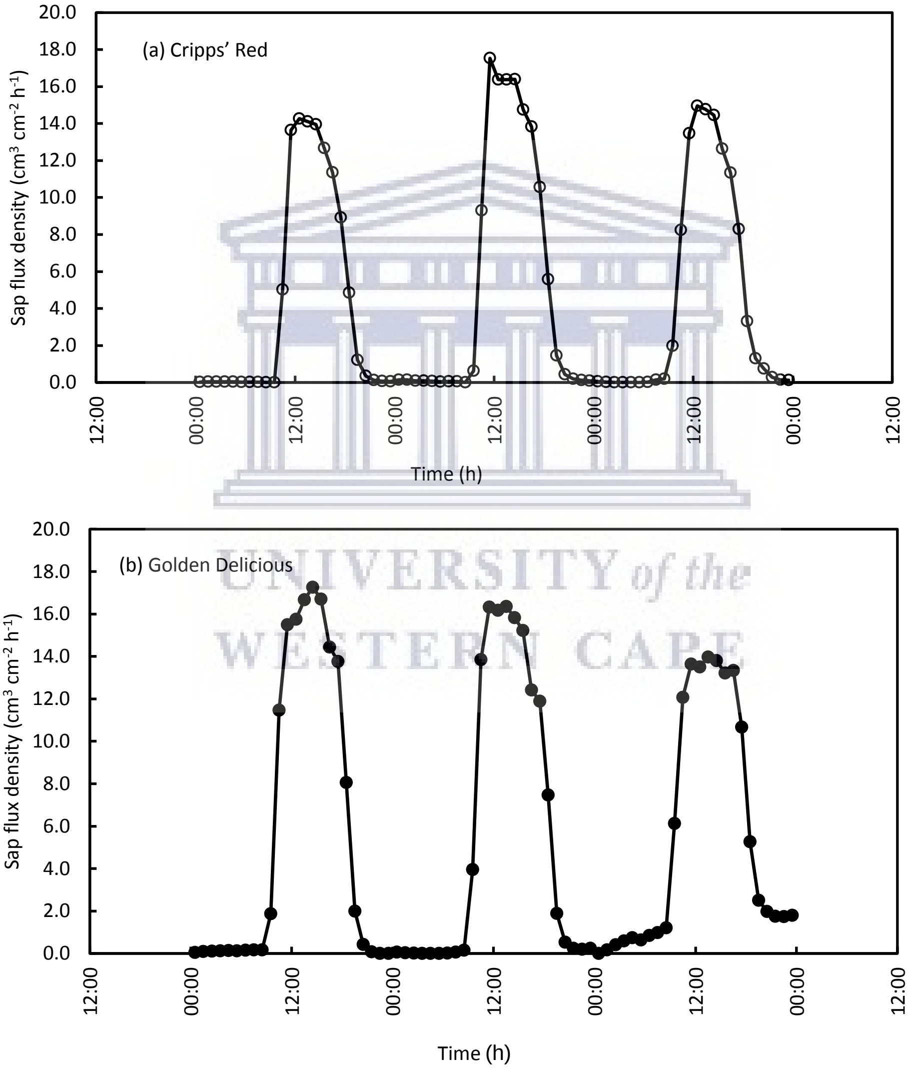

Fig 3.4: Typical variations of the sap flux density for (a) Cripps' Red and (b) Golden Delicious cultivars over a period of three days (DOY 105 - 107).

3.2.3 Effect of cultivar on plant water status and hydraulic parameters

Leaf water potential (LWP), stem water potential (SWP) and stomatal conductance (g_s) measured hourly throughout DOY 105 – 107 for Golden Delicious and Cripps' Red cultivar are shown in Figure 3.5a – c. On average LWP ranged from -0.80 to -2.20 MPa for Golden Delicious, whereas for Cripps' Red this varied between -0.85 to -2.23. Although the differences between the two cultivars were not significant ($p>0.05$), Golden Delicious cultivar had slightly lower LWP values compared with Cripps' Red cultivar (Table 3.1). A comparison of measured stem water potential of the two cultivars (Fig 3.5b) for three clear days shows that SWP was also slightly lower in the Golden Delicious cultivar, but did not significantly differ from the Cripps' Red cultivar. Stem water potential values ranged from −0.33 to −1.69 MPa for Golden Delicious and from −0.12 to −1.85 MPa for Cripps' Red.

The measured stomatal conductance (g_s) also revealed no statistical differences ($p>0.05$) between Golden Delicious and Cripps' Red cultivars. By comparison, the g_s for Cripps' Red cultivar ranged from about 2.56 to 3.30, 1.85-2.67, and 2.39-2.67 mol m^{-2} s^{-1} for DOY 105, DOY 106 and DOY 107, respectively. For Golden Delicious cultivar the stomatal conductance ranged from 2.89 to 3.90, 1.69 to 2.49 and 3.05 to 3.84 mol m^{-2} s^{-1} on DOY 105, DOY 106 and DOY 107, respectively. The maximum g_s values were always recorded in the morning hours (between 10:00 and 11:00) for both cultivars as a result of the opening of the stomata for photosynthesis, with a subsequent decrease between 12:00-14:00 in response to increasing temperature and vapour pressure deficit.

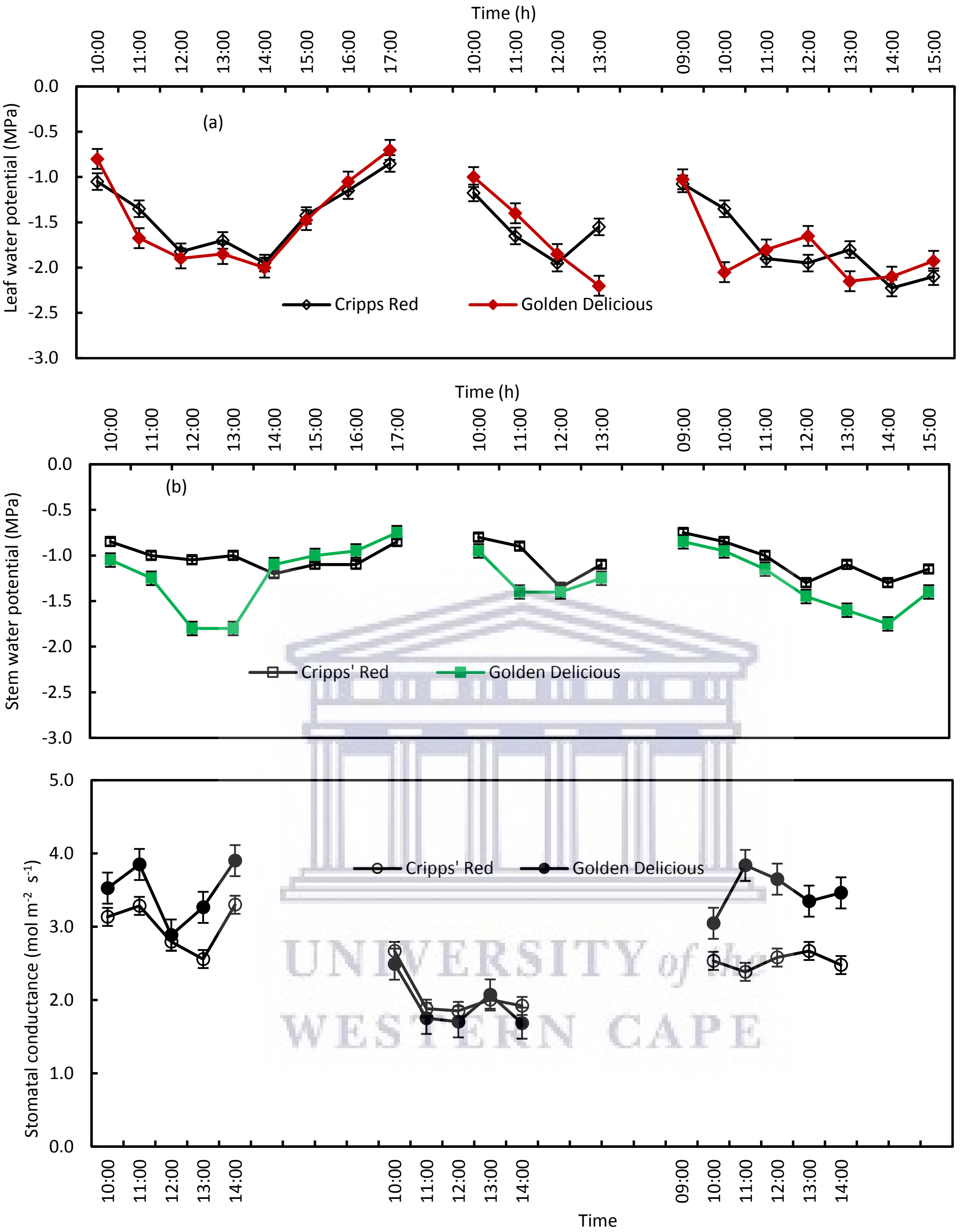

Fig 3.5: Diurnal variation of (a) leaf water potential, (b) stem water potential and (c) stomatal conductance (g_S) for Golden Delicious and Cripps' Red trees measured over a period of three days (DOY 105, 106 and 107).

The relationship between whole-tree transpiration, estimated from the sap flow measurements and water potential was used to calculate the resistance of the liquid flow pathway in trees. The hydraulic resistance (R_x) expresses the efficiency of the tree's transpiration stream to take up water and this is determined from the slope of the relationship between sap flow, and the difference between soil and leaf water potential (Equation 3.1). Hydraulic resistance from downstream of the stem (R_{sx}) on the other hand was estimated from the difference between stem and leaf water potential plotted against sap flow (Equation 3.2). The two cultivars showed no significant differences in their soil-stem R_x, and stem-leaf, R_{sx} (Table 3.1). The Golden Delicious had however slightly higher R_{sx}, (6.04 MPa h g^{-1}) as compared to the Cripp's Red cultivar, (5.13 MPa h g^{-1}).

Table 3.1: Comparison of mean sap flow, leaf water potential (LWP), stem water potential (SWP), stomatal conductance (g_s) and hydraulic parameter (R_x and R_{sx}) of two apple cultivars. R_x is the soil-to-stem hydraulic resistance and R_{sx} is the stem-to-leaf hydraulic resistance.

Cultivar	**Sap flow (L d^{-1})**	**LWP (MPa)**	**SWP (MPa)**	**g_s (mol m^{-2} s^{-1})**	**R_x (MPa h g^{-1})**	**R_{sx} (MPa h g^{-1})**
Cripps' Red	2.21 ± 0.14	-1.58 ± 0.09	-1.02 ± 0.05	2.43 ± 0.11	2.37	5.13
Golden Delicious	2.03 ± 0.11	-1.61 ± 0.11	-1.23 ± 0.09	2.84 ± 0.18	3.73	6.04

3.2.4 Water storage dynamics of young Golden Delicious and Cripps' Red trees.

The water statuses of the trees are determined by the imbalance between water uptake by the roots and loss at the evaporation sites in the leaves. The imbalance depends on the hydraulic properties of the trees e.g. the hydraulic resistance which is influenced by the xylem vessel architecture. For example, apple trees have a ring porous xylem anatomy which is generally associated with wide vessel diameters which in turn have a low hydraulic resistance (Jones, 1992). It is not clear whether different apple cultivars have different hydraulic properties. To investigate this, time lags, which are a proxy for hydraulic properties of the transpiration stream, were derived between different organs of the two cultivars. For example, to establish how fast water moved from the branches to the leaves, the stomatal conductance (itself a proxy for transpiration) was cross-correlated against the branch sap flow. This was done by imposing a four hour time difference between the two variables and decreasing the time intervals hourly. The correlation coefficient was then calculated for each time lag from the negative to positive time differences. For instance a positive time lag between the branch sap flow and transpiration (represented by the stomatal conductance) represent transpiration occurring earlier than branch sap flow and vice versa.

Several authors (e.g. Perämäki et al., 2001; Zweifel et al., 2001; Steppe and Lemeur, 2004) have reported that time lags between transpiration and sap flow can vary from minutes to several hours. As this is true for large trees, it is often assumed that in young trees the flow rate of water through the stem responds immediately to changes in transpiration (Wullschleger et al., 1998). However, the results obtained from this study clearly show that even in young trees considerable time lags can be observed. For example, the branch sap flow lagged behind the stomatal conductance by approximately 2h, for both Cripps' Red and Golden Delicious cultivars (Figure 3.6a). Stem sap flow best matched branch sap flow by imposing a 1 hour time lag in stem sap flow for both cultivars (Fig. 3.6 c & d). Similarly, the time lag between transpiration (water loss) and water uptake by both Cripps' Red and Golden Delicious cultivars was about 1 hour (Fig. 3.6 e & f). The rate of water uptake was estimated from the stem sap flow while the transpiration rate (water loss) was estimated from the scaled-up branch sap flow measurements (Fig 3.7 a & b). The time lag between the commencement of transpiration and root water uptake reflects the buffering effect of the water stored between the canopy and the rest of the tree.

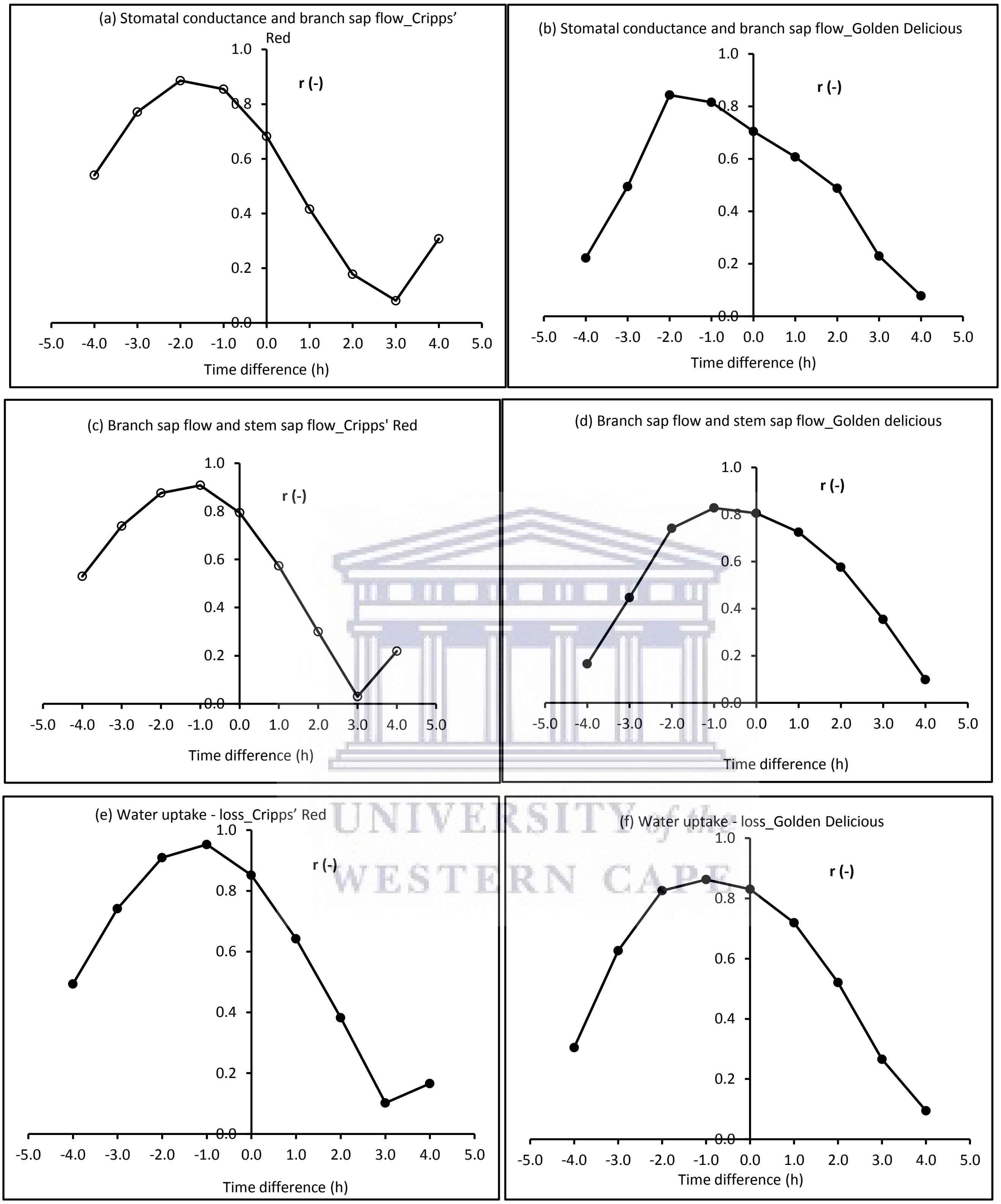

Fig 3.6: Time lags between stomatal conductance and stem sap flow (a, b), branch sap flow and stem sap flow (c, d) and water uptake (stem sap flow) and water loss (transpiration) (e, f) for Cripps' Red and Golden Delicious cultivars, respectively.

The typical diurnal course of sap flow during a clear day in late summer (15 April 2018) is shown in Fig. 3.7 a & b. The stem sap flow rate (closed triangles) gave an estimate of the rate of water uptake while the canopy level transpiration (open circles) approximated the rate of water loss. The canopy transpiration rate was estimated from the scaled up branch sap flow measurements. The time lag between the onset of transpiration and stem sap flow was at least 1 h for both Cripps' Red and Golden Delicious cultivars (Fig. 3.6 e & f). Understanding the time lags between water uptake and loss by the trees was crucial to determine the short-term reliance of the trees on the internally stored water. The results indicated that for both cultivars, internally stored water was used when leaf transpiration (estimated from sap flow measurement at branch level) exceeded the total water uptake from the soil (estimated from sap flow measurements at the base of the stem) (Fig. 3.7 a & b). In the Cripps' Red cultivar, for an example, utilization of internal water occurred between 10:00 h to 13:00 whilst replenishment occurred whenever *F* (stem sap flow) exceeds *E* (transpiration rate) and this was primarily between 15:00 and 18:00 h (Fig 3.8a). In the Golden Delicious cultivar stored water use tended to peak in the morning, between 09:00 and 12:00 h, with a decline between 13:00 and 16:00 h (Fig 3.8b). Overall there was no significant difference in internal water use which accounted for about 28 and 25% of total daily transpiration for the Golden Delicious and Cripps' Red cultivar, respectively (Table 3.1). However, the water was subsequently replaced as evidenced by stem sap flow which continued well after sunset, only stopping after 20:00 h.

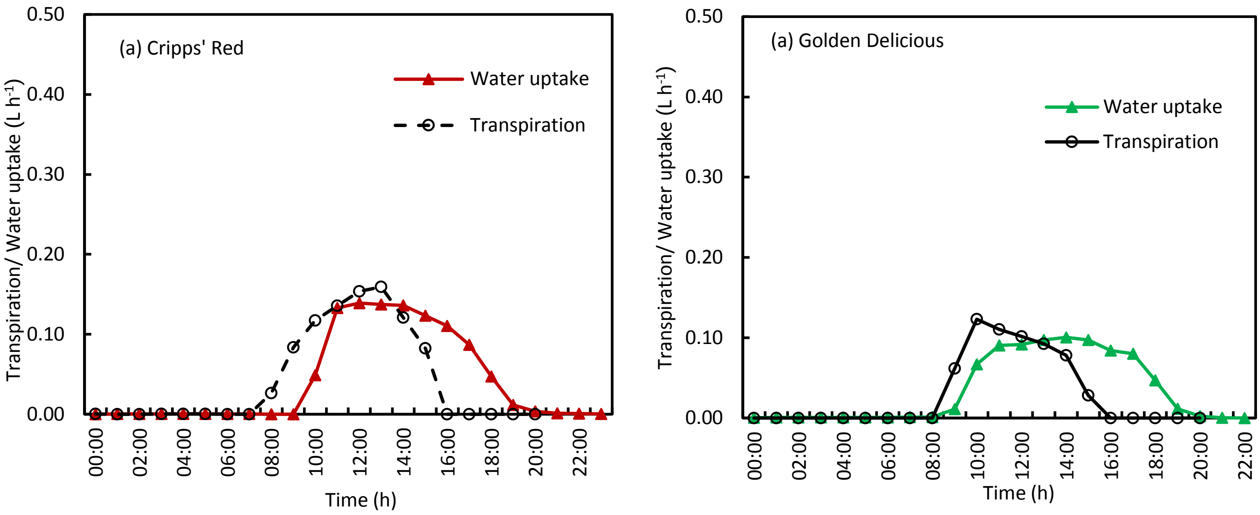

Fig 3.7: Relationship between transpiration and water uptake for (a) Cripps' Red cultivar and (b) Golden Delicious cultivar.

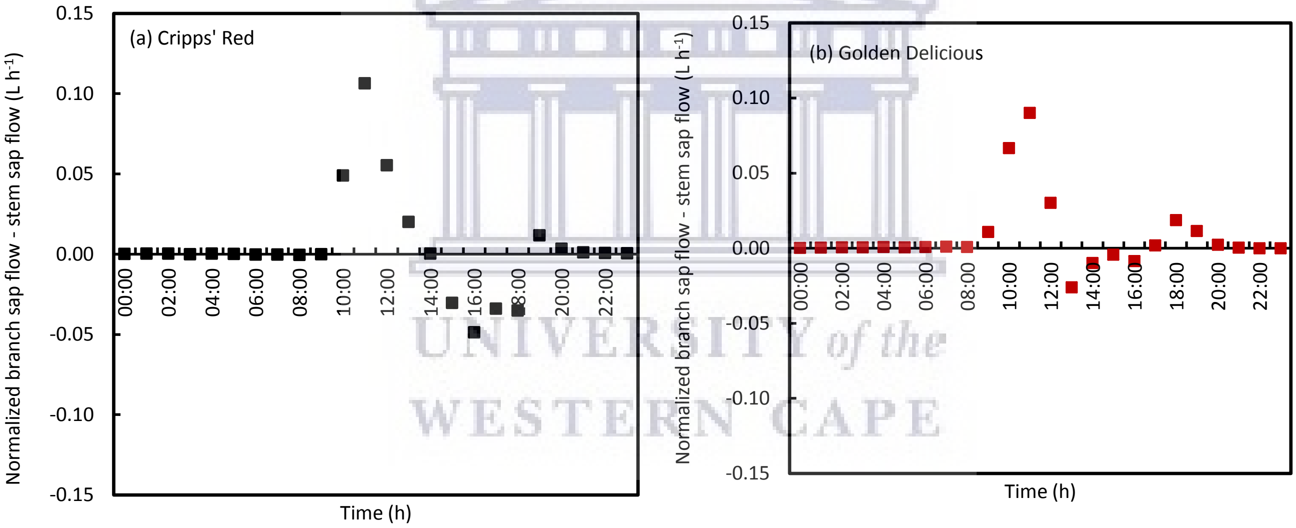

Fig 3.8: Difference between branch and stem sap flow for (a) Cripps' Red and (b) Golden Delicious cultivar. Positive values represent withdrawal of water from internal storage and negative values represent recharge.

3.4 DISCUSSION

While there are numerous apple cultivars that are being grown in various countries, very limited research has investigated whether or not there are differences in the transpiration rates driven by the differences in the physiology of the cultivars. Most of the research has focused on the differences in the yield potential of different cultivars e.g. fruit weight, dry matter, yield per tree etc. (Elsysy et al., 2019; Goke et al., 2020). Others have focused on various fruit quality attributes e.g. total soluble solids and total sugars, ascorbic acid content, fruit firmness etc (Blažek and Hlušičková, 2007; Yuri et al., 2019; Uzun et al., 2019). The results of the current study have shown that there are no significant differences in the water use characteristics of the Golden Delicious and Cripps' Red cultivars. This is in contrast to a study by Massonnet et al. (2007) who found substantial differences in the water relations and water use strategies of 'Braeburn' and 'Fuji' apple cultivars on the M9 rootstock in New Zealand. These differences were attributed to the stomatal limitation of net photosynthetic rate and lower leaf carbon isotope discrimination, although their measurements were taken at leaf level. Liu et al. (2012) also found that differences in water use efficiency of 31 apple cultivars grown under well-watered and drought-stressed conditions were mainly due to changes in stomatal conductance. Although, small and insignificant variations were also observed in the stomatal conductance between the two cultivars in this study, the differences were not consistent as shown in Fig. 3.5c. The somewhat lower conductance for the Cripps' Red could be a result of a lower stomatal density, or smaller apertures although these data were not collected. The comparison of the leaf and stem water potentials showed no differences in the leaf water potential between the two cultivars, although the Golden Delicious tended to have a lower xylem water potential than the Cripps' Red. The reasons for this trend are unclear and further investigations are needed to confirm whether or not this is a result of differences in the physiology of the two contrasting cultivars. The calculated soil to stem and stem to canopy hydraulic resistances for both cultivars showed that the highest resistance resided downstream of the stem (i.e. stem to leaves resistance) as shown in Table 3.1. This observation is consistent with other published literature (e.g. Dzikiti et al., 2007; Lambers et al., 2008). In fact it is thought that the highest resistance occurs in region of the leaf petiole but this study does not provide this detail. The Golden Delicious cultivar appeared to have a slightly higher stem to leaf resistance (R_{sx}) but it is not clear whether this was a result of the slightly bigger canopy size of this cultivar leading to a smaller denominator in Equation (3.2). This study also shows that for the two cultivars the greatest time lags existed between the branch sap flow and stomatal conductance (up to 2 hours) than between the stem and branch sap flows confirming that the highest resistance in the transpiration stream of both cultivars was downstream of the stem. Both cultivars used significant quantities of internally stored water, although the differences between the species were insignificant. In trees, the relative contribution of the internally stored water to the daily transpiration is highly variable and can account for 10–50% daily water use depending on species, ecosystem type, and tree size (Goldstein et al., 1998; Meinzer et al., 2004; Scholz et al., 2007, 2011). In our case of young apple trees, up to 25 and 28% of the daily total transpiration of the Cripps' Red and Golden Delicious cultivars was withdrawn from the internal storage pools, respectively. Similar orders of magnitudes of internal water use were reported by Dzikiti et al. (2011) were up to 25% of the daily total transpiration was withdrawn from the internal storage pools under severe soil water deficit conditions but on the Midknight Valencia orange trees.

3.5 CONCLUSIONS

This study showed that sap flux density of the two apple cultivars was not significantly different. Based on the results, the daily average water uptake of well-watered apple trees based on sap flow measurement ranged between 1 L and 2 L day^{-1} tree^{-1} for Golden Delicious and 1 and 3 L day^{-1} tree^{-1} for Cripps' Red. The total consumption of water for the period under consideration was 45 L and 39 L for Cripps' Red and Golden Delicious cultivar, respectively. The results also showed that there was substantial utilization of water stored in the stems for both Golden Delicious and Cripps' Red. The stored water was used primarily in the morning to replace transpirational losses for both cultivars and was subsequently replaced during the remainder of the day and at night. Results found from this chapter, validate the results obtained from field grown trees (next chapter) were these two cultivars with varying covers were investigated in 12 orchards.

CHAPTER 4: ASSESSING THE WATER USE AND WATER STATUS OF APPLE ORCHARDS OF VARYING AGE GROUPS

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2. *Midgley, S.J.E., Dzikiti, S., Volschenk, T., Zirebwa, F.S., Taylor, N.J., Gush, M.B., Lötze, E., Ntshidi, Z. and **Mobe, N**. (2020). Water productivity of high performing apple orchards in the winter rainfall area of South Africa. Acta Hortic. 1281, 479-486 https://doi.org/10.17660/ActaHortic.2020.1281.63.*

Summary

No accurate quantitative information currently exists on how water use of apple (*Malus domestica* Borkh.) orchards varies from planting to full-bearing age, leading to poor irrigation and water allocation decision making. This study sought to address this knowledge gap by investigating how the water use and tree water status vary with canopy cover, cultivar, and climatic conditions in 12 orchards growing in prime apple-producing regions in South Africa. The orchards were planted to the Golden Delicious/Golden Delicious Reinders® cultivars which are widely planted in South Africa and the Cripps' Pink/Cripps' Red/Rosy Glow which are high-value late-season cultivars. The performance of two transpiration reduction coefficients, one based on sap flow (K_{sf}) and the other based on soil water depletion (K_s) (FAO approach) was evaluated against the midday stem water potential (MSWP) in all the orchards. While canopy cover had a clear effect on the whole-tree sap flow rates, there were no significant differences in the transpiration per unit leaf area between the field-grown cultivars. The daily average sap flux density under unstressed conditions was highest (~284 $cm^3 \cdot cm^{-2}$ d^{-1}) in medium canopy cover orchards (30–44% fractional cover), followed by mature orchards (~226 cm^3 cm^{-2} d^{-1}), and was lowest in the young orchards (~137 cm^3 cm^{-2} d^{-1}). Canopy cover had a greater effect than growing season length on seasonal total water use. Peak daily orchard transpiration ranged from 1.7 mm for young Golden Delicious Reinders® trees to 5.0 mm in mature Golden Delicious trees that were maintained with large canopies to reduce sunburn damage to the fruit. For the red cultivars, the peak daily transpiration ranged from 2.0 to 3.9 mm, and the mature trees were maintained with less dense canopies to facilitate the development of the red fruit colour. The less dense canopies on the red cultivars had water-saving benefits since the seasonal total transpiration was lower than that of the Golden Delicious cultivar. The sap flow-derived stress coefficient was strongly correlated with the MSWP (R^2 ~ 0.60–0.97) in all the orchards while K_s was not useful in detecting plant stress due to over-irrigation.

4.1 INTRODUCTION

Semi-arid regions, such as the Western Cape Province in South Africa, parts of Spain, Italy, and other Mediterranean countries, are major producers of fruits such as apples, pears, citrus, olives, etc. (Girona et al., 2011; Cammaleri et al., 2013; Volschenk, 2017). These fruit are produced for local and global markets, mostly under irrigation, due to insufficient rainfall during summer. The availability of adequate water for irrigation is critical for sustainable production yet water resources in some fruit-producing regions face serious threats. These threats arise from growing populations, increasing competition from other economic sectors, and climate change (Annandale et al., 2011; Midgley et al., 2016; Dzikiti et al., 2018a). Despite these concerns, some studies have reported inefficient irrigation practices in apple orchards due to a lack of reliable information and tools to aid irrigation scheduling (Volschenk et al., 2003; Dzikiti et al., 2018b).

In South Africa, for example, the second National Water Resource Strategy cites irrigated agriculture as the major user of water, accounting for more than 60% of the available resources. However, nearly one third of the allocated water is lost, mainly through over-irrigation and leakages (DWA, 2013). This highlights an urgent need to increase water use efficiency for the sustainability and growth of the fruit industry. Non-beneficial water losses in orchards can be reduced through improved irrigation scheduling which can be achieved by using accurate irrigation tools and information, e.g., on crop water requirements under a range of growing conditions (Jones, 2008; Ferreres et al., 2012). Precision irrigation scheduling is also important for reducing contamination of rivers, dams, and groundwater sources through irrigation return flows (Batchelor et al., 2013).

Apple orchards in dry regions require irrigation from planting to full-bearing age, although irrigation management may differ depending on orchard age group (Hortgro, 2015). Accurate quantitative information on orchard water use and how trees respond to soil water deficit is needed (Ferreres et al., 2012) across various orchard age groups, cultivars, and production regions. Besides the work done by Massonnet et al. (2007); and Liu et al. (2012), no other studies have compared the water use characteristics of different apple cultivars. It is important to close this information gap given the wide range of apple cultivars that are commercially available. While the FAO has developed practical guidelines for estimating crop water requirements, e.g., from canopy cover estimates, these protocols require local validation for accurate irrigation scheduling (Allen et al., 1998).

Irrigation scheduling is usually done through monitoring either the soil moisture, plant water status or atmospheric variables (Dzikiti et al., 2010; Othman et al., 2014). Jones (2004) gave a detailed overview of the advantages and pitfalls of various plant-based irrigation scheduling methods. Annandale et al. (2011) and Jones (2008) summarized progress on the soil, plant, and atmospheric irrigation scheduling methods including various irrigation models. However, given that most physiological processes that determine plant growth and productivity depend on the plant rather than the soil water status, it is widely believed that precise irrigation scheduling can be achieved using plant-based water-stress indicators (Jones, 2004; Zimmermann et al., 2010).

The objectives of this study were therefore to use actual experimental data, firstly to compare the daily and seasonal water use trends and their drivers in apple orchards from planting until full-bearing age and, secondly, to establish whether the water use of apple orchards varies by cultivar (for which little information currently exists). Thirdly, we compare the sensitivity of the plant-based transpiration reduction coefficient (K_{sf}) with an available soil water–based FAO-56 transpiration reduction coefficient (K_s) in the various apple orchards. The data were collected in 12 commercial orchards in South Africa planted to apple cultivars that are commonly grown in subtropical production areas. The information derived has potential applications in improving irrigation scheduling and productivity in orchards through early detection of plant water stress, and improved parameterization of water use models.

4.2 MATERIAL AND METHODS

4.2.1 Study site and description

To understand the water use dynamics and water status of two apple cultivars with varying fractional vegetation cover, field experiments were carried out in 12 commercial apple orchards over three growing seasons: 2014/15, 2015/16 and 2016/17. The orchards were spread across two prime apple-producing regions in the Western Cape Province of South Africa: the Koue Bokkeveld (KBV) located about 150 km to the northeast of the city of Cape Town and the Elgin/Grabouw/Vyeboom/Villiersdorp (EGVV) which is about 70 km southeast of Cape Town (Fig. 4.1). Both regions have a Mediterranean-type climate although their microclimates differ. The KBV region experiences cold winters with occasional snowfall in high lying areas, and hot summers. Average daily air temperatures for the coldest month (July) are 3 to 4 °C and mean maximum air temperature for the hottest month (February) reaches 28 to 29 °C. In contrast, The EGVV region has milder summers and winters due to proximity to the Indian 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.

4.2.2 Data collection and treatment

During the 2014/15 growing season, data were collected in four orchards in the KBV region comprising two mature high-yielding (74-110 t ha^{-1}) orchards with a high effective fraction of ground covered or shaded by vegetation of about 0.64. One mature orchard was planted to Golden Delicious and the second orchard was planted to Cripps' Pink apple trees. Golden Delicious is the most widely planted apple cultivar in South Africa and elsewhere in the Mediterranean region because of the nature of its canopies (denser and therefore high LAI) (Hortgro, 2018). The Cripps' Pink on the other hand is a long season (late harvest) cultivar and its fruit are on the tree for 2 months longer than Golden Delicious.

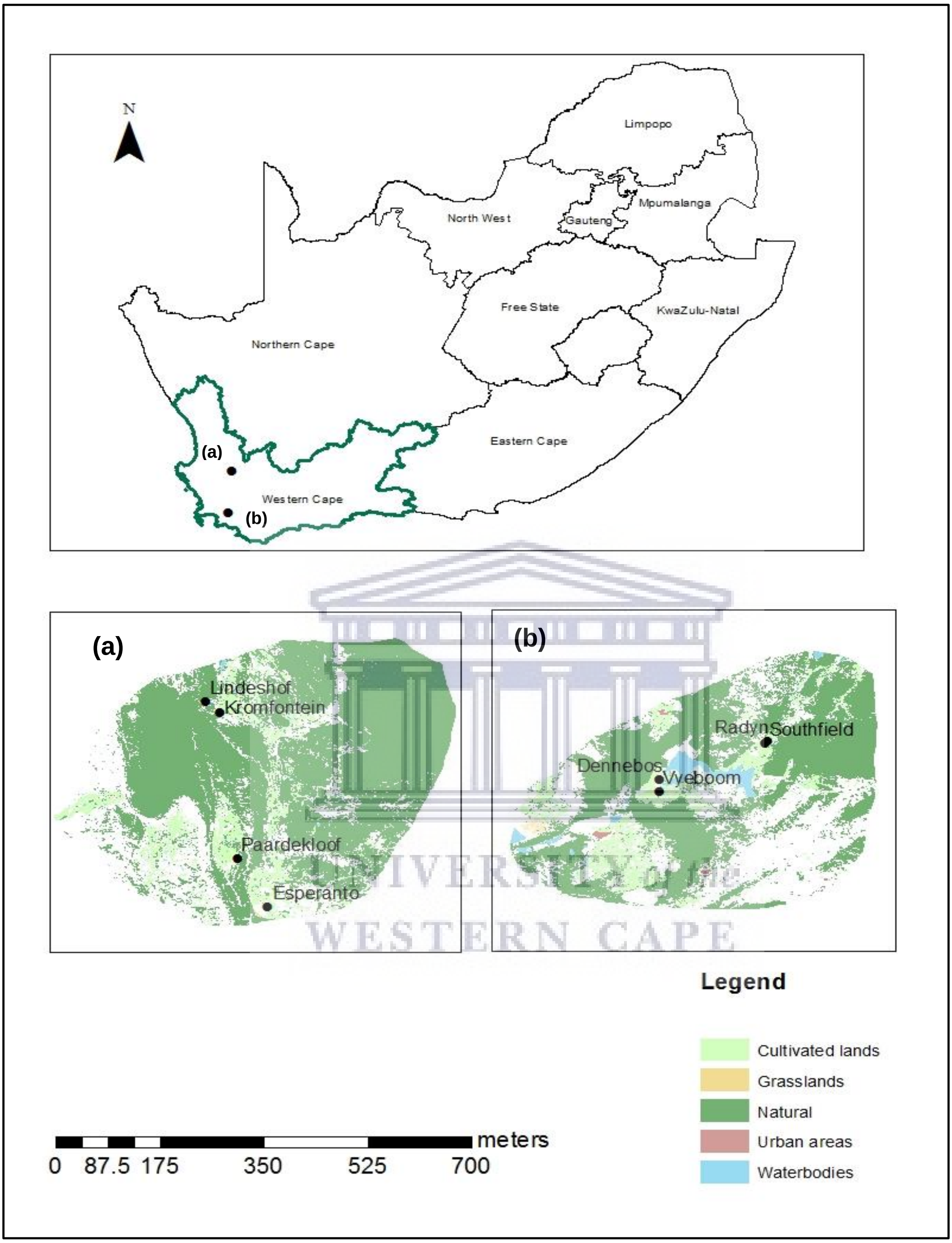

Fig. 4.1: Location of the study sites in the two prime apple producing regions in the Western Cape Province of South Africa namely: a) KBV), and b) (EGVV) region. The scale of the map only applies to the lower maps.

These orchards were located next to each other. They were both 6 ha in size and they had similar soil types namely deep sandy Fernwood soils with approximately 30% stone and no clay in the parent material (Louis Reynolds, pers. comm.[2]). Tree spacing in both orchards was 4 m x 1.5 m giving a plant density of 1 667 trees per hectare. Rootstock used was the M793 which is the industry standard. Both orchards were irrigated with medium range micro sprinkler systems.

The other two orchards had young (less than 3 yr. old) low canopy cover trees of the Golden Delicious Reinders® and Rosy Glow cultivars. Golden Delicious Reinders® is a higher chill Golden Delicious bud mutation that is less susceptible to netiform and stem-end russet than standard Golden Delicious whereas Rosy Glow is a redder bud mutation of Cripps' Pink that is marketed as Pink Lady® if it meets the fruit colour requirements. The young low canopy cover Golden Delicious Reinders® orchard was about 3.17 ha in size and trees were planted in rows with a north-south orientation. Tree spacing was similar to that of the mature high yielding orchards. The young low canopy cover Rosy Glow orchard on the other hand was about 6.3 ha and trees were planted at 3.5 m x 1.25 m spacing giving a substantially higher plant density of 2 285 trees per hectare. The rootstocks used were M793 for Golden Delicious Reinders® and MM109 for Rosy Glow, both of which are semi-vigorous.

During 2015/16, data were collected in four orchards in EGVV with similar attributes to those in KBV (yields of 100-109 t ha^{-1}). These included mature high yielding Golden Delicious, and Cripps' Pink blocks while the young low canopy cover orchards were planted to the Golden Delicious Reinders® and Cripps' Red cultivars (Table 4.1). The mature Golden Delicious orchard was 29 years old and the trees were planted on gentle sloping terrain in an east-west direction on deep sandy loam soils. Tree spacing was about 4 m x 2 m and the trees were under a micro-sprinkler irrigation system. The mature high cover Cripps' Pink orchard was about 5.2 ha in size and it was planted in 2004 (~12 yrs old) on an east facing slope. Tree spacing was about 4 m x 1.5 m planted on clayey soil with a high stone content (~33%). The young low canopy cover Golden Delicious Reinders® orchard was planted in 2011 (~4 yr old) on loamy soils with a high stone content (~ 11%). The orchard was 6.0 ha in size and tree spacing was 4 m x 2 m. The rows were planted in an east-west

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[2] Louis Reynolds, personal communication, apple farmer.

direction. The young low canopy cover Cripps' Red orchard on the other hand was planted on deep clayey soils with a low stone content (~ 1%). The orchard was 3 yr old and it was more than 5.0 ha in size. The rootstocks used were M793 and MM109 for mature and young low canopy cover orchards, respectively.

In 2016/17, measurements were taken in two orchards in each production region with medium fractional canopy cover ranging from 0.26 to 0.37 (Table 4.1). The orchards were planted to Cripps' Pink and Golden Delicious Reinders® trees, respectively, with yields ranging between 18 and 61 t ha^{-1}. In KBV, the Cripps' Pink 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 tree spacing was 4.5 m x 2.0 m giving a tree density of ~1 111 trees per ha. The trees were planted on ridges on deep sandy soils, on M793 rootstock. The Golden Delicious Reinders® orchard 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 EGVV, the Cripps' Pink orchard was 6 years old planted on an M7 rootstock which has similar attributes to the M793 rootstock. The size of the orchard was about 2.76 ha and tree spacing was 4.0 m x 2.0 m. The soil was dark red clayey loam with a high stone content. The Golden Delicious Reinders® orchard was about 6 years old also. The trees were planted in 2011 on ridges and the soil had a sandy loam texture with a high stone content. Tree spacing was similar to that of the medium canopy cover Cripps' Pink orchards.

Soil texture was predominantly sandy to sandy loam in both regions except for the medium cover Cripps' Pink in EGVV which had dark red clayey loam soils of the Kroonstad soil form (Ochric Planosol) according to the Soil Classification Working Group (1991). Soil physical and chemical analyses for the 12 orchards were done at a commercial laboratory (Bemlab Pty Ltd., South Africa). Table 4.2 summarizes the physical properties of the soils for all the orchards.

Table 4.1: Summary of the study sites used in the Koue Bokkeveld (KBV) and Elgin/Grabouw/Vyeboom/Villiersdorp (EGVV) production regions from 2014–2017. High, medium and low canopy cover denotes >45%, 30–44% and <30% fractional vegetation cover.

Year	**Region**	**Cultivar**	**Rootstock**	**Age (yr)**	**Canopy cover**	**Area (ha)**	**Plant density (trees per ha)**	**Soil texture**
2014/15	KBV	Golden Delicious	M793	22	High	6.0	1 667	Sandy loam
	KBV	Cripps' Pink	M793	9	High	6.5	1 667	Sandy loam
	KBV	Golden Delicious Reinders®	M793	3	Low	3.2	1 667	Sandy loam
	KBV	Rosy Glow	MM109	4	Low	4.0	2 285	Sandy
2015/16	EGVV	Golden Delicious	M793	29	High	6.5	1 250	Sandy loam
	EGVV	Cripps' Pink	M793	12	High	5.0	1 667	Clay loam
	EGVV	Golden Delicious Reinders®	MM109	3	Low	6.5	1 250	Sandy clay
	EGVV	Cripps' Red	MM109	3	Low	5.0	1 250	Sandy loam
2016/17	KBV	Golden Delicious Reinders®	M793	5	Medium	3.2	1 667	Sandy loam
	KBV	Cripps' Pink	M793	7	Medium	4.5	1 111	Loamy sand
	EGVV	Golden Delicious Reinders®	M7	5	Medium	5.5	1 250	Sandy clay loam
	EGVV	Cripps' Pink	MM109	6	Medium	4.5	1 250	Clay loam

Table 4.2: Typical soil classification analysis for the orchards of different age groups monitored at KBV and EGVV in 2014/15, 2015/16 and 2016/17 growing seasons. θ_{FC}= volumetric soil water content at field capacity; θ_{WP}=volumetric soil water content at the permanent wilting point; REW= readily evaporable water; TEW= total evaporable water, FBGD= Full-bearing Golden Delicious, FBCP= Full-bearing Cripps' Pink, NBGR= Non-bearing Golden Delicious Reinders®, NBRG= Non-bearing Rosy Glow, NBCR= Non-bearing Cripps' Red, BGD= Bearing Golden Delicious, BGR= Bearing Golden Delicious Reinders® BCP= Bearing Cripps' Pink.

				Soil water		**Soil texture distribution**				
Location	**Season**	**Orchards**	**Soil texture**	**θ_{FC} (cm^3 cm^{-3})**	**θ_{WP} (cm^3 cm^{-3})**	**Sand**	**Silt %**	**Clay**	**REW (mm)**	**TEW (mm)**
KBV	2014/15	FBGD	Sandy loam	0.171	0.027	83.5	2.9	13.6	7.4	23.6
		FBCP	Sandy loam	0.174	0.049	82.7	4.0	13.3	7.6	22.4
		NBGR	Sandy loam	0.187	0.023	81.0	3.3	15.7	11.9	30.4
		NBRG	Sandy	0.193	0.042	92.0	2.0	6.0	11.9	18.1
EGVV	2015/16	FBGD	Sandy loam	0.189	0.055	80.8	8.7	10.3	7.8	24.2
		FBCP	Clay loam	0.230	0.050	33.8	28.4	37.6	11.0	30.8
		NBGD	Sandy clay	0.230	0.055	15.7	35.4	48.9	7.9	26.3
		NBCR	Sandy loam	0.143	0.045	81.4	6.9	11.7	6.7	25.8
KBV	2016/17	BGD	Sandy loam	0.187	0.023	85.4	8.1	6.5	7.1	26.3
		BCP	Loamy sand	0.190	0.032	83.6	13.7	2.8	7.4	26.
EGVV		BGR	Sandy clay loam	0.230	0.055	58.3	15.3	26.5	10.2	30.4
		BCP	Clay loam	0.195	0.030	35.0	25.3	39.7	11.2	27.0

4.2.3 Meteorological data

Orchard microclimates were monitored using automatic weather stations situated close to the orchards. The stations were installed on open spaces with a uniform short grass cover that was kept well-watered. Climate variables measured included the maximum and minimum air temperatures, maximum and minimum relative humidity, solar irradiance, wind speed and direction and rainfall. All the sensors were connected to a data logger (Model: CR1000, Campbell Scientific, Inc., Logan UT, USA) that was programmed to store data at 60 minutes interval and at the daily time step. Power to each station was supplied by two 12 - volts rechargeable sealed lead-acid batteries stored in the data logger enclosure.

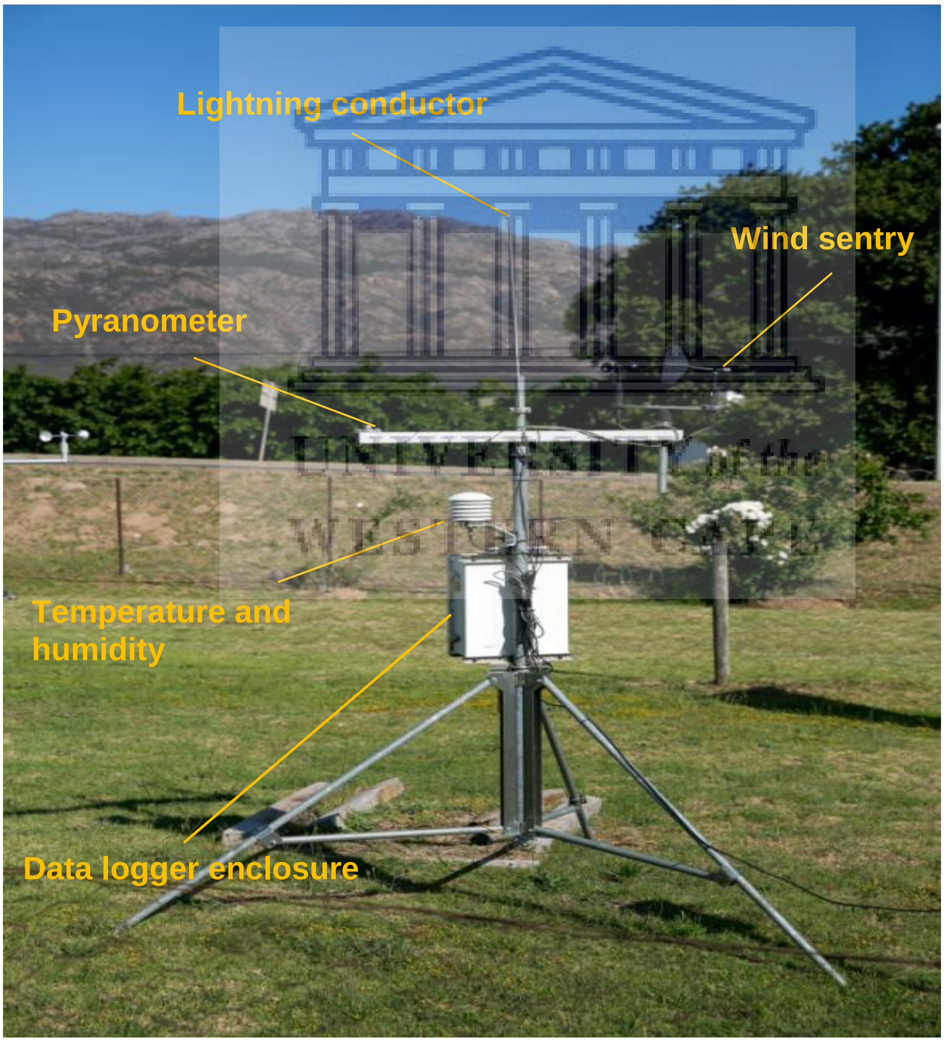

Fig. 4.2: Automatic weather station measuring basic weather elements close to the study sites.

Reference crop evapotranspiration (ET_o) was calculated for a short grass reference using the modified Penman-Monteith equation (Equation 2.19).

4.2.4 Vegetative growth and irrigation

The leaf area index (LAI – m^2 of leaf area per m^2 of ground area) of the 12 orchards was measured at regular intervals during the course of the season using the leaf area meter (Model: LAI-2000, LI-COR Inc., Nebraska, USA) on 7 trees per orchard. The measurements were taken on overcast days when the assumption that the leaves behave like black bodies was most realistic.

All orchards were irrigated using a micro-sprinkler system with one micro-sprinkler per tree delivering between 30 and 32 litres of water per hour. Irrigation frequency ranged from 2 to 3 times per week with each event lasting for 1 to 2 h early in the season. The irrigation frequency increased to daily or several times a day during the hot summer months. The amount of water applied to a tree row was monitored using electronic water flow meters (Model: ARAD Multi-Jet Water meter, Germiston, South Africa), with a resolution of 10 L per pulse installed on the irrigation lines at the beginning of a tree row (Fig 4.3). The amount of irrigation received by each tree was then 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. Table 4.3 provides detailed information on the irrigation of the various orchards.

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Fig. 4.3: Water flow meter measuring irrigation levels.

4.2.5 Monitoring soil water content

The soil monitoring system was installed close to the sap flow instrumented trees to monitor soil water contents at various depths in the root zone and beyond and at various wet/dry locations using time domain reflectometer probes (Model CS616- Campbell Sci. Inc., Logan, UT, USA). The sensors were installed in the root zone at 150 mm, 300 mm and 600 mm from the soil surface and below the root zone at the 800 mm soil depth to determine the amount of water available in the soil for trees to use and to monitor the influence of seasonal dynamics of soil water to plant water use. However, not all orchards were 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 each season for detailed soil water balance measurements, whereas soil water content measurements in the upper soil horizon were recorded in the other orchards. Detailed soil water balance was measured using thirty CS616 sensors and thirty thermocouples connected via two multiplexers (Model AM16/32B: Campbell Sci. Inc., Logan, UT, USA) to a CR1000 logger. The data were logged on an hourly basis. The logging equipment and a 12 V lead calcium battery which was used for power supply were enclosed in a strong box.

4.2.6 Transpiration measurements

To quantify the actual amount of water transpired by the mature high and medium canopy cover Cripps' Pink and Golden Delicious/ Reinders® orchards, the heat ratio method (HRM) of the heat pulse velocity (HPV) sap flow technique was used as described by Burgess et al. (2001). The heat ratio method measures both low and high flow rates with a good degree of accuracy (Steppe et al., 2010) and it is appropriate for woody species with large stem sizes. Prior to HPV installation, a stem diameter survey was conducted per orchard to identify representative trees. The survey involved measuring the stem diameter of 50-60 trees per orchard along the length of the row, and then selecting trees that represented small, average and large size classes.

Table 4.3: Summary of irrigation variables and mean soil and crop water status October–June during the three growing seasons from 2014 to 2017

Year	Region	Canopy cover	Cultivar	Irrigation			Soil water status	Plant water status
				Seasonal amount (mm)	Number of events	Mean depth (mm)	Soil water content ($cm^3\ cm^{-3}$)	Midday stem water potential (MPa)
2014/15	KBV	High	Golden Delicious	787.0	88	8.9	0.052	−1.26
	KBV	High	Cripps' Pink	1 202.0	103	11.7	0.074	−0.92
	KBV	Low	Golden Delicious Reinders®	513.0	60	8.6	0.095	−0.91
	KBV	Low	Rosy Glow	271.4	36	7.5	0.069	−2.04
2015/16	EGVV	High	Golden Delicious	820.0	100	8.2	0.158	−1.35
	EGVV	High	Cripps' Pink	837.0	88	9.5	0.191	−1.42
	EGVV	Low	Golden Delicious Reinders®	149.4	63	2.4	0.181	−1.14
	EGVV	Low	Cripps' Red	127.1	48	2.6	0.098	−1.64
2016/17	KBV	Medium	Golden Delicious Reinders®	560.1	67	8.4	0.080	−1.22
	KBV	Medium	Cripps' Pink	903.0	70	12.9	0.150	−1.52
	EGVV	Medium	Golden Delicious Reinders®	337.5	65	5.2	0.159	−1.36
	EGVV	Medium	Cripps' Pink	227.5	59	3.9	0.289	−0.98

Fig. 4.4: Heat ratio method of the heat pulse velocity (HPV) sap flow technique. (a) The green security box contains the data logger, multiplexer, relay control module and battery, (b) An enlarged view of the heat pulse velocity sap flow sensors inserted into an apple tree stem.

Sap flow sensors were installed on 3-6 trees per orchard about 10-15 cm above the scion-rootstock bud union (Fig 4.4a). This distance is sufficiently far from the disturbed wood (at the bud union) and it is also before the main branching point on the scion. Probes were inserted in the sapwood of each tree at various depths from the bark to capture the radial variation in the sap velocity within the sapwood (Wullschleger and King, 2000). 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 is comprised of heaters implanted into the stem of the trees 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 sap temperature and were connected to a multiplexer (model AM16/32B: Campbell Sci. Inc., Logan, UT, USA). Both the multiplexer and control module were connected to a data logger (Model CR1000, Campbell Scientific, Inc., Logan UT, USA). The logger was programmed to store the data at hourly intervals throughout the study duration. Rechargeable 12 V deep-cycle lead-calcium batteries were used to power the systems. Data were downloaded to a computer using an SC-USB cable connection port. Data logger, multiplexers, relay-control module and battery were housed in sealed strong box (Fig 4.4a).

The HPV data were 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 to determine the extent of the active xylem vessels (Dzikiti et al., 2017) (Fig 4.5a). The flow paths around the drilled area were clearly visible (Fig. 4.5b). The same method was used to determine the extent of the conducting sapwood area where active xylem vessels were active (Fig. 4.5c).

Fig. 4.5: (a) Methylene blue dye injected into the stem to determine the thickness of the sapwood, (b) A methylene blue dye trace illustrating the extent of the wounding width due to the implantation of sap flow probes in the stem and (c) Stem core showing the bark thickness and sapwood depth of an apple tree.

Total orchard transpiration (T, in mm·d^{-1}), expressed per unit ground area, was calculated as the product of the average tree transpiration (in L·tree^{-1}·d^{-1}) times the number of trees per hectare divided by 10 000 m^2. To use the sap flow data to compare the transpiration responses of the different apple cultivars, transpiration per unit leaf area (E_L, in mm·d^{-1}) was estimated as:

$$E_{\mathrm{L}} = T/LAI \tag{4.1}$$

where, T is orchard transpiration, and LAI is the leaf area index (m^2 of leaf area per m^2 of ground area).

Measurements of sap flow on smaller trees in the low canopy cover orchards were made using Granier probes (TDP 10: Dynamax Inc., Houston USA) (Granier, 1987).

Three healthy and actively growing trees in different stem size classes were instrumented per orchard and the average sap velocity was determined in the range 0 to 10 mm of the stems along the sensor length up to 10 mm. A stem diameter survey similar to that described for the HRM method was done to select appropriate trees to instrument. During installation, care was taken to ensure that TDP probes were positioned in the sapwood area. This is important given that sampling the air or the heartwood are the main sources of error with the Granier probes (Steppe et al., 2010). Sensors were installed at a height between 50 and 75 cm from the ground to eliminate errors due to the cold sap, especially in the morning. Reflective aluminum foil was wrapped around the probes to minimize the effects of exogenous heating on the sap temperature signals. Each TDP system was powered by one truck size battery and our assessment of the daily drop in voltage was that the batteries can last up to a month. Assessment of power drain is important given that the TDPs are continuous heating sensors which require more power than pulsing systems. The data loggers were programmed with a sampling interval of 10 s and signals were averaged every hour throughout the growing season.

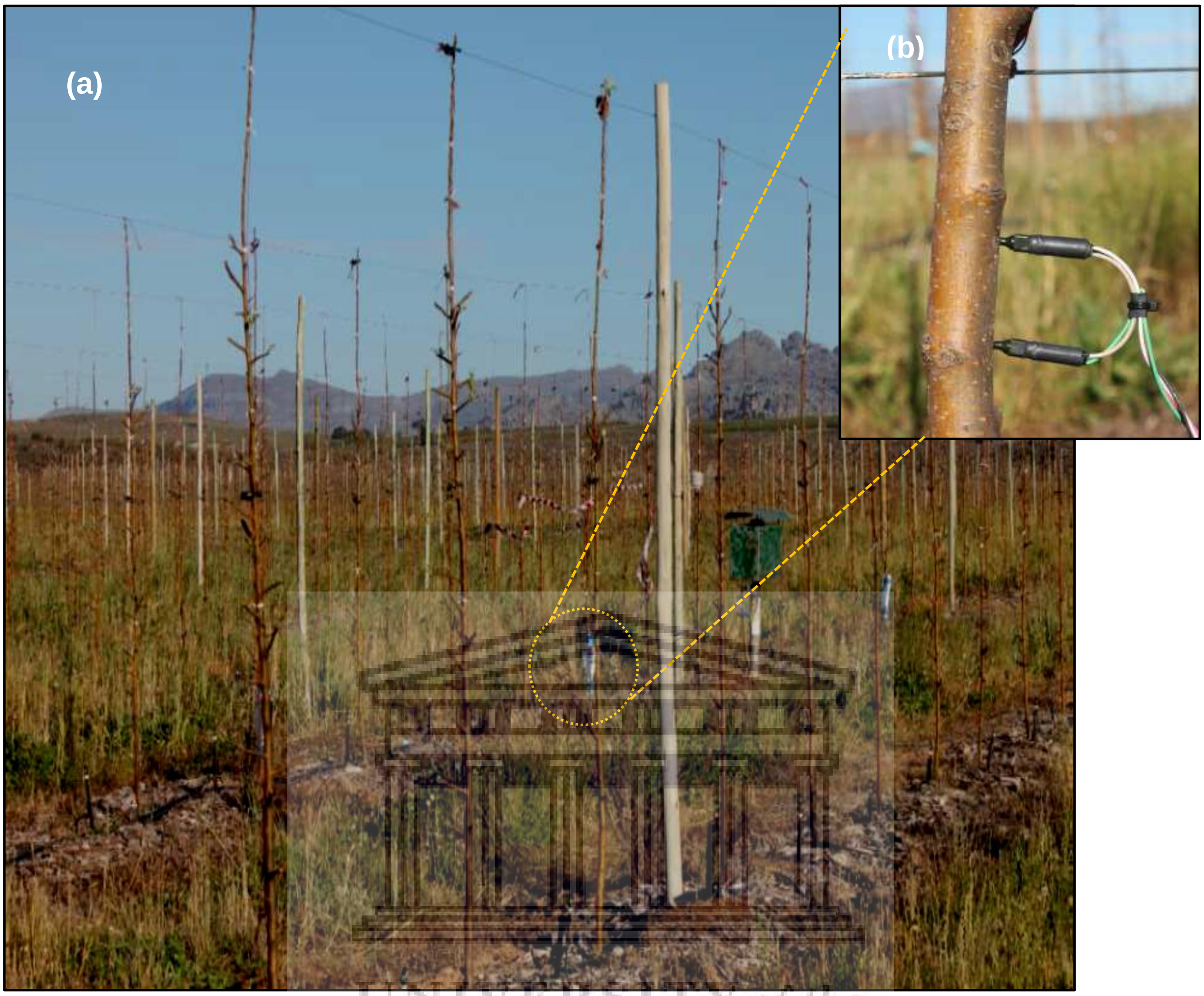

Fig. 4.6: (a) Measurement of transpiration in young orchards using Granier probes. (b) Granier probe installation using 10 mm sensors.

4.2.7 Tree eco-physiological status

Eco-physiological measurements were taken in all 12 orchards to determine whether the orchards had gone under stress during the study period. In each orchard, 5 trees were marked in the same row as the sap flow instrumented trees. Another 5 trees were marked in the next row on the opposite side of the instrumented tree row, to give a total of 10 trees per orchard. Two leaves were measured per tree for all parameters.

Plant water status, measured as midday stem water potential (MSWP) was assessed at monthly or bi-monthly intervals during the 2014/15, 2015/16 and 2016/17 growing seasons on selected 10 tagged trees using a Scholander et al. (1965) pressure chamber. Two healthy and fully expanded leaves per tree, located close to the stem, were enclosed in the morning using zip-lock silver reflective stem water potential bags (prune bags) (PMS Instrument Company, Albany, Oregon, USA) to allow the leaf water potential to equilibrate with stem water potential and all reading were at midday between 12:00 and 14:00 pm (Local time = GMT + 2 h).

Leaf transpiration rates data were collected at the leaf level in pairs of orchards planted to Golden Delicious/Golden Delicious Reinders® and Cripps' Pink/Red/Rosy Glow. These data were collected to establish whether water use varied by apple cultivar. The LI-6400 XT Photosynthesis Systems (LI-COR, Lincoln, Nebraska, USA) was used to measure 2 sun-exposed leaves per tree on 5 trees per orchard in the morning (09:00−11:00) and in the afternoon (12:00−14:00). The time difference between the leaf gas exchange measurements between the orchards was less than 1 hour given that the orchards were mostly located close to each other.

4.2.8 Water stress indicators

Two independent indicators of orchard water stress based on daily data were evaluated. The first of these was the transpiration reduction coefficient (K_S), which was calculated using daily average soil water content measurements in the root zone according to the FAO 56 guidelines (Allen et al., 1998). K_S = 1 indicates no transpiration reduction (i.e. no water stress) and this reduction factor can be expressed as:

$$K_s = \frac{\mathrm{TAW} - D_r}{(1-p)\,\mathrm{TAW}} \qquad (4.2)$$

where, D_r (mm) is the daily root zone depletion, and *p* is the depletion coefficient, which accounts for the resistance of the crop to water stress. The value of *p* = 0.50 was used in this study as proposed by Allen et al. (1998) for apple orchards. TAW (mm) is the total available water in the entire root zone calculated as:

$$\mathrm{TAW} = 1000(\theta_{FC} - \theta_{WP})Z_r \qquad (4.3)$$

where, θ_{FC} and θ_{WP} represent the volumetric soil water content at field capacity and permanent wilting point, respectively, and values were determined from water retention curves and the details are presented in Dzikiti et al. (2018b). Z_r is the effective rooting depth, which was estimated to be about 60 cm in the young orchards and 100 cm in the mature orchards, based on actual observations in selected orchards where profile pits were dug.

The second orchard water stress indicator was the plant-based transpiration reduction coefficient (K_{sf}), which was based on sap flow measurements and was calculated as:

$$K_{sf} = 1 - \frac{T}{T_p} \qquad (4.4)$$

where, T is the daily orchard transpiration expressed per orchard floor area derived from the sap flow measurements (in mm·d^{-1}), and T_p represents the potential transpiration when soil water is not limiting calculated as:

$$T_p = K_t \times ET_0 \qquad (4.5)$$

The K_t values used in this equation were obtained from the data collected on clear days after irrigation when the trees did not experience water stress. ET_o is the reference evapotranspiration (in mm·d^{-1}). According to Allen et al. (1998), K_t in Eq. 4.5 is similar to the basal crop coefficient which is defined as the ratio of the actual evapotranspiration to ET_o when the soil surface is dry. The transpiration coefficient (K_t) was calculated as:

$$K_t = \frac{T}{ET_0} \qquad (4.6)$$

where, T was the transpiration measured on a given day throughout the season.

4.2.9 Statistical analysis

Data obtained from the experiments were subjected to Analysis of Variance (ANOVA) using Statistix 10.0 statistical package to calculate the effects of cultivar and canopy cover on measured transpiration dynamics (sap flux density, whole orchard transpiration expressed per unit ground area and transpiration per unit leaf area. Means were separated by Tukey HSD at probability level of 0.05, where treatments effects were observed. Regression analysis was also performed using Microsoft Excel, to determine the relationship between transpiration and its main climate driving variables.

4.3 RESULTS

4.3.1 Weather conditions during growing seasons

In the KBV region in 2014/15, solar radiation ranged between 11.2 and 30.0 MJ m^{-2} d^{-1} with daily minimum and maximum temperatures of between 2.8°C in winter and 31.4°C in summer, respectively (Fig. 4.7a and b). The daily average vapour pressure deficit of the air (VPD) varied from 0.36 kPa in September 2014 to a peak around 3.0 kPa in March 2015 (Fig. 4.7c). The total rainfall of 280 mm measured during the study period had a very uneven distribution (Fig. 4.7d). Most of the rain was received in late spring (17%) in October and November 2014 and in late autumn to early winter (53%) in the months of May and June 2015, respectively. The seasonal (October to June) total reference evapotranspiration (ET_o) at 1 264 mm was more than 4 times higher than the rainfall.

In the EGVV region the daily solar radiation peaked at 28.6 MJ m^{-2} d^{-1} (Fig. 4.7e) with daily minimum and maximum temperatures of between 1.4°C in winter and 39.7°C in summer during the 2015/16 season, respectively (Fig. 4.7f). On warm and dry days the maximum VPD was lower than that reached in KBV the previous year, peaking at 2.5 kPa (Fig. 4.7g), highlighting the milder atmospheric evaporative demand in EGVV compared to KBV. The seasonal total reference evapotranspiration was lower in EGVV, at 1 064 mm, than that recorded in KBV during the 2014/15 growing season. Total rainfall during the 2015/16 season was 247 mm, which was low for a region with a long-term average annual rainfall of around 670 mm, confirming the drought experienced in the Western Cape region during the study period. Weather conditions in 2016/17 in both production regions followed similar trends to the previous seasons although rainfall of 149 and 218 mm was recorded in KBV and EGVV, respectively highlighting even more severe drought conditions than in the first two seasons of this study.

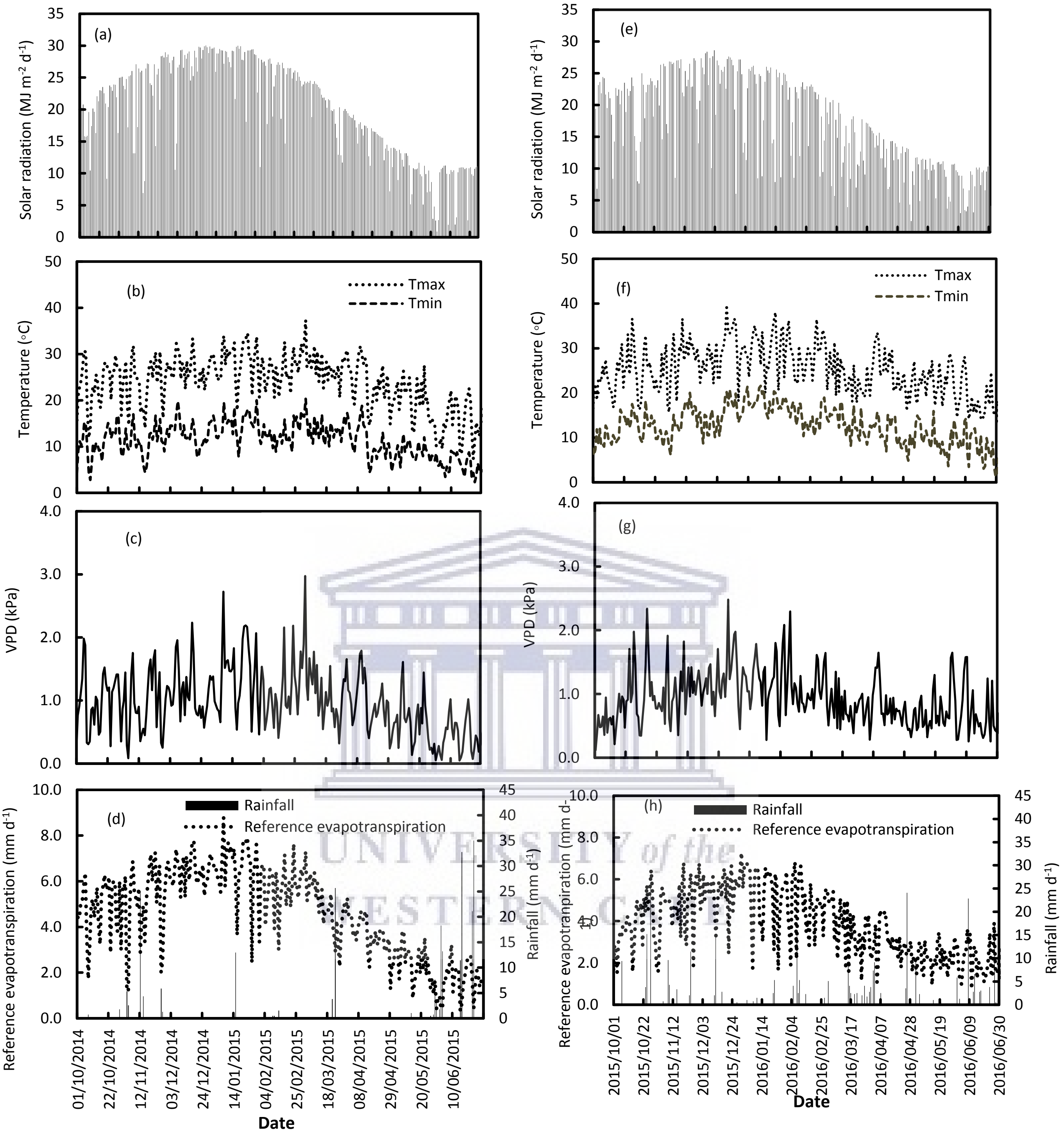

Fig. 4.7: Daily values of solar radiation (a, e), minimum and maximum temperature, Tmin and Tmax (b, f), vapour pressure deficit, VPD (c, g) and reference evapotranspiration and rainfall (d, h) during 2014/15 and 2015/16 growing seasons in two production regions (KBV (a-d) and EGVV (e-h)).

4.3.2 Leaf area index variations across orchard age groups

Leaf area index variation of the trees in the various EGVV and KBV orchards are shown in Figs 4.8 a-d. The order of magnitude of the leaf area index (LAI) of the KBV orchards was similar to the EGVV orchards. The mature Golden Delicious orchards in both production regions had a higher average LAI which peaked at 3.4 (Fig 4.8a & c). The mature Cripps' Pink orchards on the other hand had less dense, more open canopies, with the highest LAI around 2.8 for both EGVV (Fig 4.8a) and KBV (Fig 4.8c). The medium cover Cripps' Pink orchards in both production regions had slightly bigger canopies as the tree were older than those in the Golden Delicious Reinders® orchards. The maximum LAI for the medium cover Cripps' Pink was 2.1 compared to 1.5 obtained for the Golden Delicious Reinders® for EGVV (Fig 4.8b). At KBV, the maximum LAI recorded was 2.7 and 1.9 for Cripps' Pink and Golden Delicious Reinders®, respectively. Peak LAI of the young low canopy cover orchards in EGVV was approximately 1.0 for the Golden Delicious Reinders® and 0.8 for the Cripps' Red orchard. In contrast, in the KBV, peak LAI of the young orchards were higher for the Rosy Glow at 1.3 as compared the Golden Delicious Reinders® orchard at 0.7.

4.3.3 Effect of canopy cover on the transpiration

The average daily sap flux density (SFD), whole orchard transpiration expressed per unit ground area (T) and transpiration per unit leaf area (E_L), differed significantly with canopy cover at 5% level of significance, irrespective of cultivar (Table 4.4). In both production regions medium canopy cover trees had the highest daily average sap flux density, which reached 284 and 262 cm^3 cm^{-2} d^{-1} in KBV and EGVV, respectively (Table 4.4). The high canopy cover trees had the second highest sap flux density of 226 and 160 cm^3 cm^{-2} d^{-1} in the respective production regions. The young non-bearing orchards with low cover had the lowest sap flux density, i.e., between 119 and 137 cm^3 cm^{-2} d^{-1} in KBV and EGVV, respectively.

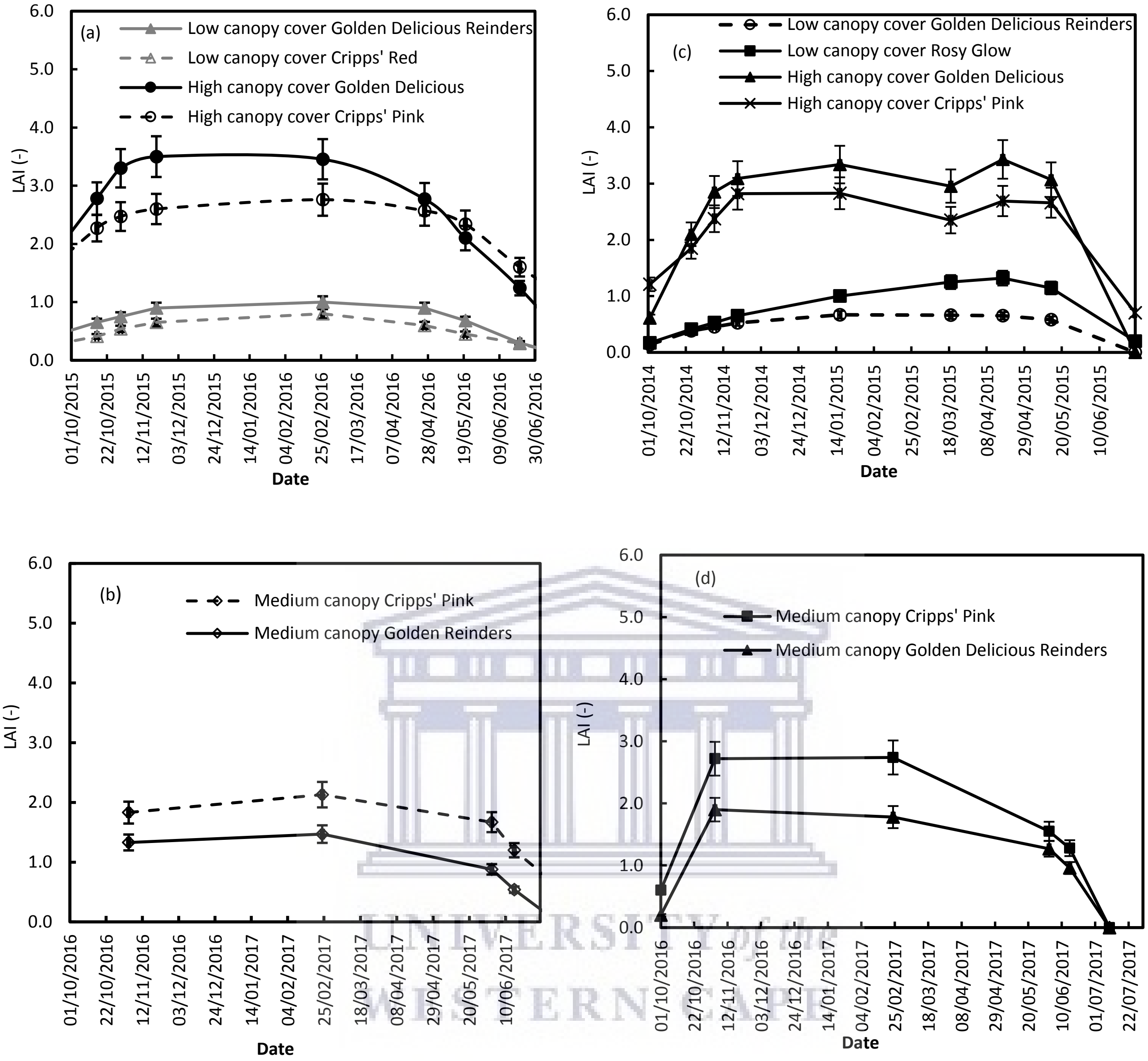

Fig. 4.8: Typical seasonal variations in the leaf area index of orchards with (a, c) high and low and (b, d) medium canopy covers in EGVV and KBV, respectively.

As expected, the average daily whole orchard transpiration per unit ground area was highest in the mature high canopy cover orchards, followed by the medium canopy orchards, and lastly the young non-bearing low canopy cover orchards (Table 4.4). The high canopy cover orchards had the highest daily average transpiration in both study sites of 3.06 mm d^{-1} in KBV and 2.95 mm d^{-1} in EGVV. For the medium canopy cover orchards, the average daily transpiration was 2.09 mm d^{-1} in KBV and 1.44 mm d^{-1} in EGVV. The young low canopy orchards had lowest mean daily whole orchards transpiration of 1.05 mm d^{-1} for orchards in KBV and 0.66 mm d^{-1} for orchards in EGVV.

Table 4.4: Effect of canopy cover on sap flux density (SFD), orchard transpiration expressed per unit leaf (E_L) and per unit ground (T) areas, respectively, of different apple orchards over three growing seasons (2014–2017)

Season	**Location**	**Canopy cover**	**SFD** **(cm^3 cm^{-2} d^{-1})**	**E_L** **(mm d^{-1})**	**T** **(mm d^{-1})**
2014/15	KBV	High	226.39 ± 2.72^a	1.05 ± 0.01^a	3.06 ± 0.04^a
		Low	118.58 ± 1.91^b	1.00 ± 0.02^b	1.05 ± 0.02^b
		Significance	*	*	*
2015/16	EGVV	High	159.91 ± 1.92^a	0.98 ± 0.01^a	2.95 ± 0.05^a
		Low	136.79 ± 2.39^b	0.71 ± 0.02^b	0.63 ± 0.01^b
		Significance	*	*	*
2016/17	KBV	Medium	284.03 ± 3.22^a	0.98 ± 0.01^a	2.09 ± 0.02^a
	EGVV	Medium	261.56 ± 3.64^b	0.82 ± 0.02^b	1.44 ± 0.04^b
		Significance	*	*	*

*Means in the same column followed by the same letter are not significantly different at P ≤ 0.05. ns = non-significant difference at P ≥ 0.05, * = significant difference at P ≤ 0.05*

4.3.4 Cultivar effect on transpiration dynamics of field grown trees

Table 4.5 shows the effect of cultivar on sap flux density (SFD), daily whole orchard transpiration per unit ground area (T) and transpiration per unit leaf area (E_L). It can be seen from Table 4.5 that, SFD and T were significantly influenced by cultivar irrespective of canopy cover. However, cultivar did not significantly affect transpiration per unit leaf area for two cultivars with varying canopy cover. On average, the transpiration per unit leaf area expressed in equivalent water depth units is around 1.00 mm d^{-1} for all the cultivars. The medium canopy cover trees had the highest sap flux density irrespective of cultivar. Within each canopy cover class, differences in the sap flux density between cultivars were inconsistent, as shown in Table 4.5, for unclear reasons. For both high and low canopy cover orchards, Golden Delicious/ Reinders cultivar had the higher SFD as compared to Cripps' Pink/ Red cultivars.

There were also no significant differences in the transpiration per unit leaf area among the cultivars across all the orchard age groups (Table 4.5). However, differences in transpiration per unit ground area (T) largely reflected differences in canopy management practices, especially for the mature orchards.

Table 4.5: Effect of cultivar on sap flux density (SFD), orchard transpiration expressed per unit leaf (E_L) and ground (T) areas of different apple orchards, including standard errors

Canopy	**Cultivar**	**SFD (cm^3 cm^{-2} d^{-1})**	**E_L (mm d^{-1})**	**T (mm d^{-1})**
High	Golden Delicious	195.07 ± 3.44^a	1.04 ± 0.01^a	3.37 ± 0.04^a
	Cripps' Pink	191.23 ± 3.44^b	0.99 ± 0.01^a	2.64 ± 0.04^b
	Significance	*	*ns*	*
Medium	Golden Delicious Reinders	244.88 ± 3.22^b	0.83 ± 0.02^a	1.35 ± 0.03^b
	Cripps' Pink	300.71 ± 3.64^a	0.97 ± 0.01^a	2.18 ± 0.02^a
	Significance	*	*ns*	*
Low	Golden Delicious Reinders	158.62 ± 2.89^a	0.84 ± 0.02^a	0.80 ± 0.02^a
	Cripps' Red	92.55 ± 3.07^b	0.86 ± 0.03^a	0.88 ± 0.02^a
	Significance	*	*ns*	*ns*

Means in the same column followed by the same letter are not significantly different at $P \leq 0.05$. ns = non-significant difference at $p \geq 0.05$, = significant difference at $p \leq 0.05$*

Since the effects of cultivar on transpiration dynamics were not clear as shown in Table 4.5. Transpiration rate measurements were then taken at leaf level to see the physiological effects of cultivar on tree water use, as shown in Fig. 4.9. From this graph there were no significant differences ($p > 0.05$) in the transpiration rates between the two cultivars subjected to the same environmental conditions. This graph was obtained by combining the gas exchange measurements from all 12 orchards. The leaf-level transpiration data which were normalized with the leaf area to support the observations from the sap flow data, i.e., that transpiration rate per unit leaf area is the same irrespective of apple cultivar. The small differences could be attributed to the effects of water stress or canopy management in some orchards. The dotted line depicts the one-to-one line.

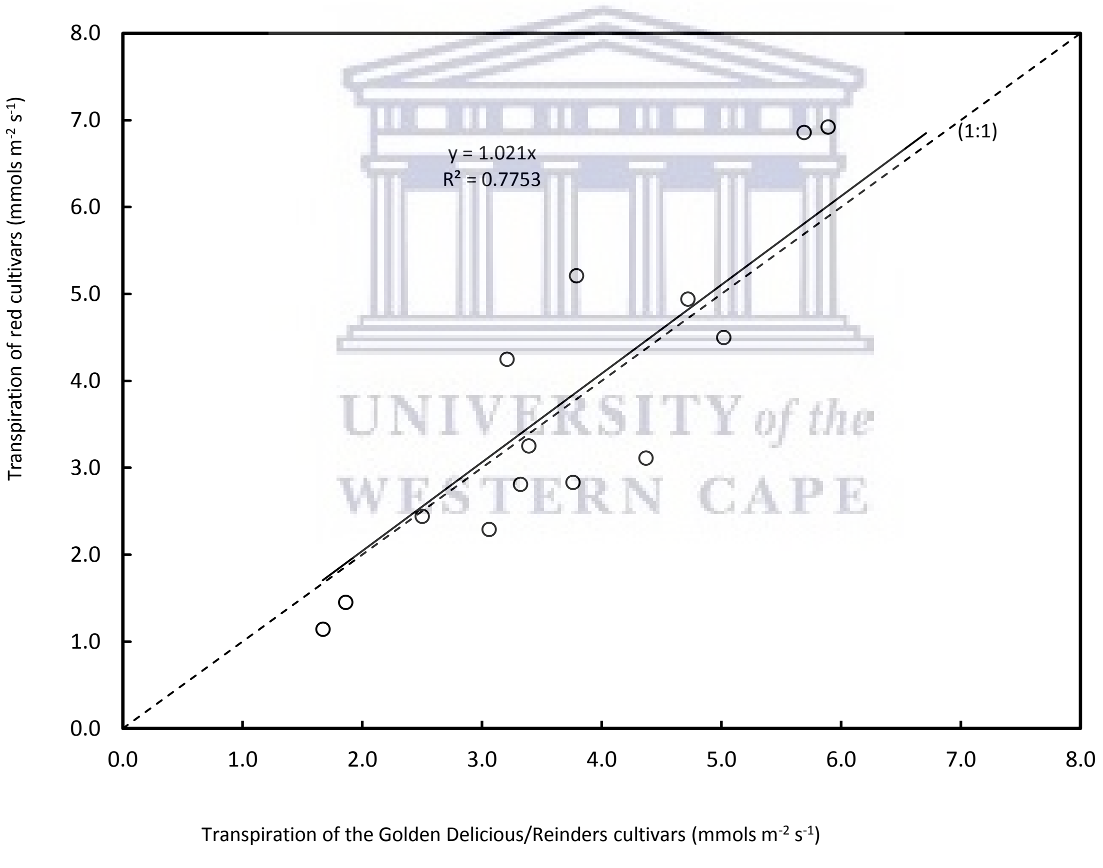

Fig. 4.9: Comparison of the leaf level transpiration rate of the pairs of Golden Delicious/Golden Delicious Reinders® and the red cultivars measured at different times during the growing season using the Photosynthesis system.

4.3.5 Seasonal water use

The high canopy cover Golden Delicious orchard had the highest daily average transpiration of 20.1 L tree^{-1} d^{-1} in comparison to the 15.0 L tree^{-1} d^{-1} measured in high canopy cover Cripps' Pink orchards. Seasonal total transpiration of high canopy cover Golden Delicious orchards during the study periods was 787 mm in KBV and 757 mm in EGVV (Table 4.6), as also reported in Dzikiti et al. (2018a, 2018b). The seasonal total transpiration for the high canopy cover Cripps' Pink orchards, on the other hand, was 589 and 631 mm in KBV and EGVV, respectively.

Table 4.6: Comparison of the effects of growing season length, specifically the late harvest of the blushed apple cultivars, on orchard water use. Winter months were from April to June. The rest were treated as summer months.

Season	**Location**	**Cultivar**	**Whole seasonal total transpiration (mm)**	**Months in the season**	**Transpiration (mm period^{-1})**	**%T**
2014/15	KBV	High canopy Golden Delicious	787	Summer	555	83
				Winter	232	17
		High canopy Cripps' Pink	589	Summer	408	69
				Winter	181	31
2015/16	EGVV	High canopy Golden Delicious	757	Summer	511	68
				Winter	246	32
		High canopy Cripps' Pink	631	Summer	427	68
				Winter	204	32
2016/17	KBV	Medium canopy Golden Delicious Reinders®	420	Summer	269	64
				Winter	151	36
		Medium canopy Cripps' Pink	547	Summer	350	64
				Winter	197	36
	EGVV	Medium canopy Golden Delicious Reinders®	249	Summer	194	78
				Winter	55	22
		Medium canopy Cripps' Pink	471	Summer	309	66
				Winter	162	34

Seasonal transpiration in the medium canopy cover orchards ranged from 249 mm for the Golden Delicious Reinders® orchard in EGVV to 547 mm for the Cripps' Pink in KBV. The range of seasonal transpiration for the young orchards was from 133 mm for the Cripps' Red in EGVV to 271 mm for the Rosy Glow in KBV. Assessing the effect of season length on the seasonal total orchard transpiration, Table 4.6 shows that there was no significant additional water use during winter by the Cripps' Pink and other related long-season cultivars. Although the long-season apple cultivars maintain a high leaf area long after irrigation has ceased, leaf transpiration seems to be very low, presumably because of the low atmospheric evaporative demand, contributing between 31-36% to the seasonal transpiration in most instances.

4.3.6 Water use drivers

The relationship between daily transpiration and its main climate driving variables, i.e., the daily total solar radiation and the daily average vapour pressure deficit of the air (VPD), is shown in Figs 4.10 a–f. Transpiration in all the orchards generally increased with increasing solar irradiance and vapour pressure deficit across all age groups. There were strong and positive linear relationships between the solar radiation and transpiration in all orchards (Fig. 4.10 a, c & e). The coefficient of determination (R^2) ranged from 0.63 to 0.74 for orchards with high canopy cover, 0.64 to 0.76 for the medium canopy cover orchards and 0.66 to 0.69 for the low canopy cover orchards. However, there was a non-linear relationship between vapour pressure deficit (VPD) and transpiration rate with the coefficient of determination being $R^2 = 0.65$ and 0.73 for the high canopy cover orchards; 0.56 and 0.58 for the medium canopy orchards and considerably lower at 0.51 and 0.56 in the low canopy cover orchards (Fig. 4.10 b, d, f). The curvilinear relationship shows that the VPD has a strong limiting effect on tree water use across all orchard age groups at values in the range of 1.5 to 2.0 kPa. The first order polynomial had the highest coefficient of determination than a linear relationship.

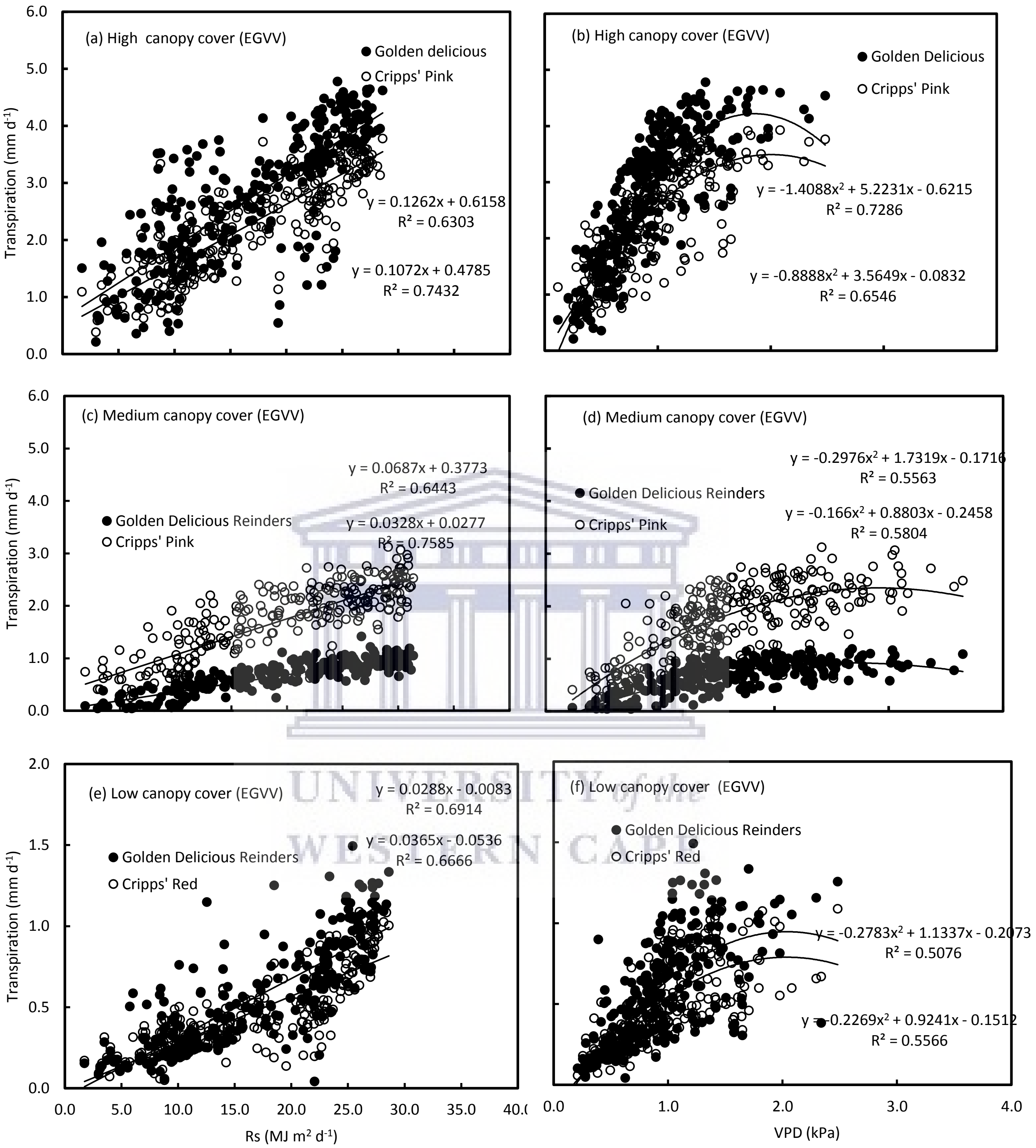

Fig. 4.10: Effects of the climatic drivers (Rs and VPD) on the daily transpiration rate for: high (a, b), medium (c, d) and (e, f) low canopy covers during the 2015/16 and 2016/17 growing seasons.

4.3.7 Transpiration coefficient variations

The mid-season peak K_t for the high canopy cover Golden Delicious orchards ranged from 0.70 to 0.74, although there was a noticeable decline in the KBV orchard due to water stress, as shown by the corresponding soil water content trend line in Fig. 4.11a. The K_t values varied from a maximum of around 0.50 to 0.60 in high canopy cover Cripps' Pink orchards (Fig. 4.11 b & f). In the low and medium canopy cover orchards peak mid-season K_t values ranged from 0.20 to 0.50, as illustrated in Fig. 4.11 c & d and g–l. There is, however, a peculiar decline in the mid-season K_t values in KBV for the high canopy cover Cripps' Pink (Fig. 4.11b), medium cover Cripps' Pink (Fig. 4.11j), and low cover Rosy Glow (Fig. 4.11d), and in EGVV in the low cover Cripps' Red orchard (Fig. 4.11h).

4.3.8 Midday stem water potential

The midday stem water potential (MSWP) during the 2014/15, 2015/16 and 2016/17 growing seasons indicated that there was no severe water stress in most of the orchards sampled (Fig 4.12 a-c). The MSWP values ranged from −0.77 to −1.06 and −0.75 to −1.79 MPa for Golden Delicious and from −1.03 to −1.46 and −1.38 to −1.50 MPa for Cripps' Pink in high canopy cover orchards in KBV and EGVV in 2014/15 and 2015/16, respectively (Fig 4.12 a & b). All these values were above the MSWP stress threshold for apples which is around −1.80 MPa (Volschenk et al., 2003 and Dzikiti et al., 2018b). In the medium cover orchards in EGVV, the MSWP ranged from −0.91 to −2.03 MPa for the Golden Delicious Reinders® orchard indicating some stress on occasions (Fig 4.12c). In the medium cover Cripps' Pink in EGVV, there seemed to be the least stress, with MSWP ranging from −0.91 to −1.32 MPa. In the medium cover orchards in KBV the measured MSWP varied from −0.84 to −1.44 MPa for the Golden Delicious Reinders® and from −0.95 to −1.71 MPa for the Cripps' Pink orchards (Fig 4.12c).

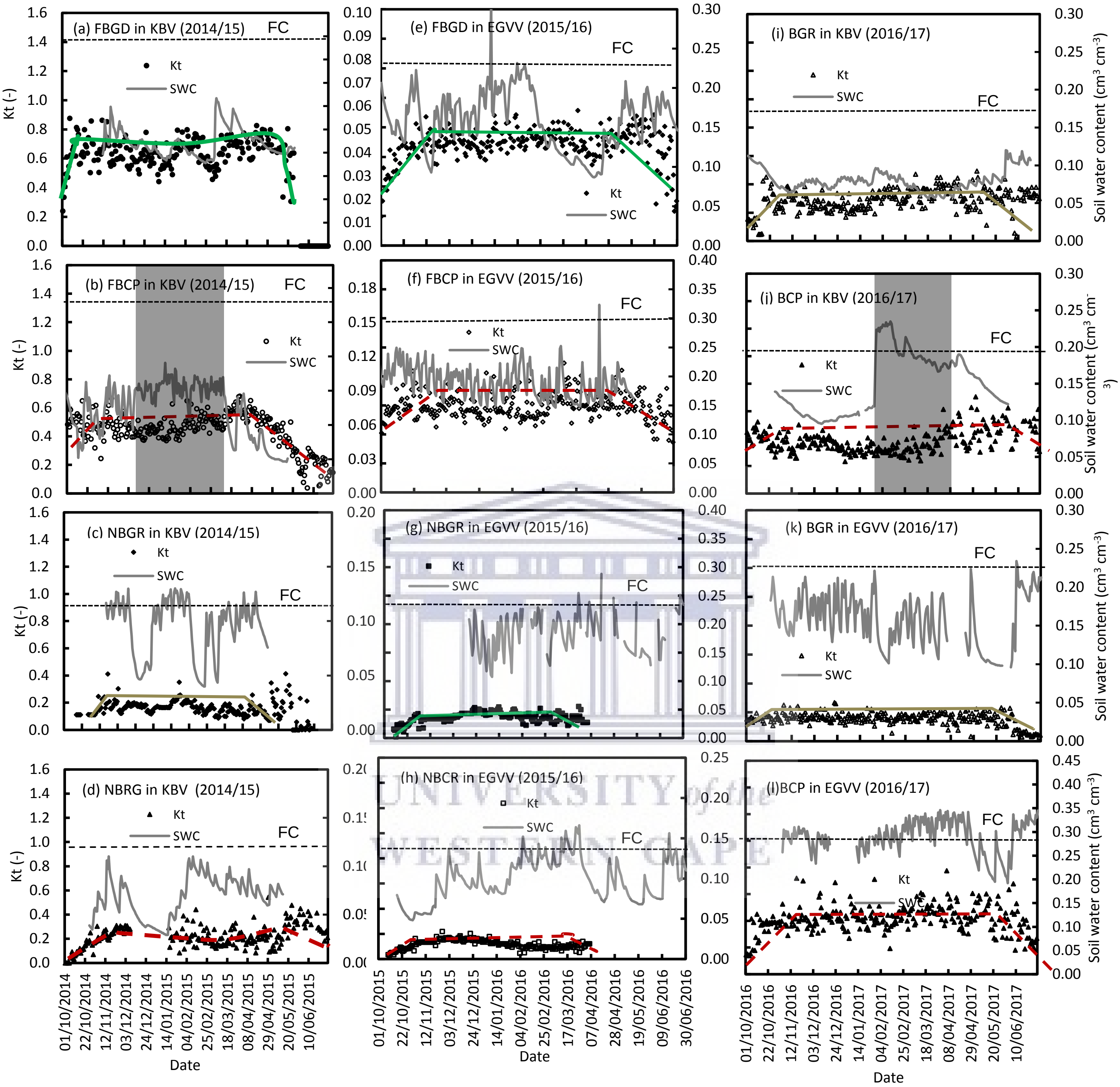

Fig. 4.11: Changes in the daily basal crop coefficient and soil water content in 12 apple orchards (a, e) high canopy cover Golden Delicious (FBGD), (b, f) high canopy cover Cripps' Pink (FBCP), (i, k) medium canopy cover Golden Delicious Reinders® (BGR), (j, l) medium canopy cover Cripps' Pink (BCP), (c, g) low canopy cover Golden Delicious Reinders® (NBGR), (d, h) low canopy cover Rosy Glow/ Cripps' Red (NBRG/NBCR) in KBV and EGVV, respectively, FC= Soil field capacity. The lines of best fit for the transpiration coefficients are indicated using different colours in the graphs.

Substantial stress was evident in the young orchards in EGVV during 2015/16 due to lower irrigation levels imposed by farmers as a drought management strategy. For example, in the low canopy cover Golden Delicious Reinders® orchard the MSWP ranged from −0.70 to −2.15 MPa compared to −1.14 to −2.10 MPa in the low canopy cover Cripps' Red orchard (Fig 4.12b), and the soil water content data showed extended periods of soil water deficit in the low canopy cover Cripps' Red orchard (Fig 4.11 h).

However, since MSWP was measured infrequently it cannot account for all the stress the trees were subjected to. Therefore, the plant-based transpiration coefficient K_{sf} and the FAO soil-based transpiration reduction coefficient (K_s) were estimated to provide continuous indication of the seasonal changes in plant water status. It is apparent from Fig. 4.13 a-c that the K_{sf} was strongly linearly related to the MSWP in the high cover (Fig. 4.13a), medium cover (Fig. 4.13b) and low canopy cover (Fig. 4.13c) orchards of the various cultivars.

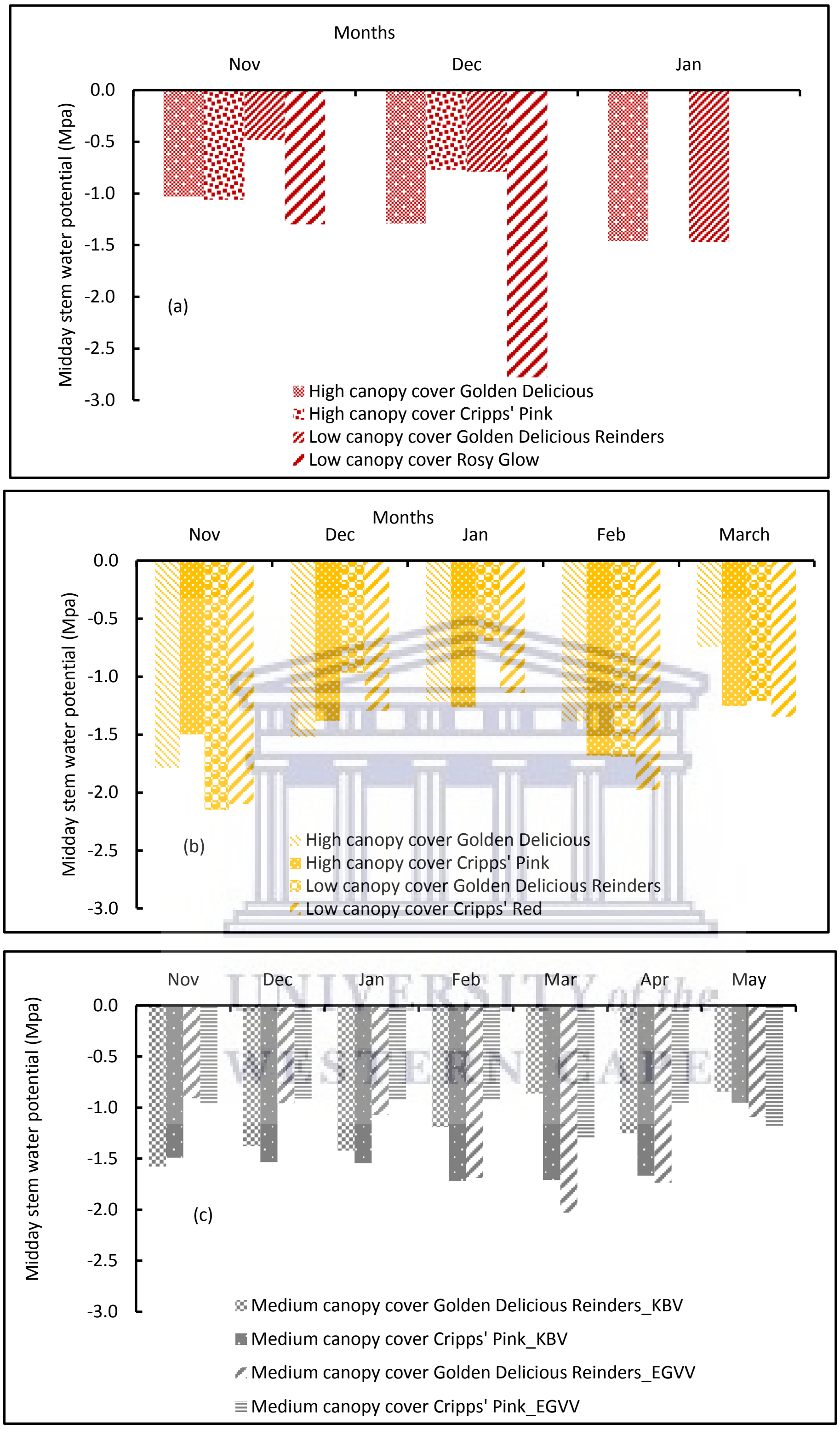

Fig. 4.12: Midday stem/xylem water potentials of the twelve orchards: (a) high and low canopy Golden Delicious/Reinders and Cripps' Pink/Rosy Glow at KBV, (b) high and low canopy Golden Delicious/Reinders and Cripps' Pink/Red at EGVV and (c) medium canopy Golden Delicious Reinders and Cripps pink (EGVV and KBV)

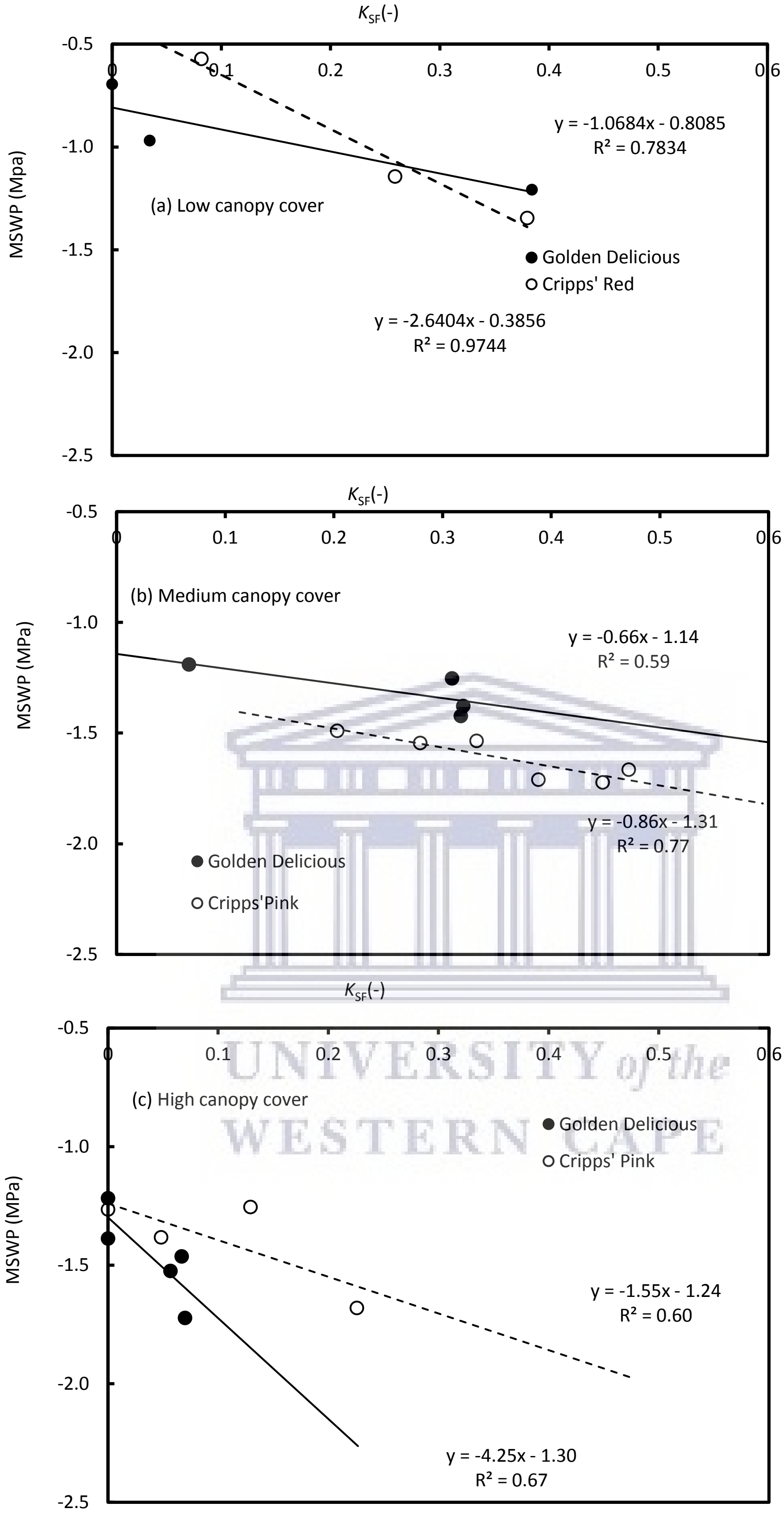

Fig. 4.13: Variations in the sap flow derived crop water stress index compared with the midday stem water potential for a Golden Delicious/ Reinders and Cripps' Pink orchards with (a) low canopy cover (b) medium canopy cover and (c) high canopy cover.

An illustration of the seasonal water stress dynamics in selected orchards is shown in Fig. 4.14 a-f. It is apparent that the K_{sf} was much more variable than K_s as it responded not only to stress induced by soil water deficit but also by very high atmospheric evaporative demand when plant water loss exceeded root water uptake (Jones, 2004). The horizontal lines on the graphs indicate K_s = 1.0, which occurs when soil water availability did not limit transpiration. Clearly the high canopy cover Golden Delicious orchard in KBV (Fig. 4.14a) experienced sustained periods of water stress with a larger transpiration reduction than the high canopy cover Golden Delicious in EGVV (Fig. 4.14b). Accordingly, the K_{sf} for the high canopy cover Golden Delicious in EGVV had a smaller amplitude, being generally lower than 0.2, while the peak fluctuated from 0.2 up to as much as 0.59 for the high canopy cover Golden Delicious in KBV. There was an inconsistent behaviour between K_s and the K_{sf} in the medium cover Cripps' Pink orchard in KBV (Fig. 4.14e). The irrigation and soil water content data clearly showed that there was over-irrigation in this orchard in the middle of the season (see region highlighted in grey shade), when the irrigation controller malfunctioned. The soil-based K_s factor indicated no stress while the K_{sf} instead indicated substantial stress. The stress detected by the K_{sf} can be attributed to waterlogging conditions and this highlights the limitations of the FAO's soil-based transpiration reduction coefficient. The low canopy cover orchards (Fig. 4.14c and Fig. 4.14d) experienced more frequent episodes of substantial stress than the medium and high cover orchards.

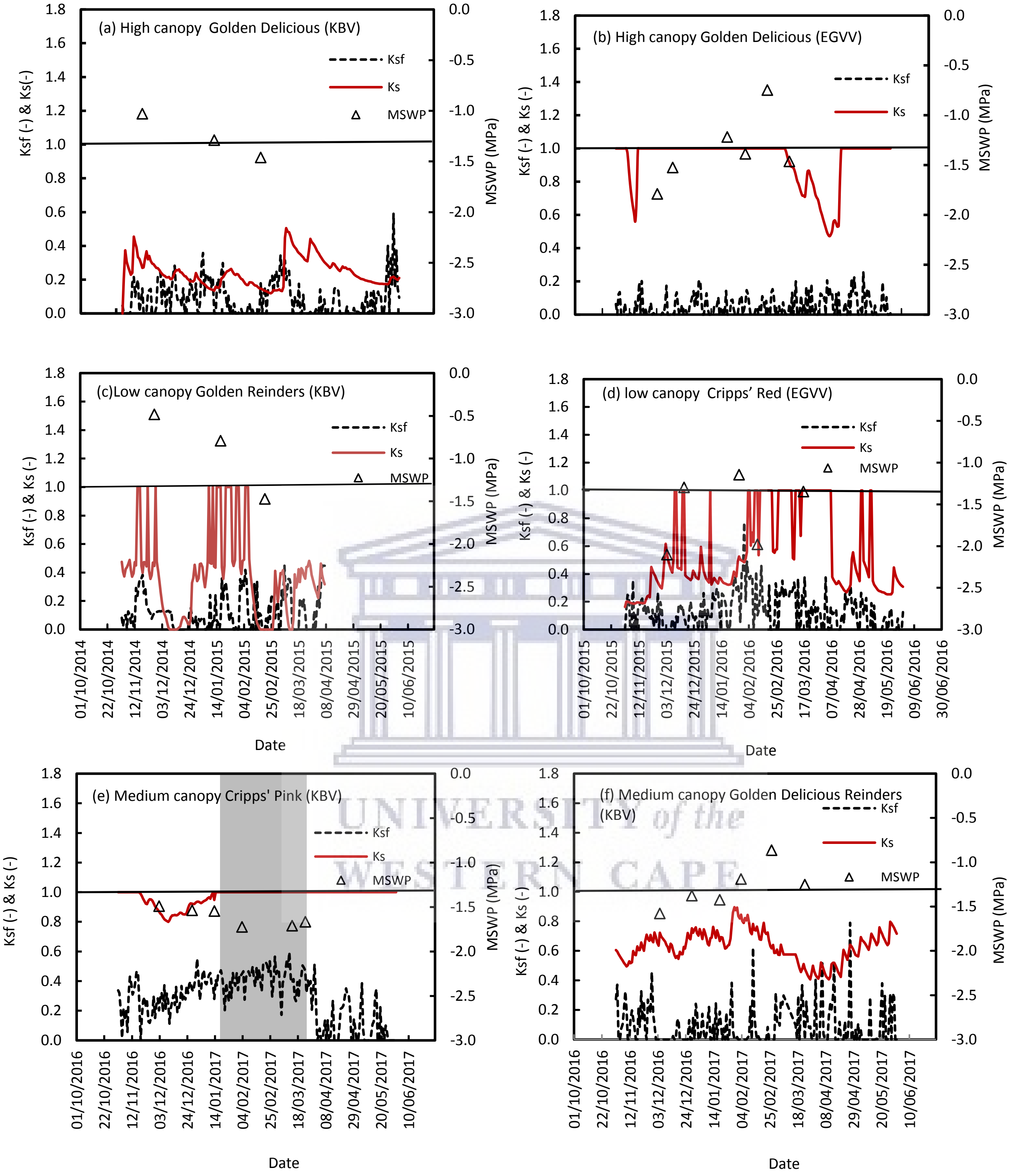

Fig. 4.14: The seasonal dynamics of the sap flow derived plant-based transpiration reduction coefficient (K_{sf}) and the soil-based transpiration reduction coefficient (K_s) and the midday stem water potential for six orchards with varying canopy cover. Region highlighted in grey shade in fig 4.14e indicates waterlogging conditions.

5.4 DISCUSSION

This study, for the first time, compares the transpiration and water stress dynamics in 12 apple orchards of different age groups planted to different cultivars that are commonly planted in the Mediterranean and subtropical regions. Golden Delicious, including its bud mutations, like Golden Delicious Reinders®, is the most widely planted cultivar accounting for at least 22% of the area under apple trees in South Africa (Hortgro, 2018). The blushed cultivars, on the other hand, e.g., Cripps' Pink, Cripps' Red and Rosy Glow are high-value, long-season (late harvest) cultivars and their fruit remains on the trees for about 2 months longer than the Golden Delicious. Because of their late harvest, it is widely believed that these orchards also have high water demands.

However, this study showed that the late harvest had no significant effect on the seasonal total transpiration by the orchards. The high canopy cover Golden Delicious/Golden Delicious Reinders® orchards were harvested mid- to end-March while the Cripps' Pink (and its mutations) orchards were harvested in late April for each of the seasons. It is evident from Table 4.6 that there were no significant differences between the two cultivars in the contribution of the March to end-of-season (June) transpiration, suggesting that there was no incremental water use by the Cripps' Pink due to the late presence of the fruit. Consistent with the observations of Dzikiti et al. (2018a, b), canopy cover during the growing season was the main driver of water use in apple orchards, although other studies, e.g., Naor et al. (1997) suggested that in similarly sized mature canopies, crop load was the main factor determining apple orchard water use. Therefore, growers should carefully manage the canopy size to reduce orchard water use.

Apple cultivars whose fruit are susceptible to sunburn damage, e.g., Golden Delicious and Granny Smith, tend to have denser canopies and vigorous shoot growth is tolerated to protect the fruit from high solar radiation (Mupambi et al., 2018). In South Africa, for example, sunburn damage losses in apple orchards is substantial accounting for as much as 29% of the total production (Gindaba and Wand, 2007; Makeredza et al., 2013). As a result, farmers take extra measures to minimize yield losses, e.g., by maintaining higher shade levels for susceptible cultivars using denser canopies, and more frequent irrigation during hot dry weather when sunburn damage risk is highest (Mupambi, 2017). Cultivars with relatively more open canopies to maximize light penetration in order to promote the development of the red fruit colour, such as the Cripps' Pink, are known to be less susceptible to sunburn due to the late maturation (Makeredza et al., 2013).

This study, which used commercial orchards, also suggests that there are no significant differences in the water use characteristics of Golden Delicious/Golden Delicious Reinders® and Cripps' Pink/Cripps' Red/Rosy Glow considering variables such as the sap flux density and transpiration per unit leaf area. It appears that the effect of cultivar on tree water use is significantly less than that of canopy cover for field-grown trees. One approach to obtain conclusive evidence on the cultivar effects on orchard water use, at least for the cultivars studied here, was to perform comparative studies, e.g., with trees of similar canopy size planted in pots maintained with similar soil conditions (see chapter 3). The results from the study showed that transpiration dynamics were not influenced by cultivar type even in young trees.

The sap flux density was highest in the medium canopy cover trees and reasons for this trend are unclear. A possible explanation is the existence of a higher proportion of older xylem vessels in the older apple trees which reduces the average sap velocity according to Cermak and Nadezhdina (1998). The low sap flux density in the low canopy cover orchards could be attributed to the small leaf area of the trees since canopy cover seemed to have a significant effect on the sap flux density. The occurrence of periods of sustained water stress in the low canopy cover orchards may also have contributed to the lower seasonal average sap flux density.

The transpiration coefficients (K_t) differed widely between orchards depending on many factors. For example, high canopy cover Cripps' Pink and Golden Delicious orchards had different mid-season K_t values, not because of the differences in the physiology of the cultivars, but because of differences in canopy management practices which influenced orchard transpiration rates. In the high canopy and some of the medium cover Cripps' Pink orchards in KBV, the decline in mid-season transpiration and hence the K_t values could probably be attributed to waterlogging, given the high irrigation levels in those orchards. All four of these orchards were planted on deep sandy soils. However, the high canopy and medium cover Cripps'

Pink in EGVV planted on heavier soils that maintained high soil water content did not experience the mid-season decline in the K_t values.

In this study low canopy cover orchards appeared to experience more frequent water stress than the medium cover and/or mature high canopy cover orchards. This can be explained firstly as a consequence of the drought that affected the Western Cape region during the study period, with farmers having to prioritize productive orchards in terms of water allocation. While the sap flow derived transpiration reduction coefficient (K_{sf}) has been evaluated in citrus orchards, we are not aware of any studies that have applied this index in apple orchards of different age groups. Here we show that the K_{sf} is a more sensitive indicator of water stress, capable of detecting either water deficit or excess irrigation that leads to waterlogging. The soil-based FAO-56 transpiration reduction coefficient posed a limitation in that it was not able to detect orchard stress due to excessive irrigation.

5.5 CONCLUSION

This study showed that canopy cover had a clear effect on the measured parameters, i.e., sap flux density, and the daily transpiration rates. It appears that there were no significant differences in the transpiration rates between the cultivars, so canopy management is critical to achieving water savings. Besides canopy cover, other factors such as crop load may also have a significant effect on the water use dynamics, although this aspect was not presented in this chapter. Growers should carefully manage the canopies to reduce orchard water use. This can be done by preventing excessive vigour, e.g., by using dwarfing rootstocks or through shoot thinning and spraying shoot growth retardants such as Regalis®. Alternatively, apple producers may also consider growing sunburn-susceptible cultivars such as Golden Delicious/Golden Delicious Reinders® under shade nets where they can be maintained with less dense open canopies on dwarfing rootstocks and likely with lower incidences of sunburn damage.

CHAPTER 5: ESTIMATING CROP COEFFICIENTS FOR APPLE ORCHARDS WITH VARYING CANOPY COVER USING FRACTION OF GROUND COVERED BY VEGETATION AND TREE HEIGHT

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2. *Z. Ntshidi, S. Dzikiti, D. Mazvimavi and* ***N.T. Mobe.*** *2020. Contribution of understorey vegetation to evapotranspiration partitioning in apple orchards under Mediterranean climatic conditions in South Africa. Agricultural Water Management. https://doi.org/10.1016/j.agwat.2020.106627.*

Summary

The FAO-56 crop coefficient (K_c) approach is widely used for making irrigation decisions. Allen and Pereira (2009) extended this approach by developing a method for estimating K_c using a density coefficient (K_d), which is estimated from the fraction of ground covered by vegetation and plant height. In this study we evaluated this method using detailed measurements of transpiration (T), evapotranspiration (ET), soil attributes, weather, and tree physiological variables in 12 apple (*Malus domestica* Borkh) orchards in the Western Cape Province of South Africa. Mid-summer canopy cover of the orchards was less than 20% in young non-bearing and exceeded 60% in mature full-bearing orchards. Data were collected over three growing seasons (October 2014 to May 2017) in orchards planted to the Golden Delicious/Reinders®, Cripps' Pink, Cripps' Red, and Rosy Glow apple cultivars. The original Allen and Pereira (A&P) method significantly overestimated the basal crop coefficients (K_{cb}) by on average 47% in mature and 103% in young orchards, respectively. However, improved K_{cb} estimates were obtained by adjusting the ratio of the resistances (i.e. rl /100) in the A&P method, where rl is the mean leaf resistance and 100 s m^{-1} is the typical resistance for annual crops. We defined a resistance parameter "α" for apple orchards, which is equivalent to the bulk canopy resistance of a well-watered tree. Replacing rl /100 with rl /α, and using the measured mean rl and other biophysical measurements to solve the A&P equation for α gave a value of ~ 37 s m^{-1}. The improved K_{cb} values were used to derive the orchard K_c taking into account the contribution of cover crops whose transpiration was measured using miniature stem heat balance sap flow gauges. The seasonal total transpiration (T) estimated as T = K_{cb} x ET_o, where ET_o is the reference ET closely matched the measured values with a RMSE (root of the mean square error) of ~ ± 16 mm. Therefore, using the mean canopy resistance which is representative of apple trees in the A&P method has the potential to accurately predict both the crop coefficients and water use of apple orchards from planting until full bearing age.

5.1 INTRODUCTION

Water is a scarce resource in major fruit producing countries such as Italy, South Africa, Spain, Morocco and others where most fruits are grown under irrigation. In South Africa, for example, irrigated agriculture uses approximately 62% of the surface water resources and yet between 30 and 45% of this water is wasted mainly due to poor irrigation practices, and leakages (NWRS-2, 2013). Inefficient irrigation practices, increasing economic activities, and changing climatic conditions all contribute to increasing water scarcity (Girona et al., 2011; Marsal et al., 2013). So, water-saving technologies and sound water management strategies, particularly irrigation scheduling, are required to ensure the long-term sustainability and growth of the fruit industry (Volschenk et al., 2003; Girona et al., 2011).

Several methods have been developed over the years to improve irrigation scheduling in orchards in order to increase the crop water productivity. These include soil-based approaches whereby soil water content sensors are used to monitor the water status in the root zone and beyond (Sui, 2018; Volschenk, 2017). While this approach is fairly widely used, it has several drawbacks. These include the need for detailed and expensive monitoring networks, lack of broad spatial representativeness across soil and orchard characteristics, and uncertainties in water movement in the soil profile. Plant-based irrigation scheduling methods use the plant as a biosensor, which integrates the soil and atmospheric conditions as well as the plant's physiological response to water deficit (Dzikiti et al., 2010; Fernández, 2017). A comprehensive review of the advantages and disadvantages of the plant-based irrigation scheduling methods was given by Jones (2004).

The FAO-56 approach, described by Allen et al. (1998), is the most widely used climate-based crop water requirement estimation method due to its simplicity and robustness. In this approach, crop evapotranspiration (ET) is estimated as the product of the reference evapotranspiration (ET_o) and a crop coefficient (K_c). Allen et al. (1998) tabulated typical K_c values for a range of irrigated crops. Several studies have compared the results obtained using the FAO-56 method with actual evapotranspiration measured using various techniques (Marin et al., 2016; Allen, 2000; Gupta et al., 2017; Zanotelli et al., 2019; Paço et al., 2006). The results demonstrate the need to adjust the tabulated crop coefficients to specific growing conditions. In an attempt to make the crop coefficients transferrable to different sites and climatic regions, Allen and Pereira (2009) used readily available data to estimate the crop coefficients and this method is referred hereafter as the A&P method. Allen and Pereira (2009) found that both the K_c and the basal crop coefficient (K_{cb}) could be determined using the fraction of ground covered by the vegetation, crop height, and the degree of stomatal regulation under wet soil conditions. However, other studies have shown mixed performances of the A&P method relative to the measured crop water consumption. For example, Paço et al. (2019) found a good agreement between the A&P K_{cb} values and those measured using sap flow sensors in an olive orchard in Portugal. In another study by Taylor et al. (2015) in three citrus orchards, the A&P method overestimated the sap flow derived K_{cb} by up to 127% under sub-tropical and Mediterranean-type growing conditions in South Africa.

In this chapter, we evaluated the A&P method using detailed field data collected in 12 apple orchards with varying canopy cover ranging from young non-bearing to mature high yielding orchards in the Western Cape Province of South Africa. The specific objectives were: 1) to evaluate the performance of the A&P method using actual measured field data over a range of fractional canopy cover, apple cultivars, and microclimates, 2) to investigate and document sources of uncertainty in the A&P method and to propose improvements: and 3) to extensively validate the improved A&P method to estimate the water use rates of apple orchards under Mediterranean climatic conditions. In addition, for the first time, we incorporate detailed measurements of cover crop transpiration into the A&P method to produce accurate crop coefficients for micro-sprinkler irrigated apple orchards with substantial cover crops growing between the tree rows. The hypothesis is that by parameterizing the A&P method for specific crop types, one can refine K_{cb} and K_c and get accurate estimates of crop water requirements.

5.2 MATERIALS AND METHODS

5.2.1 Study sites

The study was carried out on 12 commercial micro-irrigated apple orchards in two prime producing regions (KBV and EGVV) during three growing seasons (2014/15, 2015/16 and 2016/17). Sites were selected based on 'best practice' irrigation and agronomy. All orchards were assumed to be free of water stress. Detailed description of the study sites are given in sub-section 4.2.1., Chapter 4.

5.2.2 Data collection

5.2.2.1 Transpiration measurement

Tree transpiration in mature high and medium canopy cover orchards, was measured during the apple growing season (October to June) on between three and six trees of different stem sizes using the heat ratio method (HRM) of monitoring sap flow (Burgess et al., 2001). In young non-bearing low canopy cover orchards, sap flow was measured using Granier probes (TDP 10: Dynamax Inc., Houston USA) (Granier, 1987). Details on the installation of HRM and Granier probe equipment utilised are described under sub-sections 4.2.6.

5.2.2.2 Evapotranspiration measurement

Actual evapotranspiration from the orchards was measured using two open path eddy covariance systems (Fig 5.1). Because of the high costs associated with operating these systems, data were collected in specific short window periods in spring, summer and winter, respectively as summarized in Table 5.1. The flux tower systems comprised of sonic anemometers (Model: CSAT3, Campbell Sci. Inc., Utah, USA) that measure wind speed in 3-D, and infrared gas analysers IRGA (Model: LI-7500A, LI-COR Inc, Lincoln, Nebraska, USA) for measuring the atmospheric water vapour and carbon dioxide concentrations. Both sensors were installed at heights ranging from 1.2 to 1.8 m above the mean tree canopy height depending on the size of the orchard, which varied from ~ 3.8 to 7.0 ha. The flux towers were located downstream of the prevailing wind direction to maximize the fetch. Other sensors to quantify the orchard energy balance included single component net radiometers

(Model: CNR1, Kipp & Zonen, Delft, The Netherlands), soil heat flux plates (Model: Hukse Flux, Campbell Sci. Inc., Utah, USA) installed at 8 cm depth in undisturbed soils around each flux tower with one set under the tree canopies and the second in the open but away from the tractor tracks. CS616 soil moisture probes and soil averaging thermocouples (Campbell Sci. Inc., Logan UT, USA) were installed at 2 and 6 cm, respectively, in the neighborhood of each soil heat flux sensor from the surface in order to correct the measured fluxes for the energy stored by the soil above the plates.

Fig. 5.1: Open path eddy covariance system monitoring evapotranspiration in a full-bearing 'Golden Delicious' orchard at Southfield farm in Villiersdorp.

Table 5.1 Summary of the eddy covariance data collection in apple orchards

Seasons	**Regions**	**Site name**	**Canopy size**	**Cultivar**	**Measurement periods**
2014/15	KBV	Lindeshof	Low cover	Golden Delicious Reinders®	17 Oct 2014 21 Oct 2014 - 24 Oct 2014 08 Nov 2015 - 26 Nov 2014 29 Nov 2015 - 03 Dec 2014
2015/16	EGVV	Southfield	High cover	Golden Delicious	10 Oct 2015 – 12 Oct 2015 17 Oct 2015 24 Oct 2015 – 03 Nov 2015 24 Nov 2015 – 28 Nov 2015 12 Dec 2015 – 16 Dec 2015 12 Feb 2016 – 03 Mar 2016
		Radyn	High cover	Cripps Pink	31 Oct 2015 – 04 Nov 2015 12 Dec 2015 – 17 Dec 2015 02 Apr 2016 – 15 Apr 2016 20 Apr 2016 – 03 Mar 2016
		Vyeboom	Low cover	Golden Delicious Reinders®	23 Jan 2016 – 02 Feb 2016 05 Feb 2016 – 08 Feb 2016 12 Feb 2016 – 17 Feb 216
2016/17	KBV	Lindeshof	Medium cover	Golden Delicious Reinders®	20 May 2017 – 01 Jun 2017
		Esperanto	Medium cover	Cripps Pink	19 Jan 2017 – 24 Jan 2017
		Vyeboom	Medium cover	Golden Delicious Reinders®	03 Feb 2017– 05 Feb 2017
		Dennebos	Medium cover	Cripps Pink	15 Mar 2017 – 21 Mar 2017 30 Mar 2017 – 31 Mar 2017 07 Apr 2017 – 09 Apr 2017

The two systems were each powered by three truck size batteries and changed twice a week. The signals were sampled at a frequency of 10 Hz and the outputs were averaged at 30 min intervals using CR3000 and CR5000 data loggers (Campbell Sci. Inc., Utah, USA). The high frequency data were processed using the EddyPro v 6.2.0 software (LI-COR Inc., Lincoln, Nebraska, USA) to correct the data for the lack of sensor levelness, sensor time lags, fluctuations in the air density, among others. The data were further corrected for latent energy balance closure using the Bowen ratio approach as described briefly in Chapter 2.

5.2.2.3 Weather data

Measurements of weather variables are described in sub-section 4.2.3. The weather variables used in this analysis included wind speed and relative humidity.

5.2.2.4 Leaf area index

Orchard leaf area index (LAI – m^2 of leaf area per m^2 of ground area) in each orchard was measured at monthly intervals using a leaf area meter (Model: LAI-2000, LI-COR Inc., Lincoln, Nebraska, USA). These data were collected on overcast days when the leaves approximated black bodies. The fraction of the ground surface covered by vegetation at midday (f_c) was estimated from the LAI measurements using the relationship $f_c = 1\text{-}e^{-k\,LAI}$, where k is the extinction coefficient taken as equal to 0.6 (Impens and Lemeur, 1969).

5.2.2.5 Stomatal conductance

The stomatal resistance (rl) was measured at monthly intervals using an infrared gas analyser (Model: LI-6400, Li-COR, Inc., Lincoln, Nebraska, USA). Data were collected on two healthy sun-exposed leaves from ten tagged trees per orchard around midday from 12h00 to 14h30. The midday xylem water potential (ψ_x) was measured on the same ten trees using a pressure chamber (Model: 615, PMS Instrument Company, Albany, Oregon, USA). Detailed information is given in sub-section 4.2.7.

5.2.2.6 Estimation of vegetation fractional cover

Effective fraction of ground cover by the vegetation (fc_{eff}) near solar noon was estimated as:

$$fc_{eff} = \frac{f_c}{\sin(\beta)} \leq 1 \tag{5.1}$$

where, f_c is the fractional cover and β is the mean angle of the sun above the horizon during the period of maximum evapotranspiration, and can be calculated as:

$$\beta = \arcsin[\sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)] \tag{5.2}$$

where, φ represent the site latitude (in radians) which is negative in the southern hemisphere and δ is the solar declination (in radians) which can be calculated as:

$$\delta = 0.409 x \sin\left(\frac{2\pi}{365} DOY - 1.39\right) \tag{5.3}$$

where, DOY represents the Julian Day of Year (with 01 January representing DOY =1) (Monteith and Unsworth, 1990).

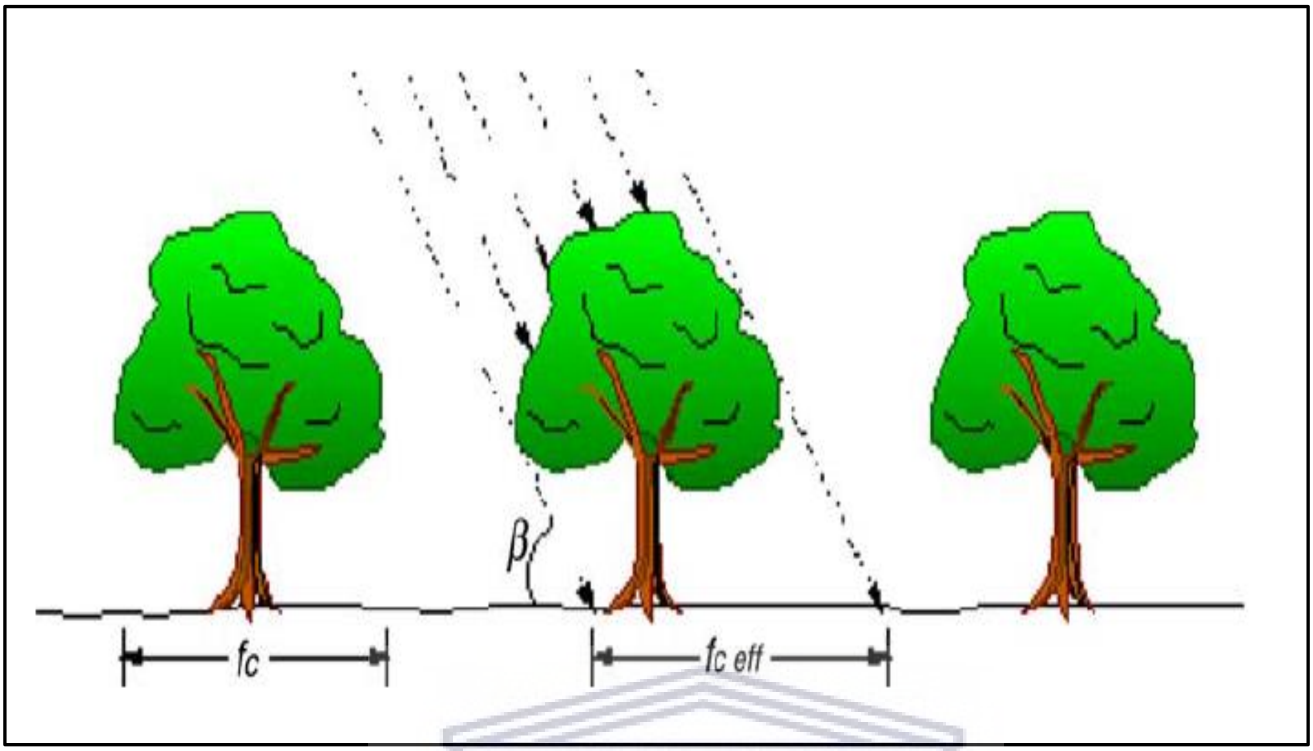

Fig. 5.2: Schematic for row crops showing fraction of surface (f_c) covered by vegetation as measured from the top, effective fractional cover (fc_{eff}) and mean angle of the sun above the horizon at midday (β) (Source: Allen and Pereira, 2009).

5.2.3 Calculation of crop coefficients

5.2.3.1 Basal crop coefficients (K_{cb})

According to Allen et al. (1998), the basal crop coefficient (K_{cb}), also referred to as the transpiration crop coefficient, is given by:

$$K_{cb} = \frac{T}{ET_o} \tag{5.4}$$

where T is the orchard transpiration (in mm d^{-1}) derived from the sap flow measurements. Orchard level transpiration was calculated as the sum of the products of the sap flux density (U) 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:

$$T = \sum_{i=1} SAI_i \times U_i \tag{5.5}$$

where U_i is the average sap flux density in a specific stem size class and each of the sap flow instrumented trees was assigned to an appropriate stem diameter class. Equation (5.4) assumes that the orchards did not suffer significant water stress. This was a reasonable assumption based on the measurements of tree water status as the orchards were generally well-watered. Sustained periods with water stress were excluded from the analysis.

Given that K_{cb} is dependent on the amount of vegetation, and also to ensure that the basal crop coefficients are transferable between fields, Allen and Pereira (2009) proposed a density coefficient (K_d) which they defined as:

$$K_d = \frac{K_{cb} - K_{c\min}}{K_{cbfull} - K_{c\min}} \qquad (5.6)$$

where K_{cmin} is the minimum basal coefficient for bare soil, K_{cbfull} is the estimated basal crop coefficient under conditions of nearly full ground cover (LAI ≥ 3.0). According to the A&P method, the density coefficient is estimated from the effective vegetation cover (fc_{eff}) and the mean tree height (h) as:

$$K_d = \min(1, M_L\, fc_{eff}, fc_{eff}^{\left(\frac{1}{1+h}\right)}) \qquad (5.7)$$

where M_L is a multiplier on fc_{eff} describing the effect of canopy density on shading. We used values of M_L =2.0 for mature orchards, and 1.5 for orchards with low and medium canopy cover, respectively. In situations where K_{cbfull} is not measured, it can be estimated from

$$K_{cb\,full} = F_r\left(\min(1.0 + 0.1h, 1.20) + [0.04(u_2 - 2) - 0.004(RH_{\min} - 45)]\left(\frac{h}{3}\right)^{0.3}\right) \qquad (5.8)$$

where U_2 is the mean wind speed measured at 2.0 m height and RH_{min} is the minimum relative humidity (%). According to Allen and Pereira (2009), the parameter F_r, which can be considered as a K_{cb} adjustment factor through crop stomatal control and has values in the range 0 to 1, was estimated using the following equation:

$$F_r = \frac{\Delta + \gamma(1 + 0.34u_2)}{\Delta + \gamma(1 + 0.34u_2 \frac{r_l}{100})} \tag{5.9}$$

where Δ is the slope of the saturation vapour pressure vs temperature curve (Pa ºC^{-1}), and γ is the psychrometric constant (Pa ºC^{-1}). rl is the mean leaf resistance for the vegetation in question (s m^{-1}). According to the A&P method, values of rl for apple orchards were suggested as 140 s m^{-1} for the initial and midseason periods and 370 s m^{-1} at the end of the season. In addition, the resistance value of 100 s m^{-1} in the denominator of equation (5.9) is the mean resistance for annual crops and this could be a source of uncertainty for perennial crops like most fruit trees. Using the suggested parameters on apple orchards led to significant over-estimates of K_{cb} for orchards of all age groups as will be discussed in detail in the results section. Consequently, we replaced the 100 s m^{-1} in equation (5.9) with a resistance parameter α which can be considered to represent the minimum unstressed canopy resistance for apple trees. We then inverted equation (5.9) using measured values of the climatic variables, the K_{cbfull} in equation (5.8) derived from sap flow measurements of transpiration at the mid-season stage of a mature well-watered apple orchard (LAI ~ 3.6) and the measured average leaf resistance (rl) for all the 12 orchards of about 202 s m^{-1}. We solved the A&P equation for α and obtained a mean value of about 37 s m^{-1}.

The micro-sprinkler irrigated orchards had cover crops and weeds of varying densities between the tree rows. These ranged from exotic grass species such as the tall fescues (*Festuca arundinacea*) to various indigenous grasses such as heart-seed love grass (*Eragrostis capensis*) and other species. To account for the cover crop transpiration, the whole orchard K_{cb} was estimated according to the A&P method as:

$$K_{cb} = K_{cb\text{cover}} + K_d \left(\max\left[K_{cb\,full} - K_{cb\text{cover}}, \frac{K_{cb\,full} - K_{cb\text{cover}}}{2} \right] \right) \tag{5.10}$$

where $K_{cbcover}$ is the basal crop coefficient due to the cover crop. The seasonal dynamics of the cover crop LAI were monitored in at least five orchards at regular intervals throughout the season using a destructive sampling technique. In this method, plants in several 50 cm x 50 cm quadrants were harvested and their leaf area measured manually using a leaf area meter (Model: LI-3000, Li-COR, Inc., Lincoln, Nebraska, USA). Estimates of cover crop transpiration (T_c) were obtained using three to four miniature stem heat balance sap flow gauges (Model: SGA2, Dynamax, Houston, USA) installed on straight portions of individual grass blades. The sensors were installed during short window periods lasting a few days at a time to avoid damage by farm machinery. The transpiration data to determine the maximum basal coefficient for the cover crops ($K_{cbfullc}$) was collected in winter (July 2017) when the trees were leafless and there was no shading of the cover crops.

To convert the sap flow gauge readings to transpiration expressed over the entire orchard floor (T_c, in mm h^{-1}) first we normalized the sap flow (SF, in cm^3 h^{-1}) of each instrumented plant with the leaf area (A, in cm^2). Then we multiplied the average of the normalized sap flow with the understorey leaf area index (LAI_c) and the fraction of the orchard floor occupied by the understorey vegetation (f_g).

$$T_c = \frac{\overline{SF}}{A} \times LAI_c \times f_g \times 10 \qquad (5.11)$$

Since it was not practical to measure T_c throughout the season, a simple model was developed to estimate the understorey transpiration. The maximum cover crop basal crop coefficient ($K_{cbfullc}$) was then determined using Equation (5.12):

$$K_{cbfullc} = \frac{T_c}{ET_o} \qquad (5.12)$$

The density coefficient for the cover crops (K_{dc}) was subsequently derived according to Allen and Pereira (2009) as:

$$K_{dc} = 1 - e^{-0.7 \times LAIc} \qquad (5.13)$$

$K_{cbcover}$ was then determined by combining equations (5.6), (5.12), and (5.13) assuming K_{cmin} of about 0.15 (Allen and Pereira, 2009).

5.2.3.2 Determining orchard crop coefficients (K_c)

The whole orchard K_c values were determined also using the density coefficient as proposed by Allen and Pereira (2009) as:

$$K_c = K_{soil} + K_d \left(\max \left[K_{cfull} - K_{soil}, \frac{K_{cfull} - K_{soil}}{2} \right] \right) \qquad (5.14)$$

where K_{cfull} represents K_c from a fully covered soil with some background evaporation and it was calculated as:

$$K_{c\,full} = \max \left(\left\{ 1.2 + \left[0.04(u_2 - 2) - 0.004(RH_{\min} - 45) \right] \left(\frac{h}{3} \right)^{0.3} \right\}, \left\{ K_{cb} + 0.05 \right\} \right) \qquad (5.15)$$

K_{soil} in equation (5.14) represents the average K_c from the non-vegetated (exposed) portion of the surface and reflects the impact of wetting frequency, and soil type. This was determined taking into account evaporation from the wet and dry portions of the orchard floor as:

$$K_{soil} = K_{ewet} + K_{edry} \qquad (5.16)$$

where K_{ewet} was calculated following Allen et al. (2005) as:

$$K_{ewet} = \frac{TEW - (TEW - REW)\exp\left(\frac{-\left(t_w E_{so} - REW\right)}{TEW - REW} \right)}{t_w ET_o} f_w \qquad (5.17)$$

where TEW is the total evaporable water which represents the depth of water that can be evaporated from the surface soil layer when the layer has been initially completely wetted. REW represents the readily evaporable water which represents the cumulative evaporation during stage 1 drying (Allen et al., 1998). t_w is the average time between independent wetting events which was calculated to be on average 2.7 days for wetting due to irrigation. E_{so} is the potential evaporation rate from a wet soil surface as described in equation (5.17), and f_w represents the fraction of the orchard floor that is wetted by irrigation or rain [0-1].

K_{edry} in this study was taken as a constant at 0.06 based on microlysimeter measurements of soil evaporation, and also given that the study area receives very little rainfall during the fruit growing season.

TEW was estimated as:

$$TEW = 1000(\theta_{FC} - 0.5\theta_{WP})Z_e \qquad (5.18)$$

where θ_{FC} and θ_{WP} represent the volumetric soil water content at field capacity and permanent wilting point, respectively ($cm^3\ cm^{-3}$) and Z_e is the effective depth of soil evaporation which was taken as 0.15 m (Allen et al., 1998).

REW was calculated from soil texture data according to Ritchie et al. (1989) as:

$$\begin{aligned} REW &= 20 - 0.15(Sa) && \text{for } Sa \geq 80 \qquad (5.19)\\ REW &= 11 - 0.06C = (Cl) && \text{for } Cl \geq 50\\ REW &= 8 + 0.06(Cl) && \text{for } Sa < 80 \text{ and } Cl < 50 \end{aligned}$$

where Sa is the percentage fraction of sand in soil and Cl is the percentage fraction of clay in the soil which were determined for the twelve orchards at a commercial laboratory.

To account for the presence of tree cover on soil evaporation (E_{so}) used in equation (5.17), we used the expression proposed by Allen et al. (2005) wherein:

$$E_{so} = (K_{c\max} - K_{cb})ET_O \qquad (5.20)$$

where K_{cmax} is the maximum crop coefficient for the surface under full vegetation and it is equal to K_{cfull} (equation 5.15); K_{cb} is the basal crop coefficient calculated according to equation (5.10).

5.2.4 Statistical analysis

Daily values of measured and estimated T were compared using the linear regression analysis. Root mean square error (RMSE), mean absolute error (MAE and Nash-Sutcliffe efficiency (NSE) were used to evaluate the model's performance as:

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} \left(Y_i^{obs} - Y_i^{sim} \right)^2 \right]^{0.5} \tag{5.21}$$

$$MAE = \frac{1}{N} \sum_{i=1}^{N} \left| Y_i^{obs} - Y_i^{sim} \right| \tag{5.22}$$

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim} \right)^2}{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim} \right)^2} \right] \tag{5.23}$$

where N is the total number of observations, the subscript i denoted the ith observation, Y^{obs} and Y^{sim} superscripts refers to the measured and predicted values and Y^{mean} are the means of the model-based and measured values, respectively.

5.3 RESULTS

5.3.1 Water use dynamics of apple orchards with varying canopy cover

There were clear differences in the water use patterns of the orchards with different canopy cover. The typical seasonal dynamics of the reference evapotranspiration (ET_o), actual evapotranspiration (ET), transpiration (T) and irrigation in young, medium and high canopy cover orchards are shown in Fig. 5.3 (a-c). In the young Golden Delicious Reinders® orchard (Fig. 5.3a), for example, the measured ET was lower than the ET_o, but higher than the sap flow derived T as expected. On warm days following irrigation, the measured ET was quite high, exceeding 4 mm d^{-1} due to high evaporation rates from the wet orchard floor. This is clearly evident for the period October to November 2014. At this time, orchard floor evaporation accounted for close to 60% of ET in the young orchard (Fig. 5.3a). The orchard floor evaporative losses were exacerbated by the tall and dense cover crop and weeds that grew on the orchard floor at the beginning of the season (September to late October). However, as the residual soil moisture from the winter and spring rains depleted, the vegetation between the rows became patchy and less vigorous. So periods of sustained water deficit (e.g. from 08 February to 07 March 2015) resulted in the measured transpiration being of the same order of magnitude as the measured ET (see region marked with an oval circle in Fig. 5.3a). Water stress was deliberately imposed on the trees during this time by withholding irrigation in order to derive the soil water retention curve for the orchard. The fact that the sap flow derived transpiration was close to the eddy covariance measured ET when evaporation from the orchard floor was negligible confirms that the two techniques agreed well. Taylor et al. (2015) reported a similar observation for mature drip irrigated citrus orchards in South Africa.

The measured ET, in the medium (Fig. 5.3b) and the high canopy cover orchards (Fig 5.3c), were comparable with the ET_o in most cases. As expected, tree transpiration contributed the most to the ET of the older orchards. The high ET rates early in the growing season (October 2014) for the mature Cripps Pink (Fig 5.3c) were a result of transpiration by the dense cover crop and weeds and evaporation from the wet soil when tree canopy cover was still low. The actual ET measured ranged from 0.4 to 4.1 mm d^{-1} in young orchards, 1.3 to 5.7 mm d^{-1} in the medium cover, and 0.94 to around 6.6 mm d^{-1} in the mature orchards. The high ET rates, which were close to ET_o, especially in mature orchards, confirm that the orchards were well-watered in most instances, although periods of water stress were also observed on occasion. The measured tree transpiration peaked at about 1.7 mm d^{-1} for the young orchards, 3.1 mm d^{-1} for the medium cover orchards and 3.8 mm d^{-1} for the mature Cripps Pink orchard. The maximum contribution of evaporation from the orchard floor accounted for between 30 and 50% of ET in medium cover orchards, falling to between 18 and 32% in mature high canopy cover orchards.

5.3.2. Measured vs calculated basal crop coefficients

The major advantage of the Allen and Pereira (2009) method is that the crop coefficients can be calculated from readily available information which makes the method very appealing for practical irrigation scheduling. The K_{cb} for example, can be calculated from estimates of the fractional vegetation cover, tree height and microclimatic data using equations 5.6 to 5.10. In this way, different crop coefficients for mature and young orchards are derived leading to more accurate irrigation decision making. However, using the parameters published by Allen and Pereira (2009) for apple orchards to derive the K_{cb} values for orchards with varying canopy cover led to significant over-estimates. Figure 5.4 illustrates typical trends of K_{cb} for entire growing seasons for young, medium, and high canopy cover orchards. In these examples, the A&P method over-estimated K_{cb} by 103, 69 and 47% for the young, medium, and high canopy cover orchards, respectively. Similar trends were observed for the remaining nine orchards whose data are not shown.

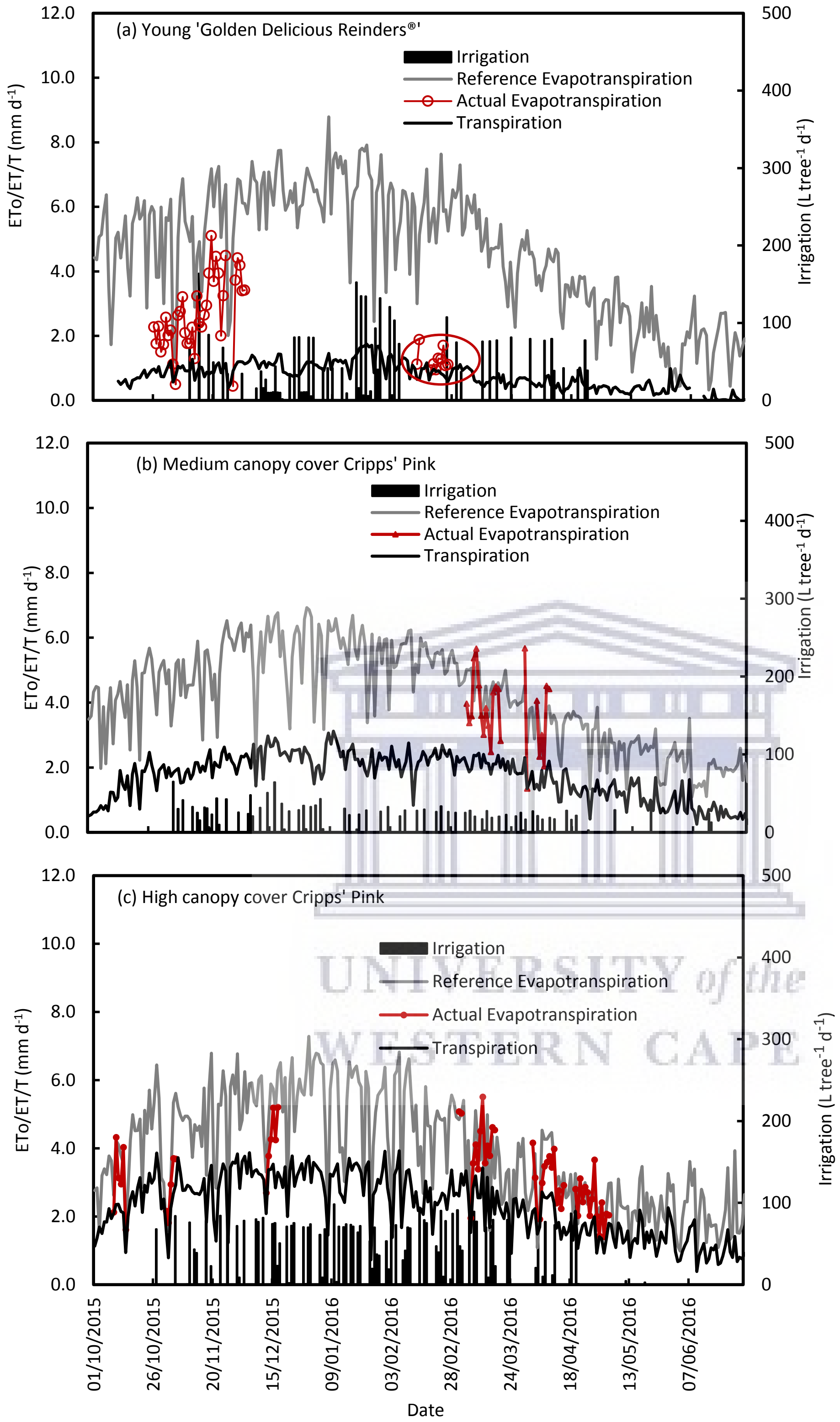

Fig. 5.3: Typical seasonal trends in the daily reference evapotranspiration (ETₒ), measured transpiration (T), and actual evapotranspiration (ET) of apple orchards with: a) low, b) medium, and c) high canopy cover.

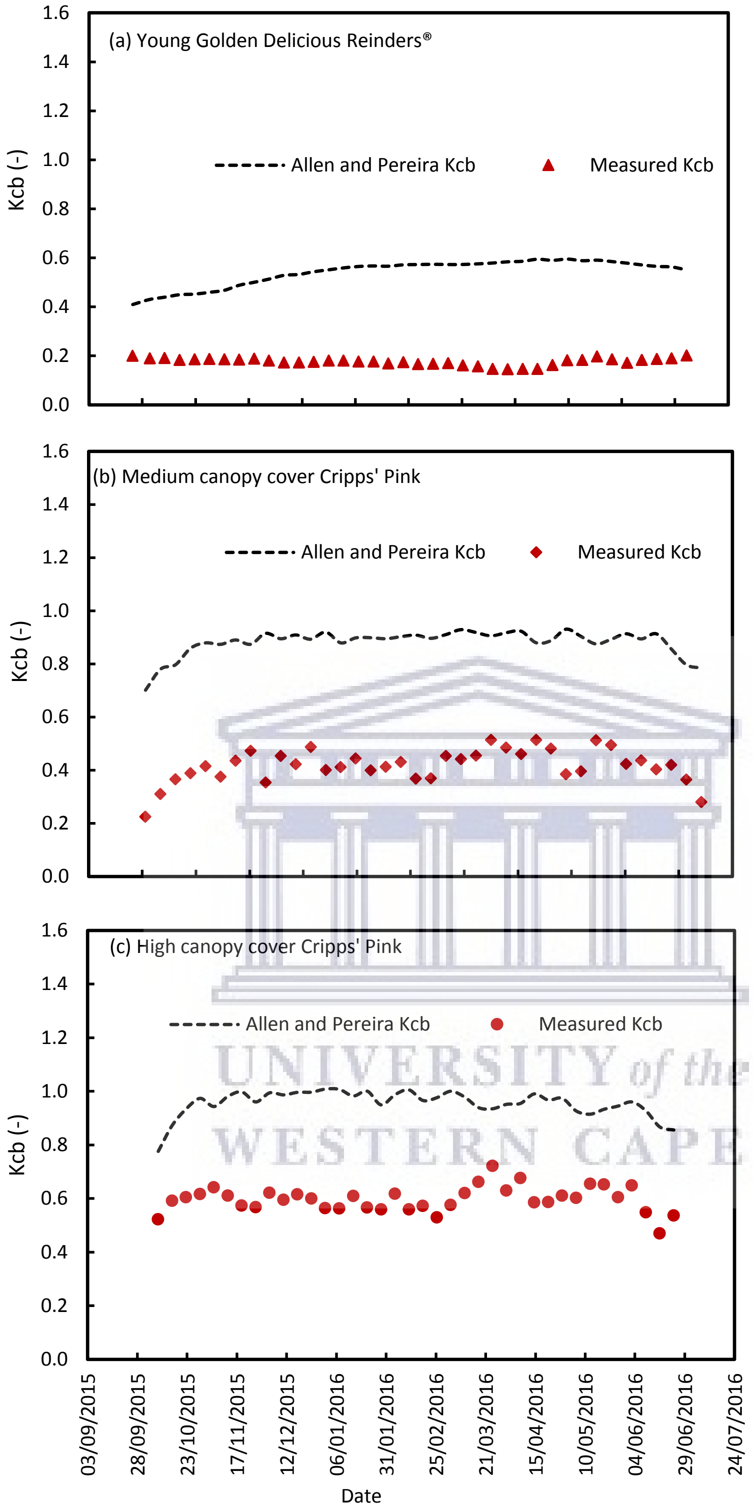

Fig. 5.4: Comparison of the sap flow derived basal crop coefficients (open dots) with those determined using the original Allen and Pereira (2009) method (black line) for apple orchards with: a) low, b) medium, and c) high canopy cover orchards in the Western Cape Province of South Africa.

A possible source of uncertainty causing the poor fit resides in equation (5.9) in which the ratio of the leaf resistances is used to adjust K_{cb} through the adjustment factor, F_r, as proposed by Allen and Pereira (2009). For this reason, we collected detailed data to further investigate how the tree water status and environmental factors influenced the leaf resistance of apple trees (Table 5.2). The measured stomatal resistance for the 12 apple orchards ranged from 100 to just over 500 s m^{-1}. The average resistance for the irrigation season (November to April) for all the orchards was around 202 s m^{-1}. An extremely high resistance of about 2 446 s m^{-1} was observed once in the young Rosy Glow orchard when the irrigation system malfunctioned (Fig. 5.5 a). Over the course of all the growing seasons, the mean leaf resistance showed an exponentially decreasing trend with the rising midday stem water potential (ψ_x) as shown in Fig. 5.5 a. This confirms that the stomata opened as the tree water status increased (less negative ψ_x). Using the leaf resistance measured for apple orchards, and also using the value of α = 37 s m^{-1} derived in this study led to improved estimates of K_{cb} for all the 12 orchards.

Table 5.2: Eco-physiological and climate parameters monitored in KBV and in EGVV during the three growing seasons for all the 12 orchards. T_a= average air temperature; RH_{min}= minimum relative humidity; ψ_x= midday xylem water potential; Z= elevation above sea level; rl= leaf resistance.

Region	Date	Orchard	Ta (°C)	RH_{min} (%)	ψ_x (MPa)	Z (m)	rl (s m^{-1})
KBV	2014/11/24	NBRG	20.1	34.3	-1.30	800	241
	2015/01/14	NBRG	25.3	22.3	-2.78	800	2446
	2014/11/26	NBGR	14.2	49.7	-0.48	800	114
	2015/01/16	NBGR	14.3	38.4	-0.79	800	109
	2015/02/19	NBGR	18.5	31.6	-1.47	800	209
EGVV	2015/12/16	NBGD	19.1	40.6	-0.97	350	161
	2016/01/27	NBGD	20.2	40.6	-0.70	350	175
	2016/02/10	NBGD	26.1	14.7	-1.69	350	168
	2016/03/16	NBGD	21.3	39.8	-1.21	350	157
EGVV	2015/12/16	NBSD	19.1	40.6	-1.30	350	214
	2016/01/27	NBSD	20.2	40.6	-1.14	350	239
	2016/02/10	NBSD	26.1	14.7	-1.98	350	515
	2016/03/16	NBSD	21.3	39.8	-1.35	350	174
KBV	2016/12/03	BGD	20.2	17.0	-1.58	800	299
	2016/12/27	BGD	19.3	38.6	-1.38	800	166
	2017/01/17	BGD	21.0	11.4	-1.42	800	310
	2017/02/02	BGD	17.9	37.5	-1.19	800	188
	2017/02/25	BGD	16.9	19.5	-0.86	800	236
	2017/03/22	BGD	23.3	22.2	-1.25	800	336
KBV	2016/12/02	BCP	20.5	24.3	-1.49	800	439
	2016/12/28	BCP	19.1	37.2	-1.54	800	258
	2017/01/13	BCP	18.3	31.0	-1.54	800	342
	2017/02/03	BCP	21.0	26.7	-1.72	800	276
	2017/03/13	BCP	19.1	16.4	-1.71	800	220
	2017/03/23	BCP	18.3	22.9	-1.66	800	358
EGVV	2016/11/24	BGR	20.4	35.7	-0.91	350	109
	2016/12/21	BGR	20.6	29.4	-0.96	350	197
	2017/01/12	BGR	22.7	27.6	-1.07	350	132
	2017/02/06	BGR	23.8	24.3	-1.69	350	236
	2017/02/24	BGR	25.2	25.4	-2.03	350	430
	2017/03/20	BGR	25.4	20.4	-1.74	350	336
EGVV	2016/12/01	BCP	21.8	25.7	-0.96	350	98
	2016/12/22	BCP	20.2	33.2	-0.91	350	101
	2017/01/16	BCP	20.0	33.7	-0.92	350	91
	2017/02/07	BCP	24.6	18.2	-0.93	350	87
	2017/03/10	BCP	23.2	14.3	-1.31	350	142
	2017/03/24	BCP	17.4	31.0	-0.96	350	101
KBV	2014/11/25	FBCP	22.9	23.5	-1.06	800	142
	2015/01/15	FBCP	19.8	45.5	-0.77	800	104
KBV	2014/11/25	FBGD	22.9	23.5	-1.03	800	180
	2015/01/15	FBGD	19.8	45.5	-1.29	800	125
	2015/02/17	FBGD	23.9	9.3	-1.46	800	205
EGVV	2015/12/15	FBGD	19.9	27.4	-1.52	350	202
	2016/01/26	FBGD	20.4	38.4	-1.22	350	133
	2016/02/09	FBGD	24.4	27.4	-1.39	350	176
	2016/02/26	FBGD	18.4	47.2	-0.75	350	120
	2016/03/04	FBGD	24.7	25.0	-1.46	350	215
EGVV	2015/12/15	FBCP	19.9	27.4	-1.38	350	168
	2016/01/26	FBCP	20.4	38.4	-1.26	350	154
	2016/02/09	FBCP	24.4	27.4	-1.68	350	152
	2016/03/04	FBCP	24.7	25.0	-1.26	350	127

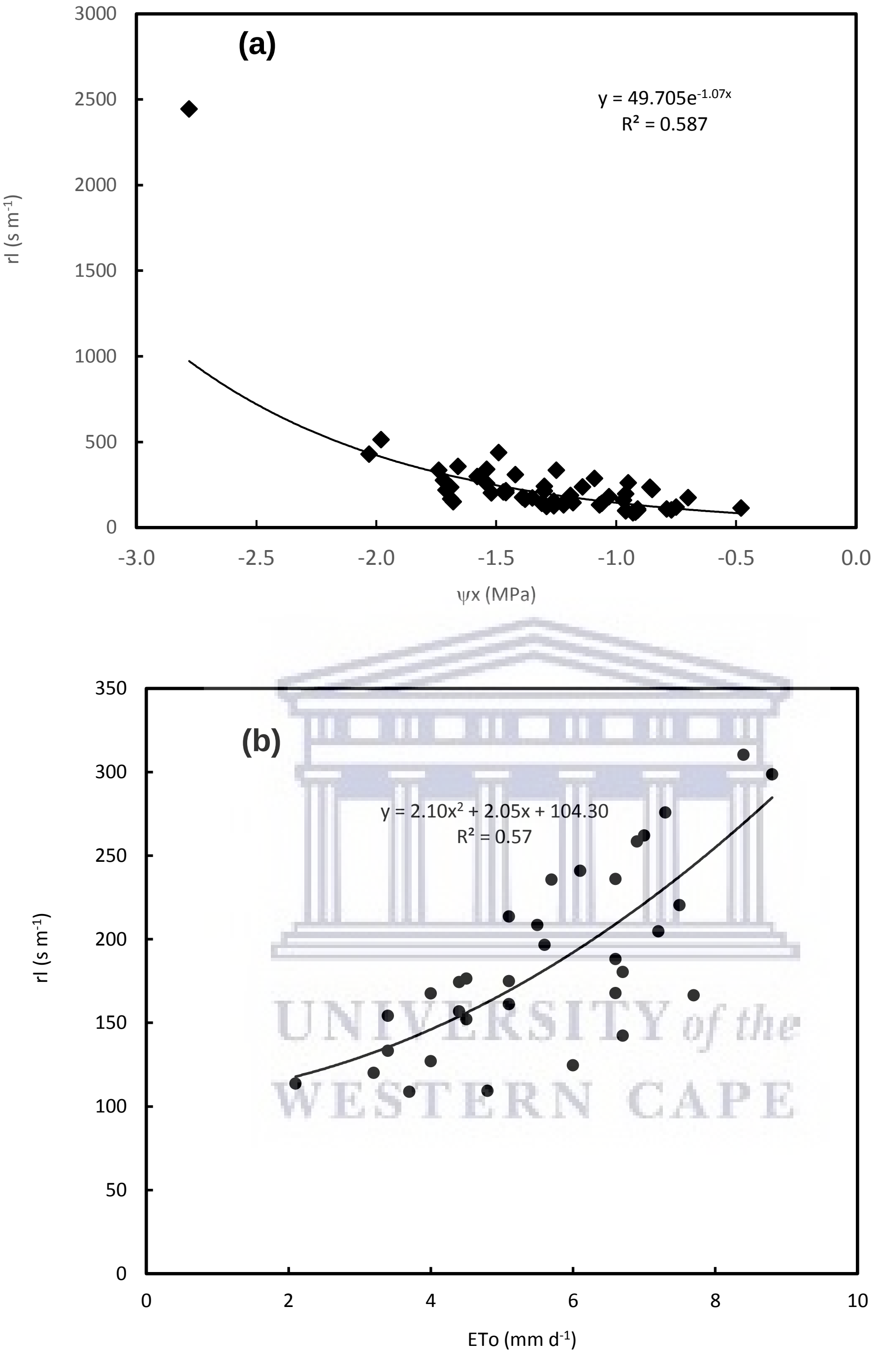

Fig. 5.5: Effect of a) the midday xylem water potential, and b) the daily total reference evapotranspiration on the average midday stomatal resistance of 12 apple orchards over three growing seasons (2014-2017).

Figures 5.6 a-f show examples of six orchards with different cultivars and canopy cover classes. The improved A&P approach predicted the K_{cb} quite accurately for all the orchards. This result suggests that using crop-specific information improves the accuracy of the estimated crop coefficients derived using the A&P approach. This appears to be particularly the case for fruit trees whose physiology differs quite substantially from annual crops.

5.3.3 Estimating the orchard transpiration using improved K_{cb}

The improved basal crop coefficients were used to predict the monthly transpiration totals, calculated as $T = K_{cb} \times ET_o$. Figure 5.7 shows that the predicted transpiration was comparable with the sap flow measured values for orchards with low, medium and high canopy cover. A summary for all the 12 orchards is shown in Table 5.3. In the high canopy cover Cripps' Pink orchard the monthly transpiration was slightly underestimated in October, but marginally overestimated from November to the end of the growing season (Fig. 5.7a). The good performance of the model was, however, confirmed by the statistical parameters (MAE = 12.9 mm, RMSE = 7.84 mm, NSE = 0.68 and R^2 = 0.92). NSE is the Nash-Sutcliffe Efficiency calculated according to Dzikiti et al (2018a). In the medium canopy cover Cripps' Pink and young Golden Delicious Reinders® orchards, the monthly measured transpiration was slightly underestimated throughout the growing season, except for the month of May and April, respectively. Nevertheless, the model performance was still satisfactory with an MAE of 5.36 and 5.07 mm, RMSE of 6.46 and 6.36, NSE of 0.86 and 0.47 and R^2 of 0.94 and 0.81 for medium canopy cover Cripps' Pink and young Golden Delicious Reinders® orchards, respectively (Fig. 5.7 b-c).

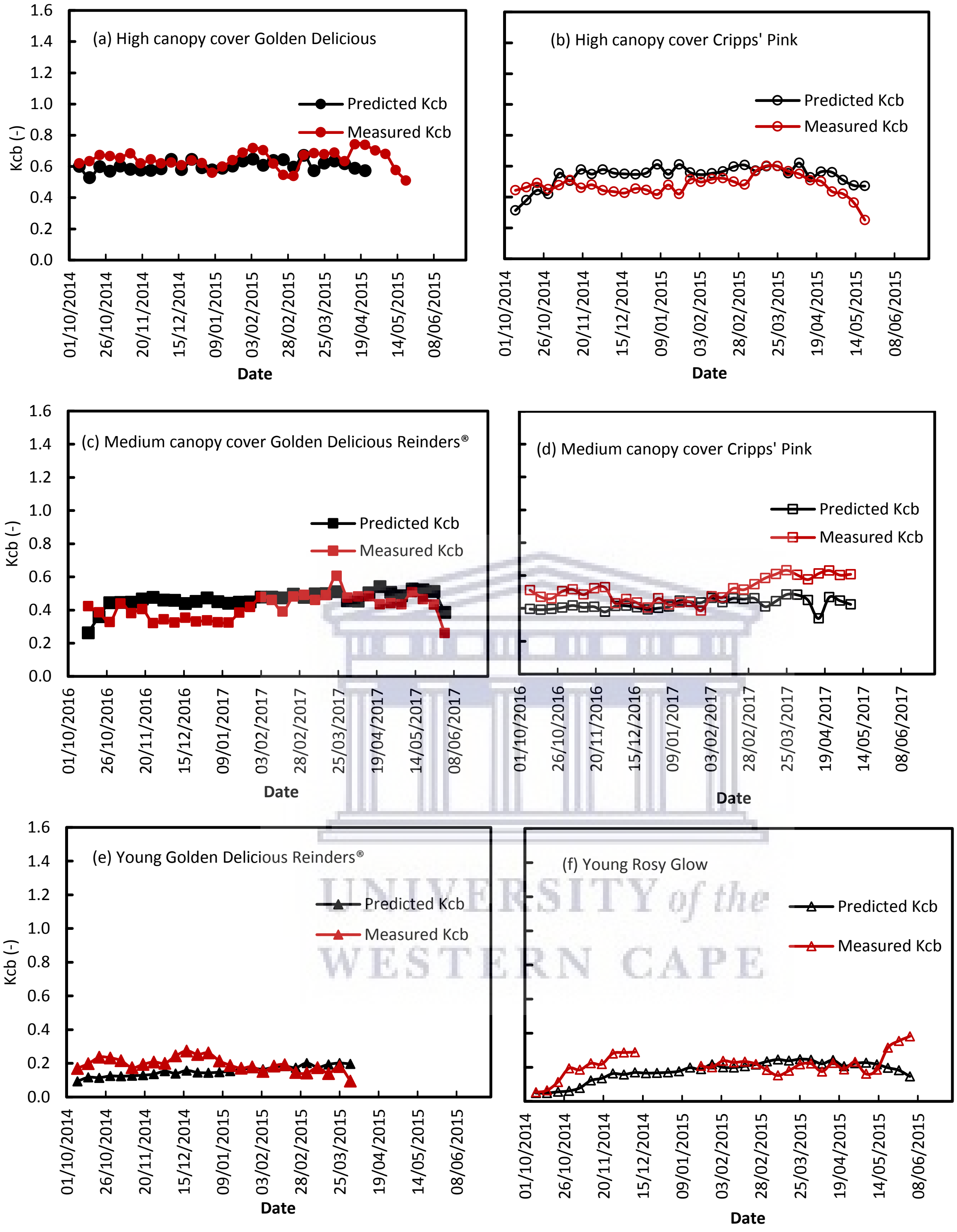

Fig. 5.6: Illustration of the performance of the improved Allen and Pereira basal crop factor calculation method on Golden Delicious and Cripps' Pink apple cultivars in: (a – b) - high canopy cover, (c – d) - medium canopy cover, and (e – f) - low canopy cover orchards.

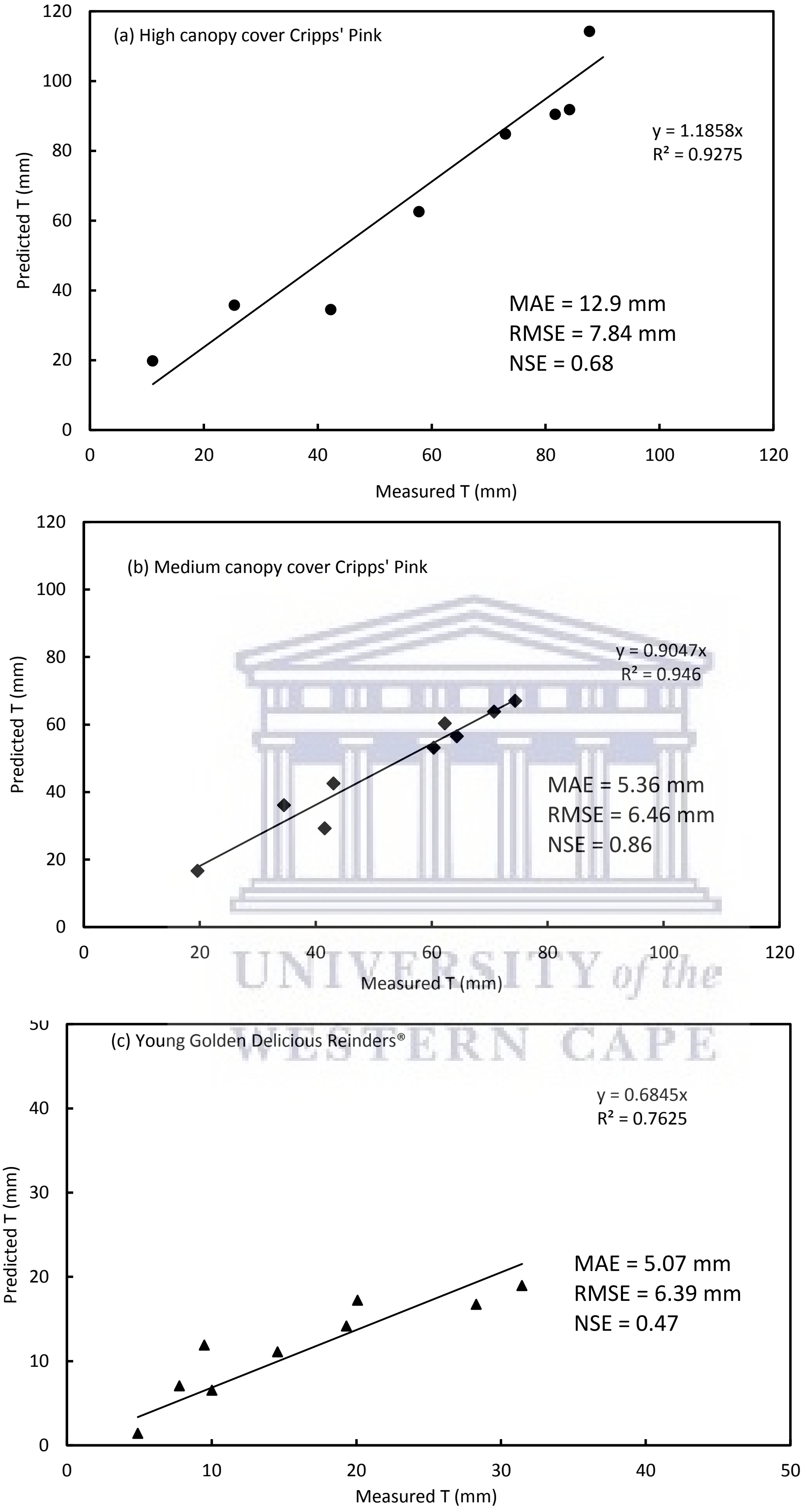

Fig. 5.7: Comparison of the measured and calculated monthly total transpiration rates of orchards with high (a), medium (b) and low canopy cover (c).

Table 5.3: Comparison between monthly predicted and measured transpiration for orchards with varying canopy cover. R^2 is the coefficient of determination, RMSE is the root of the mean square error, MAE is mean absolute error and N is the number of observations.

	Full canopy cover					**Medium canopy cover**					**Low (young) canopy cover**					
Month	**T_predicted (mm)**	**T_measured (mm)**	**R^2**	**RMSE (mm)**	**MAE (mm)**	**T_predicted (mm)**	**T_measured (mm)**	**R^2**	**RMSE (mm)**	**MAE (mm)**	**T_predicted (mm)**	**T_measured (mm)**	**R^2**	**RMSE (mm)**	**MAE (mm)**	**N**
October	47.61	59.22	0.52	14.35	11.61	25.13	38.43	0.43	17.32	13.30	5.01	11.37	-	7.25	6.36	4
November	90.88	89.78	0.37	9.74	8.33	51.92	53.11	0.68	9.71	8.78	15.03	26.71	0.77	12.43	11.68	4
December	116.18	107.66	0.36	14.36	10.96	62.69	61.21	0.55	13.81	12.21	22.23	34.87	0.75	12.65	12.64	4
January	118.01	107.57	0.41	15.68	10.45	61.19	57.88	0.72	10.12	8.43	23.62	33.09	0.80	10.30	9.48	4
February	92.29	92.31	0.62	8.49	7.95	56.68	53.40	0.94	4.94	4.23	21.01	23.83	0.83	4.14	2.94	4
March	82.33	85.57	0.12	8.19	7.00	51.60	54.25	0.93	6.05	5.53	18.65	18.77	0.69	4.34	3.78	4
April	59.62	63.22	0.64	6.72	5.96	36.76	39.66	0.61	10.35	7.20	15.49	14.24	0.68	2.49	2.47	4
May	39.03	45.71	0.12	13.96	11.85	28.63	30.95	0.44	9.43	6.72	9.69	11.46	0.72	2.72	2.33	4

5.3.4 Estimating orchard ET using improved crop coefficients

The eddy covariance energy balance closure varied with orchard canopy cover as illustrated for the mature high, medium and young low canopy cover orchards in Fig. 5.8 (a-c). These calculations were done using hourly data collected over two to three clear days. It is apparent that the closure ratio was higher for the mature (0.95) as compared to medium and young orchards with 0.73 and 0.79, respectively. These differences can be explained by, among other things, the more uniform vegetation cover in mature orchards while the orchard surface was more heterogeneous in medium and young orchards.

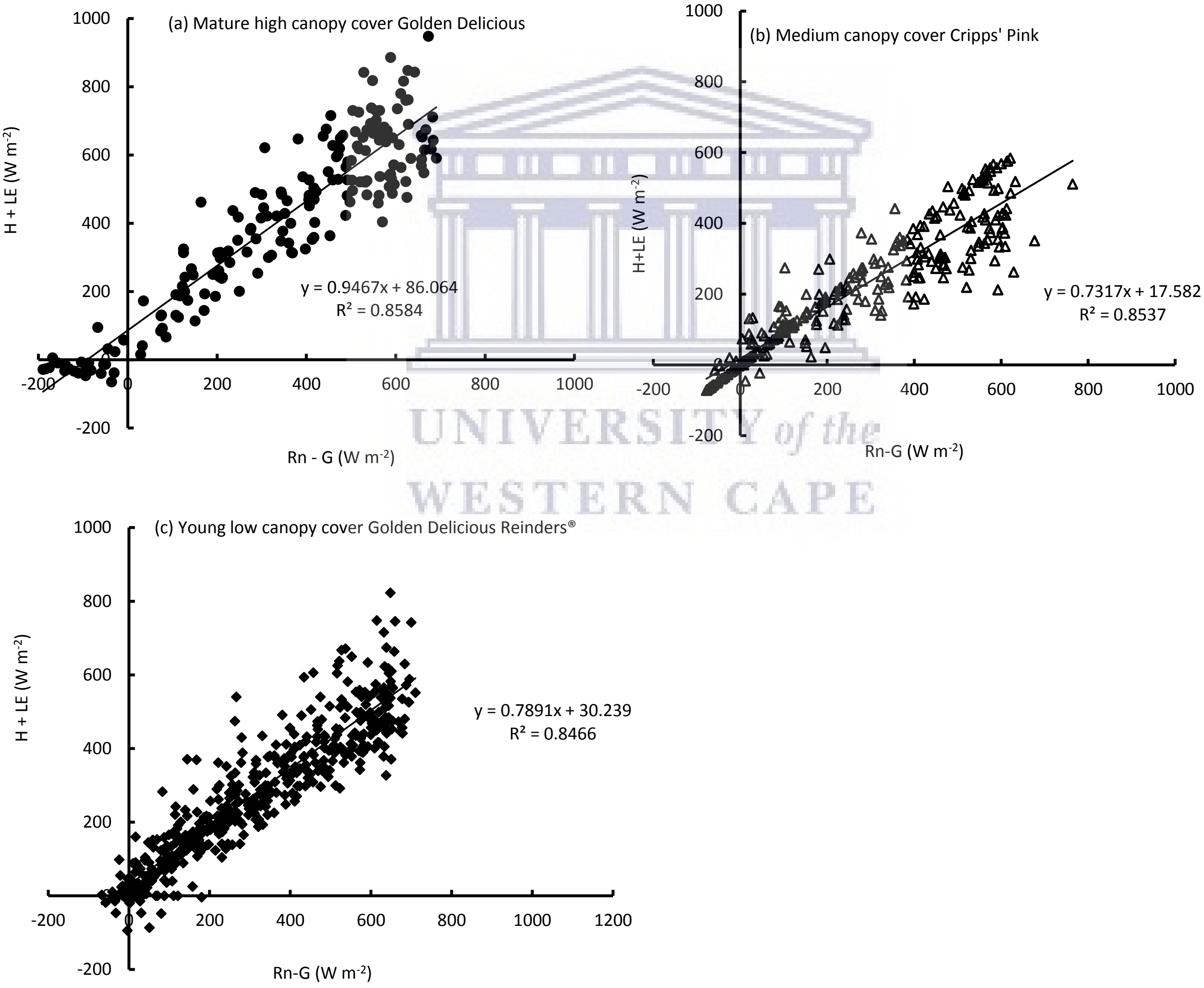

Fig. 5.8: Energy balance closure for (a) a mature full-bearing and (b) a medium intermediate bearing and (c) a young non-bearing apple orchard.

The crop coefficients (K_c) for all the orchards were fairly well predicted by the improved A&P method and Fig. 5.9 shows the data only for clear days. Cloudy days were excluded as these produced unrealistically high values due to the low reference evapotranspiration. For the first time, the contribution of the cover crop to the orchard K_c is also included in this analysis. As far as the author is aware, no studies have assessed the cover crop contribution, in detail, to the whole orchard crop coefficients. The average leaf area index of the cover crops (LAI_c) was about 0.24 which gave a density function (K_{dc}) of ~0.15 using equation 5.13. The daily total transpiration for a typical clear day in winter expressed over the full orchard surface was around 0.9 mm d^{-1} while the reference evapotranspiration was around 4.0 mm d^{-1}. This gave a full-cover K_{cb} for the cover crops of about 0.225 and an average $K_{cbcover}$ of approx. 0.034 as detailed in the methodology. The maximum observed leaf area index for the cover crops was around 1.0 and, following the above procedure, this gave a $K_{cbcover}$ of about 0.08. Therefore, the following cover crop threshold values were used for estimating the K_{cb} of microsprinkler irrigated apple orchards: i.e. $K_{cbcover} = 0$, for bare orchard floor ($LAI_c<0.1$); $K_{cbcover} = 0.03$ for moderate density cover crop ($0.1< LAI_c < 0.8$) which was the most common cover type, and $K_{cbcover} = 0.1$, for orchards with tall and density cover crops ($LAI_c \geq 0.8$).

The crop coefficients for the mature orchards in Fig 5.9 tended to be high because most of the ET data were collected when canopy cover had reached its maximum in summer (see Table 5.2). The larger spread of the K_c values in the young orchards is a result of the high ET observed early in the growing season when the orchards had dense cover crop and weeds while the atmospheric evaporative demand was still comparatively low.

Orchard ET, calculated as ET = K_c x ET_0 where K_c is the crop coefficients derived from the improved A&P method, closely matched the eddy covariance derived ET values in Fig. 5.10. The data shown in Fig 5.10 is for the three orchard classes (i.e. low, medium and high canopy cover) for days when the eddy covariance data were collected. The calculated orchard ET was within 10% of the eddy covariance measured values.

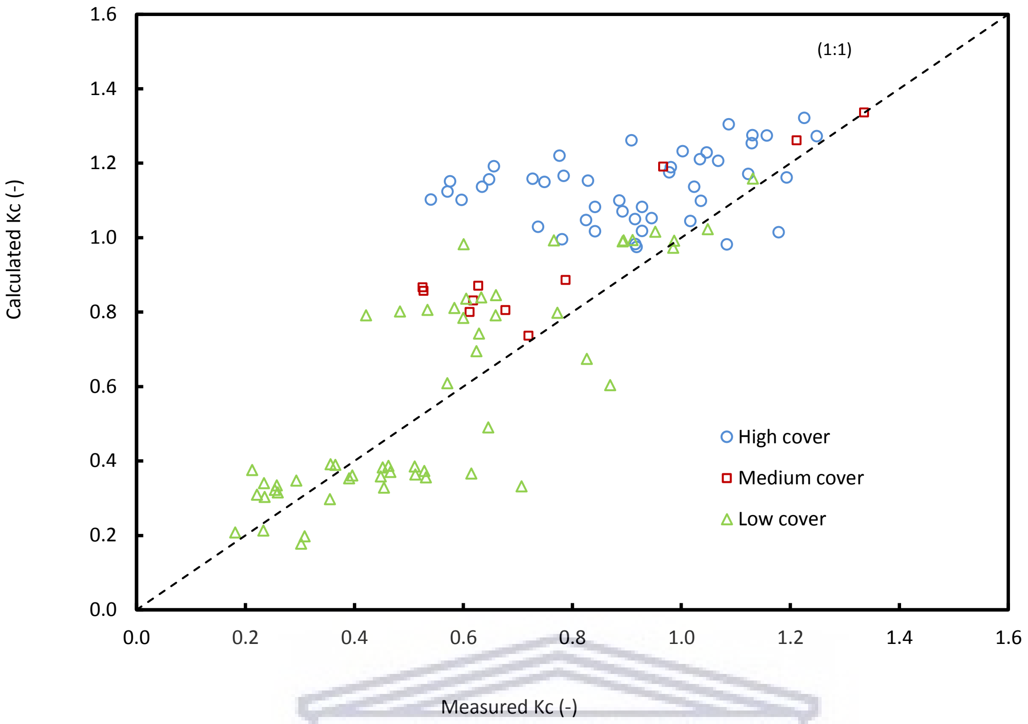

Fig. 5.9: Comparison of the crop coefficients determined with the improved A&P method with measured values for 12 apple orchards

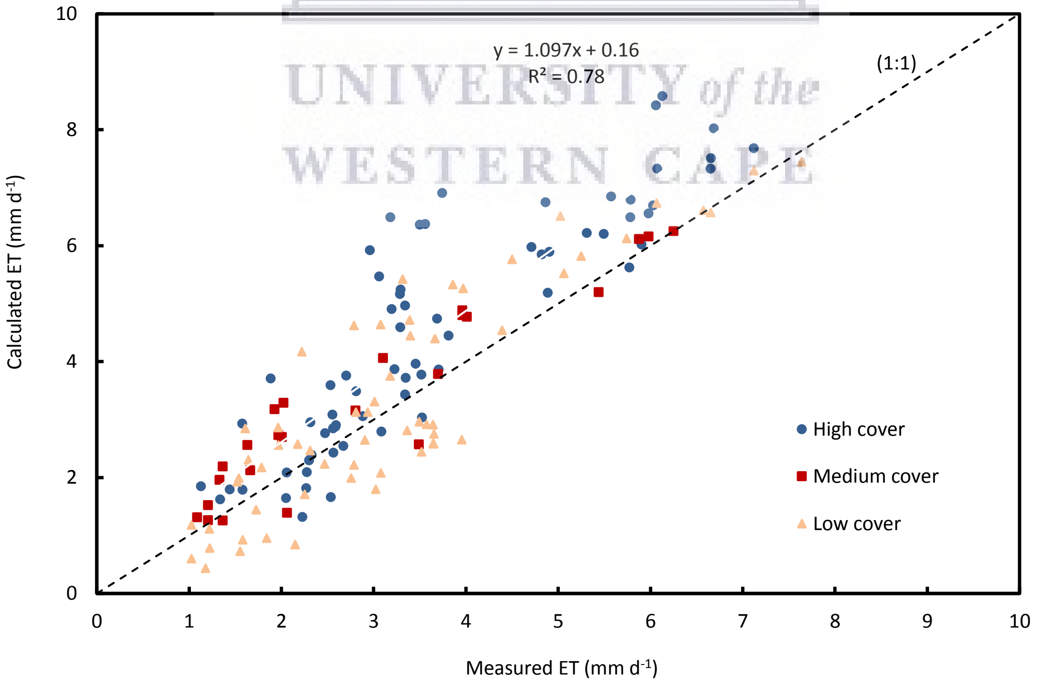

Fig. 5.10: Evapotranspiration predicted using the improved crop coefficients and measured by the eddy covariance system.

5.4 DISCUSSION

The FAO-56 crop coefficient approach for estimating crop water requirements under well-watered conditions is a standard approach that has been widely adopted and used for irrigation management, particularly irrigation scheduling (Girona et al., 2011; Volschenk, 2017; Gush et al., 2019). However, accurate estimates of crop water requirements with this method require accurate crop coefficients and this is the major limitation of the method as the published FAO crop coefficients are not readily transferable between fields and growing regions (Casa et al., 2000; Allen, 2000; Lascano, 2000). To address this challenge, Allen and Pereira (2009) have advanced the original FAO-56 approach by proposing a method whereby crop coefficients (K_{cb} and K_c) are estimated using readily available crops data such as the fraction of ground cover, and crop height.

This method has a very high potential for improving irrigation management through improved crop coefficients given the simple inputs that are required to calculate the K_c values. For this reason, the A&P method has been the subject of research interest and several studies have evaluated its performance, albeit with mixed results (Jiang et al., 2014; Taylor et al., 2015; Paço et al., 2019). For example, Jiang et al. (2014) applied the A&P method on maize in the Great Plains of China. They observed a close fit between the measured and calculated crop coefficients using the parameters published by Allen and Pereira (2009) for the maize crop. Observations from the present study indicate that the A&P method significantly over-estimates the crop coefficients for apple orchards under the Mediterranean-type growing conditions consistent with the conclusions by Taylor et al. (2015) on citrus orchards in South Africa. Taylor et al. (2015) however, proposed using a variable leaf resistance term in equation 5.9 instead of a fixed one to improve the K_{cb} estimates. This was a logical step given that citrus trees are known to have a very strong stomatal control of leaf gas exchange (Cohen and Cohen, 1983; Dzikiti et al., 2011). Taylor et al. (2015) noted a strongly linear relationship between the leaf resistance and the reference evapotranspiration. The leaf resistance for citrus had a much wider range than for apple trees varying from around 500 to close to 3 000 s m^{-1}. In contrast to citrus trees, the rl – ET_o relationship for apple trees was in fact non-linear as shown in Fig. 5.5 b. These data exclude instances when the orchards were experiencing water stress. The orchards were deemed to be under water stress when the midday stem water potential was lower than -2.0 MPa following Dzikiti et al. (2018a, b). With no water stress, the rl-ET_o relationship for apple trees suggests that the stomatal resistance increases sharply with the increasing atmospheric evaporative demand. This trend is due to the high sensitivity of apple trees to high vapor pressure deficits of the air (Gush et al., 2019).

Applying the rl - ET_o relationship to the A&P method as proposed by Taylor et al. (2015) also did not yield satisfactory results in this study likely because of the differences in the physiology of citrus and apple trees (data not shown). Apple trees have a narrower range of leaf resistance (100 – 515 s m^{-1}) than citrus which lead to a higher F_r ratio causing high K_{cb} values. In another study, but on olive trees in Portugal, Paço et al. (2019) also observed inconsistencies between the A&P crop coefficients and those determined from eddy covariance measurements. They also adjusted the F_r ratio, but by trial and error to obtain accurate crop coefficients which also agreed with the simulations by the SIMDualKc model (Paço et al., 2014). Our study however, provides a possible procedure for adjusting the F_r term objectively based on the physiology of the crop without resorting to trial and error.

The fact that Jiang et al. (2014) obtained satisfactory results on an annual crop (maize) using the A&P parameters as published, yet applications on three different perennial crops (citrus, olive, and apples) required adjustments for stomatal sensitivity suggests that there is need to differentiate between annual and perennial crops in the A&P approach. Here we demonstrate that using the rl for apple trees and replacing the leaf resistance of an annual crop (~100 s m^{-1}) with the canopy resistance of well-watered apple trees gave more realistic results for 12 orchards comprising different cultivars and canopy cover fractions. This observation is, to some extent, expected given the differences in the hydraulic properties of tree crops and annual crops which are dominated by non-woody species e.g. maize, mealies, wheat etc. Findings in this study support the use of an appropriate tree reference resistance in the A&P method for fruit trees rather than the grass reference (~100 s m^{-1}) being used for all crop types.

5.5 CONCLUSIONS

While the need for a method to derive accurate crop coefficients using readily available information is essential for precise water resources management, this study demonstrates that there is also a need for a detailed understanding of the physiology of the specific crops. Different crops regulate their stomatal aperture in different ways to regulate water use to balance CO_2 gain and transpiration losses. For apple trees in a semi-arid Mediterranean-type climate typical of the Western Cape Province of South Africa, replacing the standard annual crop resistance (= 100 s m^{-1}) with the unstressed canopy resistance for apple trees of 37 s m^{-1} gave more realistic estimates of crop coefficients for apple orchards. From our assessment, the input data requirements to accurately determine the K_c and K_{cb} values of crops using the improved A&P method include the fractional vegetation cover, tree height, average wind speed at 2.0 m, minimum relative humidity, and the bulk canopy resistance of the species concerned although we are yet to test this approach on other fruit tree species. However, the approach accurately predicted both the seasonal transpiration and daily evapotranspiration in 12 apple orchards under the Mediterranean climatic conditions in the Western Cape Province of South Africa. The contribution of the cover crops transpiration to the orchard crop coefficients appeared to be quite small. Accurate crop coefficient information can be incorporated into precision irrigation management decision support systems leading to significant water savings which are critical for the sustainability and growth of the fruit industry. While the A&P method is potentially useful for deriving crop coefficients, crop specific information is needed to improve accuracies.

CHAPTER 6: MODELLING WATER USE OF APPLE ORCHARDS USING THE DUAL SOURCE PRIESTLEY-TAYLOR JPL MODEL

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Summary

Accurate estimates of orchard evapotranspiration (ET) and its components are important for precise irrigation scheduling, irrigation system designs, and optimal on-farm water allocation particularly in water-limited environments. Direct measurements of ET remain costly, laborious and sometimes difficult to apply over heterogeneous surfaces such as crop fields. Therefore, accurate crop water-use models are required for precise on-farm water resources management. In this study, we adopted and improved the Priestley-Taylor Jet Propulsion Laboratory (PT-JPL) model developed by Fisher et al 2008 to estimate crop water use across different apple plants. Specifically, the model was developed to quantify the partitioning of apple orchard water use into beneficial (tree transpiration) and non-beneficial water use (orchard floor evaporation) as influenced by tree canopy cover. Data were collected in twelve orchards spread across key apple producing regions in the Western Cape Province of South Africa over three growing seasons (2014/15, 2015/16, 2016/17). Model ET estimates were tested against ET data measured; using the eddy covariance method and transpiration measured based on sap flow monitoring techniques. The results showed that the original Fisher PT-JPL model performed poorly in ET estimation across all the orchards under study. The original model yielded lower R^2, ranging from 0.02 to 0.64 and Nash-Sutcliffe Efficiency (NSE) from -10.93 to 0.20. Thus, we subsequently improved the model by incorporating soil moisture and vapour pressure deficit stress factors and by introducing a variable Priestley and Taylor coefficient (α). The modified PT-JPL model demonstrated an improvement in ET estimates. The RMSE of the estimated daily ET varied from ±0.60 mm d^{-1} to ±1.99 mm d^{-1} whereas the MAE varied from ±0.49 mm d^{-1} to ±1.91 mm d^{-1}, while the R^2 varied from 0.54 to 0.75 in orchards with varying canopy cover. The findings of this work underscore the utility of the modified PT-JPL model for estimating ET and its components in apple orchards from planting until the trees reach full-bearing age.

6.1 INTRODUCTION

In South Africa, like other dry parts of the world, irrigated agriculture is widely practiced. Water resources in such regions are scarce; but the demand by agricultural, domestic, and industrial users is increasing drastically (Dehghanisani et al., 2006). Currently, irrigated agriculture uses more than 60% of the surface water resources in semi-arid countries such as South Africa, Australia and Spain (NWRS-2, 2013, Smith and Consulting, 2014 and Expósito and Berbel, 2017). In South Africa, mainly in the Eastern and Western Cape Provinces of the country up to 94% of the apple fruit are produced under irrigation (Hortgro, 2018). In view of the growing population and global climate change and variability, which are likely to cause increasing incidences of droughts in most semi-arid regions, it is expected that irrigation demand will increase in the near future (Midgley and Lotze, 2011). There therefore, is a need to identify and adopt effective irrigation management strategies that increase the water productivity, i.e. producing more fruit per unit volume of water used (Gush et al., 2019).

In recent years, methods and tools needed to improve management of actual water use by crops in irrigated agriculture have significantly increased providing useful insights on plant water use patterns (Koech and Langat, 2018). So far, plant water use can be measured using a range of methods. These include:1) soil water balance methods (Gong et al., 2007), 2) lysimetry (Mpelasoka et al., 2001), 3) eddy covariance (Ouyang et al., 2013), 4) Bowen ratio energy balance (Zanotelli et al., 2019), 5) scintillometry, 6) sap flow methods (Fernández., 2017), 7) remote sensing energy balance (Odi-Lara et al., 2016), and 8) satellite based evapotranspiration (ET) estimates using vegetation indices (Liou and Kar, 2014). However, the drawback of all these methods is that they are expensive and computationally complex. For example, they require unique technical expertise and a considerable dedication of time and effort (Elfarkh et al., 2020). Given the practical limitations of these methods, the development of simple but robust and operational models for estimating water use is required. These will aid farmers with sustainable utilization and management of limited water resources, especially in arid and semi-arid regions.

To date, a number of models have been developed and are presently used to estimate actual water use in fruit trees. Examples include the Soil Water Balance

(SWB) model (Annandale et al., 2003; Volschenk et al., 2003), the big leaf Penman-Monteith type model (e.g., Rana et al., 2005; Dragoni and Lakso, 2011), dual source Shuttleworth and Wallace type models (e.g., Allen et al., 1998; Li et al., 2010; Ortega-Farias et al., 2012; Dzikiti et al., 2018a) and models using remote sensing data (Odi-Lara et al., 2016). Given the heterogeneity that characterises orchard environments comprising trees in rows, bare ground, cover crops, and at times the mulch, dual source models provide more accurate ET estimates. These models partition ET into transpiration (T) and substrate/orchard floor evaporation (E_s) components (Kool et al., 2014; Dzikiti et al., 2018a). However, many of these models require parameters which are not easy to obtain such as the aerodynamic and stomatal resistances, and these can be sources of uncertainty.

To address this, we modified the PT-JPL model developed by Fisher et al. (2008), which avoids the calculation of both the aerodynamic and surface resistances. The accuracy of this method depends mainly on the biophysical multipliers or stress factors that scale potential ET to actual ET, using a minimum amount of meteorological data and vegetation parameters (Aragon et al., 2018). The PT-JPL model has intensively been used for estimating ET worldwide and has been successfully applied over a wide range of biomes that included croplands, deciduous broadleaf forests, evergreen needle leaf forests, and grasslands, mixed forests, savannas and open shrub-lands (Zhang et al., 2017; Shao et al., 2019; Yang et al., 2019) but its application and performance in orchards remains undocumented. The results from these studies showed moderate to strong relationships between observed and actual ET estimated using the PT-JPL (García et al., 2013; Ding et al., 2013; Zhang et al., 2017; Moyano et al., 2018; Shao et al., 2019, Dzikiti et al., 2019; Gomis-Cebolla et al., 2019). This information therefore indicated that this model can be useful where detailed meteorological data are not available.

The goal of this present work was to parameterize and evaluate the utility and the performance of the PT-JPL model in twelve apple orchards with varying canopy sizes ranging from young low canopy to mature high canopy cover orchards in the Western Cape Province of South Africa. To our knowledge, this model has not widely applied to crop fields and its performance in orchards of varying canopy cover characteristics remains unknown. The main objectives of this study were: (1) to apply the original PT-JPL model as published in apple orchards with varying fractional canopy cover and different cultivars, and (2) to re-parameterize and improve the PT-JPL model applied to row irrigated tree crops such as fruit orchards in semi-arid regions.

6.2 MATERIALS AND METHODS

To evaluate and validate the performance of the PT-JPL model across orchards with varying attributes (canopy cover and cultivar), *in-situ* data were collected from 12 commercial apple orchards over three growing seasons 2014/15, 2015/16 and 2016/17. The orchards were situated in two prime apple-producing regions in the Western Cape. Geographical map showing the locations of 12 orchards within the Western Cape is given in sub-section 4.2.1 (Fig 4.1).

During the first and second growing seasons, data were collected in eight orchards, which included four mature orchards (with effective canopy cover of about 0.65) and four young non-bearing orchards (with low canopy cover of between 0.14 and 0.26) planted to the Golden Delicious/Reinders® and Cripps' Pink/ Cripps' Red/ Rosy Glow cultivars. Data were collected in four orchards in KBV during the 2014/15 season and a further four orchards in EGVV during the 2015/16 growing season. In the 2016/17 season, measurements were taken in two orchards in each production region with medium fractional canopy cover ranging from 0.26 to 0.37 planted to the same cultivars. A detailed description of the study sites is given in sub-section 4.2.1.

6.2.1 Data collection

6.2.1.1 Transpiration, evapotranspiration and weather data

Actual evapotranspiration (ET) was measured using an open-path eddy covariance (EC) system that was deployed in each orchard during specific window periods to measure the latent and sensible heat fluxes. Details regarding the instrumentation, data processing and deployment periods is described in sub-section 5.2.2. Orchard microclimate was measured using automatic weather stations installed in an open space with uniform grass close to each orchard (Fig 4.2).

6.2.1.2 Soil water content

In each orchard, seasonal dynamics of the soil water content were monitored continuously at different depths in the root zone and beyond (~150 to 800 mm) (see sub-section 4.2.5). Three to 30-time-domain reflectometer probes (Model: CS616, Campbell Sci. Inc., Logan, UT, USA) connected to dataloggers (Model: CR1000, Campbell Scientific, Inc., Logan UT, USA) were used to measure the soil water content and all the outputs were sampled every 60 min.

6.2.1.3 Satellite data

Since the PT-JPL model requires the normalized difference vegetation index (NDVI) and fractional vegetation cover as input parameters, Landsat and Sentinel images with less than 10% cloud cover were downloaded from the USGS Earth Explorer data portal (https://earthexplorer.usgs.gov/) website for the three growing seasons. Landsat images were only used for one growing season (2014/15) in the KBV region since Sentinel 2 was launched in June 2015. The images were atmospherically corrected using the Dark Object Subtraction (DOS1) model under Semi-Automated Classification (SCP) embedded in Quantum Geographic Information system (QGIS) 3.4.10 software (https://gisenglish.geojamal.com/2019/11/download-qgis-310-coruna-nov-2019.html). All image bands were converted from digital number values to reflectance. The NDVI values can range from -1.0 to 1.0, where NDVI close to 1 indicates dense green vegetation cover and a value close to 0 no vegetation, possibly urban areas and negative values mainly result from water.

The NDVI was calculated as:

$$NDVI = \frac{NIR - RED}{NIR + RED} \tag{6.1}$$

where NIR and RED are the reflectance of near infrared and red wavebands, respectively. A description of the spectral bands that make up Sentinel 2 and Landsat 8 are shown in Table 6.1. For Sentinel, Band 8 and band 4 were used whereas for Landsat, bands 5 and 4 were used.

Table 6.1: Corresponding Landsat-8 and Sentinel-2 bands and characteristics considered in this study.

Landsat 8			**Sentinel 2**		
Band	**Wavelength (µm)**	**Resolution (m)**	**Band**	**Wavelength (µm)**	**Resolution (m)**
Band 2 – Blue	0.45 – 0.51	30	Band 2 – Blue	0.46 – 0.52	10
Band 3 – Green	0.53 – 0.59	30	Band 3 – Green	0.54 – 0.58	10
Band 4 – Red	0.64 – 0.67	30	Band 4 – Red	0.65 – 0.68	10
Band 5 – NIR	0.85 – 0.88	30	Band 8 – NIR	0.79 – 0.90	10
			Band 8A – vegetation red edge	0.85 – 0.87	20
Band 6 – SWIR 1	1.57 – 1.65	30	Band 11 – SWIR 1	1.57 – 1.66	20
Band 7 – SWIR 2	2.11 – 2.29	30	Band 12 - SWIR 2	2.10 – 2.28	20

NIR = Near infrared and SWIR = Shortwave infrared

6.2.2 Modelling water use of apple orchards with the PT-JPL model

The daily ET and its components were modelled using the PT-JPL model. The accuracy of this model mainly depends on accurate determination of eco-physiological constraint functions to downscale potential ET to actual evapotranspiration. A detailed description of the original PT-JPL model is provided in Fisher et al. (2008). Here the focus is on changes that improved the performance of the model in apple orchards with varying canopy cover. The latent heat flux (λE, in W m^{-2}) was calculated as:

$$\lambda E = \lambda E_c + \lambda E_s \tag{6.2}$$

where, λEc (W m^{-2}) is the energy equivalent of canopy transpiration and λEs (W m^{-2}) is the energy for soil evaporation. For this particular study, the evaporation from a wet canopy surface was not considered, as this did not improve the model given that we were dealing with micro-sprinkler irrigated crops. In addition, we demonstrate that ET estimation and its constituent components (T and E$_S$) can be significantly improved over the original model performance which was based on recommended (Fisher et al., 2008) eco-physiological stress factors and parameters for orchards of all age groups as will be discussed in detail in the results section.

It is known that water use from apple orchards is highly sensitive to soil water deficit and the vapour pressure deficit of the air (VPD) (Dzikiti et al., 2018a; Lo Bianco, 2019). Therefore, we tried to improve the model by introducing two stress factors; one for soil moisture (f_{SM}) and the other for vapour pressure deficit of the air (f_{VPD}). We also replaced the general Priestley and Taylor (P-T) coefficient (often taken as ~1.26) by adopting a variable coefficient as described by Tanner and Jury (1976). This approach partitions the P-T coefficient into the soil evaporation (α_s) and canopy transpiration coefficients (α_c), respectively under energy-limited conditions. A number of studies have shown that the general P-T coefficient is not constant over the entire growing season. It however, varies greatly with crop type, soil moisture availability and climatic conditions (Pereira et al., 2007; Lei and Yang, 2010). Soil evaporation (α_s) and canopy transpiration (α_c) coefficients were then calculated according to Agam et al. (2010) as:

$$\propto_s = \begin{cases} 1 & for\ \tau \le \tau_0 \\ \alpha - \frac{(\alpha-1)(1-\tau)}{1-\tau_0} & for\ \tau > \tau_0 \end{cases} \tag{6.3}$$

$$\alpha_c = \frac{(\alpha - \alpha_s \tau)}{(1-\tau)} \tag{6.4}$$

where, α is the P-T coefficient under energy-limited conditions with a full canopy cover, taken as 1.26, τ_0 is a critical value of τ at which canopy cover is sufficient, which ranges between 0.20-0.50 and τ is the fraction of net radiation transmission reaching the soil surface, calculated based on the Beer-Lambert's law as:

$$\tau = \exp(-k_{Rn} \times LAI) \tag{6.5}$$

where, k_{Rn} is the extinction coefficient for net radiation, which was taken as a constant with a value of 0.6 (Li et al., 2010) and LAI is the leaf area index which was calculated as:

$$LAI = (-\ln(1 - f_{IPAR})/k_{PAR}) \tag{6.6}$$

where, k_{PAR} is the extinction coefficient for photosynthetically active radiation with a value of 0.5 and f_{IPAR} is the fraction of the photosynthetically active radiation ($IPAR$) intercepted by the canopy calculated as: $f_{IPAR} = NDVI - 0.05$ (Ershadi et al., 2014).

The canopy transpiration was estimated, using four physiological constraints/ stress factors considered to regulate potential transpiration.

$$\lambda E_c = f_g\, f_T\, f_{SM}\, f_{VPD}\, \alpha_C \frac{\Delta}{\Delta + \gamma}(R_n - R_{ns}) \tag{6.7}$$

where, f_g is the green canopy fraction, f_T is the plant temperature constraint, f_{SM} is the soil moisture constraint, f_{VPD} is the vapour pressure deficit (VPD) constraint, α_c is the modified canopy transpiration P-T coefficient, Δ is the slope of the saturated vapour pressure versus air temperature curve (kPa $^oC^{-1}$), γ is the psychrometric constant (kPa $^oC^{-1}$), R_n is the net radiation (W m^{-2}) incident at the top of the canopies and R_{ns} (W m^{-2}) is the net radiation that reaches the soil surface which was calculated following Beer's law:

$$Rn_s = \left(R_n \exp\left(-k_{Rn} LAI\right)\right) \tag{6.8}$$

The soil evaporation component was then calculated as:

$$\lambda E_s = f_{SM} \alpha_s \frac{\Delta}{\Delta + \gamma}\left(R_{ns} - G\right) \tag{6.9}$$

where, α_s is the modified soil evaporation P-T coefficient and G is the soil heat flux (W m^{-2}). The eco-physiological constraint functions which are used as a proxy for plant and water stress are given by the following (Ershadi et al., 2014):

$$f_g = \frac{f_{APAR}}{f_{IPAR}} \tag{6.10}$$

$$f_T = \exp\left(-\left(\frac{T_{\max} - T_{opt}}{T_{opt}}\right)^2\right) \tag{6.11}$$

$$f_{SM} = \left(\frac{SWC - SWC_{\min}}{SWC_{\max} - SWC_{\min}}\right)^{\beta} \tag{6.12}$$

$$f_{VPD} = \exp\left(-k_{vpd} \times VPD\right) \tag{6.13}$$

where, f_{APAR} is the fraction of the photosynthetically active radiation absorbed PAR calculated as: $f_{APAR} = m_1 \times NDVI + b_1$ where, m_1, b_1, β and k_{vpd} are parameters obtained by model optimization (Table 6.2), $T_{\max}$ is the daily maximum temperature at which stomata close (in °C), T_{opt} is the optimum temperature for the growth of apple trees (in °C), SWC is the average daily volumetric soil water content (cm^3 cm^{-3}) measured using the CS616 soil moisture probes, $SWC_{\min}$ is the volumetric soil water content at the permanent wilting point and $SWC_{\max}$ is the volumetric soil water content at the field capacity.

Table 6.2: Model parameters used in estimating Priestley-Taylor Jet Propulsion Laboratory model daily biophysical constraints, plant variables and energy variables applied to high, medium and low canopy cover orchards.

Parameter	**Description**	**Values**	**References**
αPT	Priestly and Taylor coefficient	1.26	Priestley and Taylor, 1972
β		1	Fisher e al., 2008
$b1$		1.2*-0.04	Fisher e al., 2008
$b2$		-0.05	Fisher e al., 2008
$m1$		1.2*1.136	Fisher e al., 2008
$m2$		1.0	Fisher e al., 2008
τ_0	Critical value of τ at which canopy cover is sufficient	0.20-0.50	Agam et al., 2010
k_{vpd}		0.20	This study
k_{PAR}	Extinction coefficient for photosynthetically active radiation	0.50	Fisher et al., 2008
k_{Rn}	Extinction coefficient for net radiation	0.60	Li et al., 2010
T_{opt}	Optimum temperature for plant growth	25 °C	Fisher et al., 2008

6.2.3 Assessment of model performance

Daily values of measured, estimated actual ET, and its component (T) were compared using linear regression analysis. Root mean square error (RMSE), mean absolute error (MAE), and Nash-Sutcliffe efficiency (NSE) were used to evaluate the model's performance (see equations 5.21 - 5.23).

6.3 RESULTS

6.3.1 Time series of NDVI

The NDVI has been used widely to study the relation between spectral variability and the changes in vegetation growth rate. It is also used as a proxy for vegetation greenness as well as to detect vegetation changes. The time series of the monthly NDVI values in apple orchards with varying canopy cover are depicted in Fig. 6.1 a-b. Mature high canopy orchards had the highest NDVI values, followed by medium canopy cover orchards and young low canopy cover orchards had the lowest values. As shown in Fig. 6.1a, the highest NDVI values in mature orchards were found when the trees reached full canopy and the values ranged between 0.64 and 0.74 with the average orchard LAI of ~ 3.4. The young low canopy cover orchards had lower NDVI values than either the medium and mature orchards, with values ranging from 0.38 to 0.51.

6.3.2 Measured vs original PT-JPL modelled ET

The original Fisher PT-JPL model has been widely tested and validated to estimate actual crop ET and its components over a range of crops and ecosystems. In this study simulations were ran first with the original model and compared the model predictions with the measured eddy covariance ET flux data for orchards with high, medium and low canopy cover. Figure 6.2 (a-c) shows the correlations between the flux tower and modelled ET performance for selected window periods when actual ET data was collected, and Table 6.3 highlights the model performance.

The regression analysis showed a poor linear relationship between simulated and measured daily ET for all the orchards. The coefficient of determination (R^2) ranged between 0.21 and 0.35, NSE was -1.55, -1.19 and 0.20 for mature high, medium and young low canopy covers, respectively. The NSE values were significantly less than zero and not closer to one for all the orchards suggesting poor performance of the model. Similar results were observed for the remaining four orchards that had sufficient ET data points (see Table 6.3).

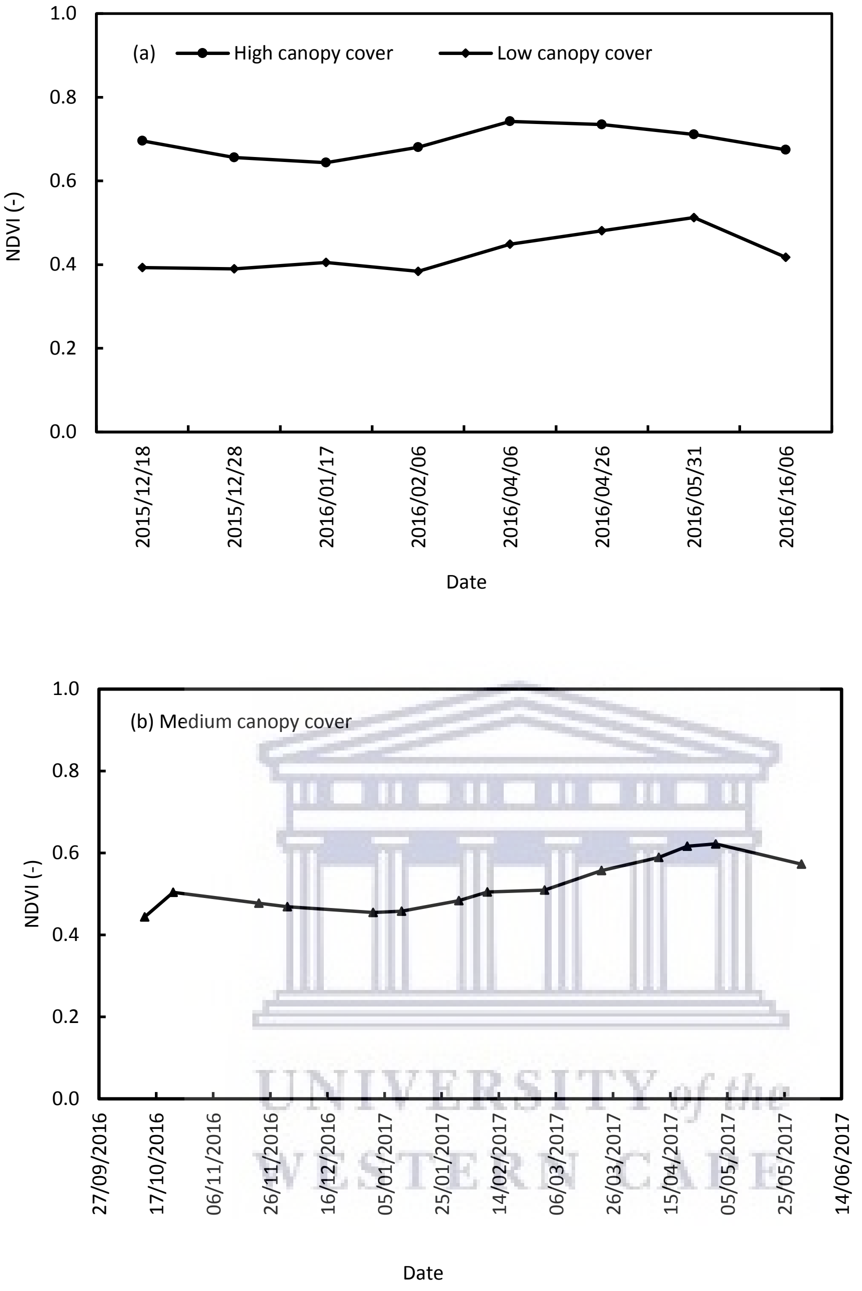

Fig. 6.1: Time series of normalised difference vegetation index (NDVI) values of apple orchards with a) high and low, b) medium canopy covers.

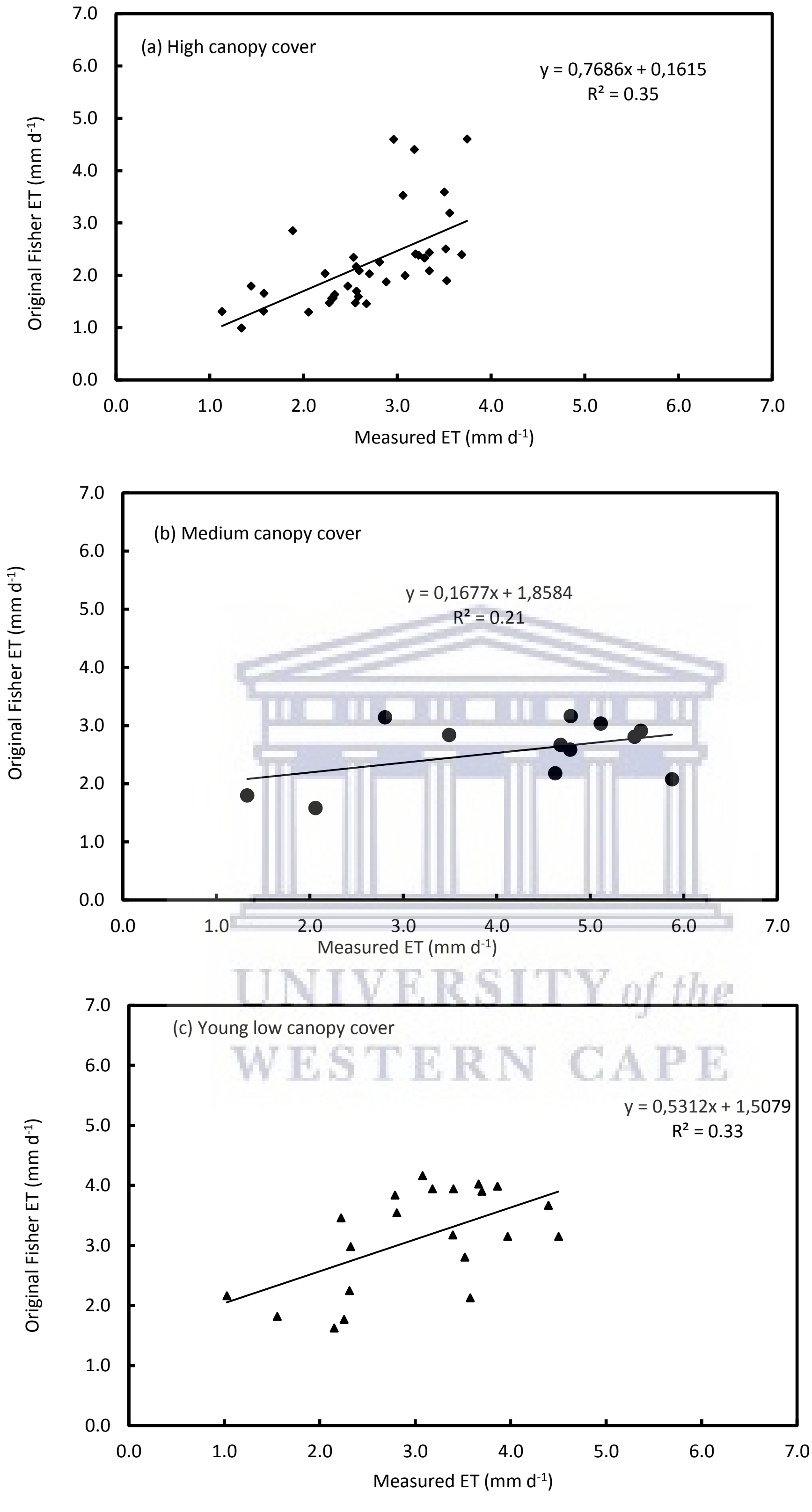

Fig. 6.2: Relationships between the daily measured evapotranspiration (ET) using the eddy covariance system and estimated by the original Fisher Priestley–Taylor Jet Propulsion Laboratory (PT-JPL) model in apple orchards with (a) high and (b) medium and (c) low canopy covers..

Table 6.3: Summary statistics for the performance of the original Fisher and modified PT-JPL model for predicting evapotranspiration at sites in KBV and EGVV during the 2014/15, 2015/16 and 2016/17 growing seasons.

Season	**Region**	**Orchard name**	**PT-JPL Original Fisher**					**Modified PT-JPL**					
			Slope	**R^2**	**NSE**	**RMSE (mm d^{-1})**	**MAE (mm d^{-1})**	**Slope**	**R^2**	**NSE**	**RMSE (mm d^{-1})**	**MAE (mm d^{-1})**	**N**
2014/15	KBV	FBGD	-	-	-	-	-	-	-	-	-	-	-
		FBCP	-	-	-	-	-	-	-	-	-	-	-
		NBGD	-0.12	0.02	-1.80	3.47	3.40	0.84	0.54	0.17	1.48	1.30	34
		NBRG	-	-	-	-	-	-	-	-	-	-	-
2015/16	EGVV	FBGD	-0.12	0.11	-5.25	3.41	2.96	0.58	0.75	0.41	1.07	0.91	28
		FBCP	0.77	0.35	-1.55	1.01	0.94	1.20	0.55	0.42	0.60	0.49	29
		NBGR	0.42	0.29	0.22	0.76	0.60	0.92	0.71	0.50	0.64	0.57	19
		NBCR	-	-	-	-	-	-	-	-	-	-	-
2016/17	KBV	BGD	1.34	0.65	-0.31	0.70	0.59	1.21	0.67	0.12	1.09	1.00	14
		BCP	0.28	0.96	-10.93	3.24	3.17	0.43	0.67	0.08	1.99	1.91	6
	EGVV	BGD	-	-	-	-	-	-	-	-	-	-	-
		BCP	0.17	0.21	-1.19	2.07	1.78	0.72	0.57	0.35	0.63	0.54	16

FBGD=Full-bearing Golden Delicious, FBCP= Full bearing Cripps' Pink, BGD= Bearing Golden Delicious Reinders®, BCP= Bearing Cripps' Pink, NBGD=Non-bearing Golden Delicious Reinders®, NBRG= Non-bearing Rosy Glow, NBCR=Non-bearing Cripps' Red.

6.3.3 Modified canopy transpiration and soil evaporation P-T coefficient

Figure 6.3a & b, presents the variation of the modified canopy transpiration and soil evaporation P-T coefficient for orchards with varying age groups**.** It is evident from results that the modified P-T coefficient differed greatly from the general value of 1.26. The ranges of the modified canopy transpiration P-T coefficient values were 1.33–1.39, 1.41–1.58, and 1.48–1.58 for the mature high canopy, medium canopy, and young low canopy cover orchards, respectively. For the soil evaporation, the P-T coefficient was highest under the young low canopy cover orchards, followed by the medium and then the mature high canopy cover orchards. The magnitude of both the canopy transpiration and soil evaporation P-T coefficients were mainly driven by the direct effect of LAI. Therefore, it can be deduced from the study that the smaller the fractional cover (LAI), the higher the soil evaporation and canopy transpiration P-T coefficient. Using the modified P-T coefficient and stress factors led to improved estimates of ET and its components for all the 12 orchards.

6.3.4 Performance of the improved PT-JPL model

The modified PT-JPL model predicted the daily transpiration rates for the entire season reasonably well except in May and June when the trees were reaching the senescence stage (Fig. 6.4). Typical examples for three orchards with high, medium and low canopy cover are shown in Fig.6.4 a–c. The trends in the other orchards were similar to those shown in Fig. 6.4 and statistical comparisons of the model estimates against measured transpiration data are shown in Table 6.4. Daily transpiration in mature high canopy cover orchard was reasonably predicted by the modified PT-JPL model throughout the growing season with an R^2 model of 0.78. The root mean square error was low at ±0.66 mm d^{-1} while the mean absolute error (MAE) was only ±0.50 mm d^{-1} and the Nash-Sutcliffe efficiency (NSE) was 0.65 (Table 6.4). Model predictions of transpiration in medium canopy cover orchards were also reasonable with overestimation and underestimation at the start and end of the growing season, respectively. The root mean square and mean absolute errors were ±0.46 and ±0.35 mm d^{-1}, respectively (Table 6.4). The modelled vs measured transpiration in the young low canopy cover orchards was quite reasonable, although the scatter tended to be larger (Fig. 6.4c). Reasons for the low predictive ability of the model in young orchards are not clear. The R^2 of modelled and measured T values was 0.56, and the RMSE was ±0.29 mm d^{-1}.

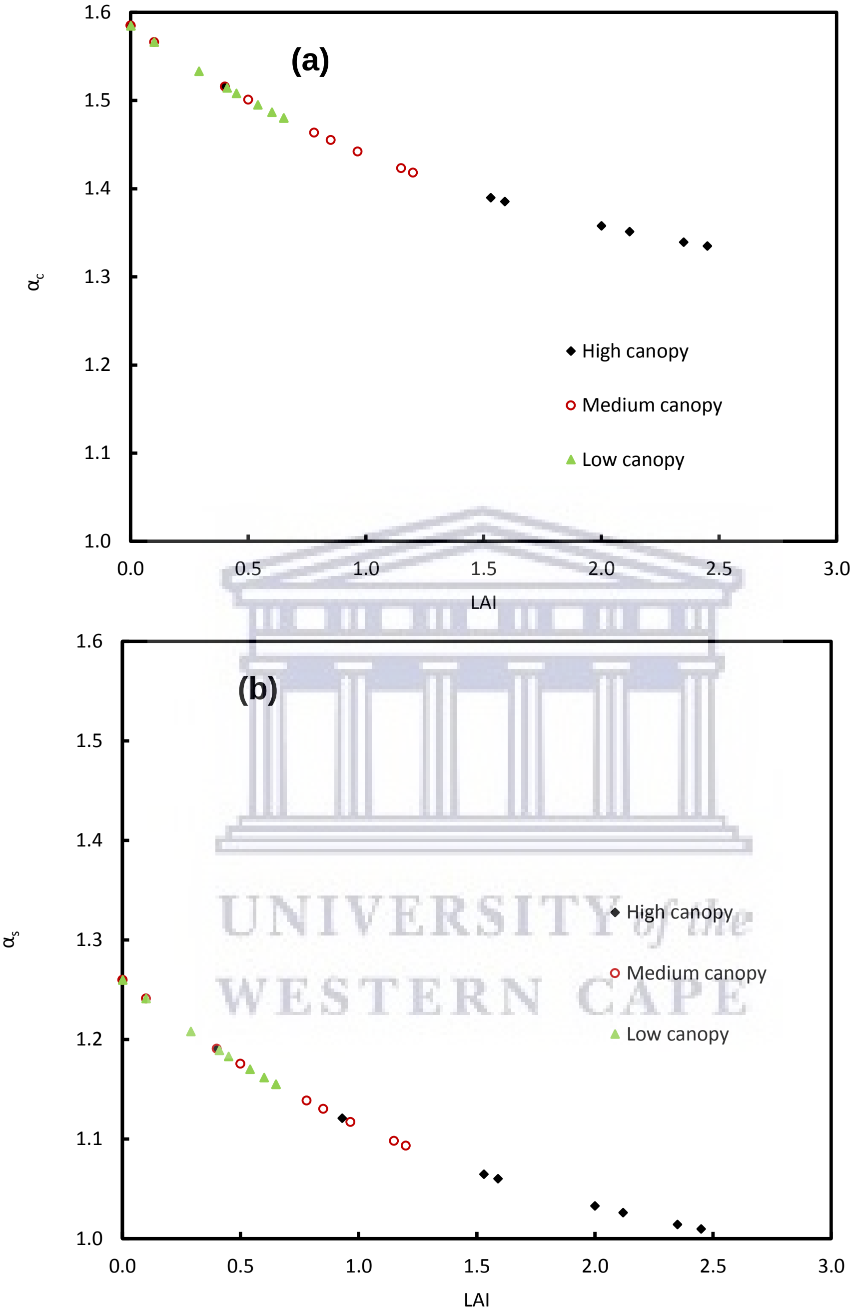

Fig. 6.3: Relationships between modified (a) canopy transpiration (α_c) and (b) soil evaporation (α_s) Priestley and Taylor coefficients, and leaf area index (LAI) for apple orchards with varying canopy cover.

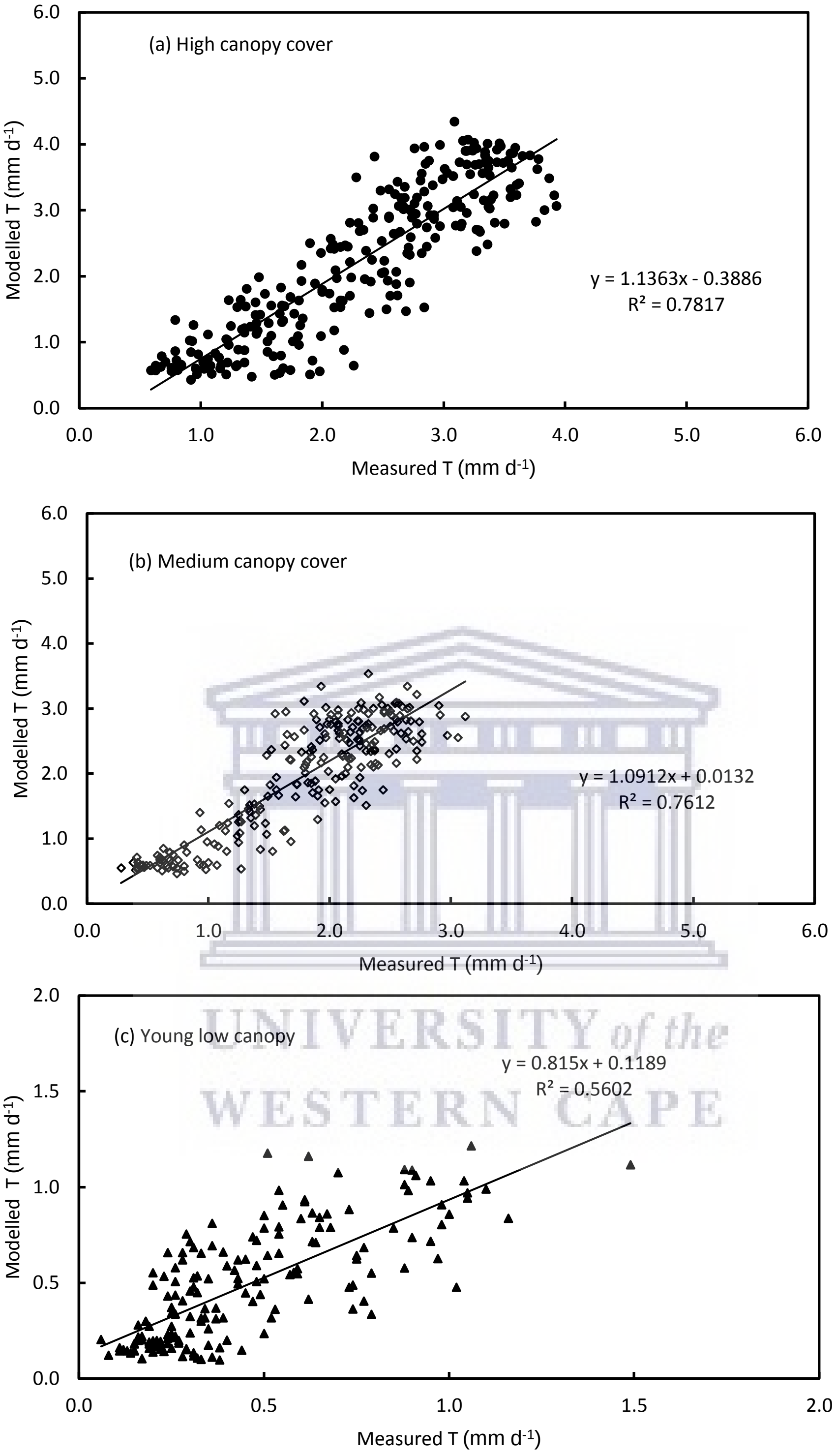

Fig. 6.4: Comparisons between the measured and modelled daily transpiration (T) over the entire growing season in (a) high, (b) medium and (c) low canopy cover.

Table 6.4: Summary statistics for the performance of the original Fisher and modified PT-JPL model for predicting transpiration at sites in KBV and EGVV during the 2014/15, 2015/16 and 2016/17 growing seasons.

Season	**Region**	**Orchard name**											
					PT-JPL Original Fisher					**Modified PT-JPL**			
			Slope	**R^2**	**NSE**	**RMSE (mm d^{-1})**	**MAE (mm d^{-1})**	**Slope**	**R^2**	**NSE**	**RMSE (mm d^{-1})**	**MAE (mm d^{-1})**	**N**
2014/15	KBV	FBGD	1.26	0.70	0.38	0.63	0.52	1.01	0.84	0.54	0.73	0.62	189
		FBCP	1.42	0.35	-0.35	0.74	0.58	1.10	0.66	0.42	0.50	0.40	120
		NBGD	1.73	0.55	-4.63	0.84	0.69	0.98	0.64	0.51	0.25	0.19	191
		NBRG	0.84	0.43	0.39	0.34	0.26	0.94	0.65	0.41	0.28	0.22	141
2015/16	EGVV	FBGD	1.00	0.74	0.50	0.80	0.63	0.91	0.81	0.65	0.66	0.50	274
		FBCP	1.14	0.78	0.50	0.63	0.54	1.13	0.81	0.61	0.55	0.44	266
		NBGR	1.33	0.57	-0.84	0.47	0.38	0.89	0.73	0.35	0.29	0.23	197
		NBCR	2.07	0.20	-5.19	0.59	0.45	0.39	0.71	0.16	0.32	0.26	258
2016/17	KBV	BGD	0.85	0.56	0.34	0.52	0.43	1.05	0.62	0.27	0.55	0.45	264
		BCP	0.72	0.33	-1.42	0.82	0.70	1.09	0.63	0.20	0.42	0.35	127
	EGVV	BGD	1.98	0.62	-4.01	0.69	0.53	0.80	0.73	0.63	0.29	0.24	134
		BCP	1.12	0.76	0.66	0.39	0.30	1.09	0.80	0.55	0.46	0.35	251

FBGD=Full-bearing Golden Delicious, FBCP= Full bearing Cripps' Pink, BGD= Bearing Golden Delicious Reinders®, BCP= Bearing Cripps' Pink, NBGD=Non-bearing Golden Delicious Reinders®, NBRG= Non-bearing Rosy Glow, NBCR=Non-bearing Cripps' Red

6.3.5 Evapotranspiration partitioning

The seasonal dynamics of ET and its components in high, medium and low canopy cover orchards are shown in Figs 6.5 a-c. The modelled daily ET and its components showed that orchard floor evaporation dominated ET at the beginning of the season in all orchards. However, the rapid increase in leaf area after bud break resulted in transpiration being almost double the orchard floor evaporation in November and this trend persisted throughout the season for mature high canopy orchards (Fig 6.5a). Tree transpiration contributed 75% to ET in mature orchards. In young low canopy cover orchards, however, orchard floor evaporation was higher than tree transpiration throughout the growing season (Fig. 6.5c). The high evaporation from the orchard floor was a result of the relatively small canopy cover (peak LAI ~ 1.0) even in the summer season when the canopy size was at its maximum. The evaporation from the canopy and orchard floors accounted for 22% and 78%, respectively, of the total ET (Fig. 6.5c). Lastly, in the medium canopy cover orchards the contribution of the orchard floor evaporation and transpiration to ET were almost equal throughout the growing season (Fig. 6.5b). In terms of the percentage of each component, transpiration contributed 59% of the ET whilst, 41% came from the soil evaporation.

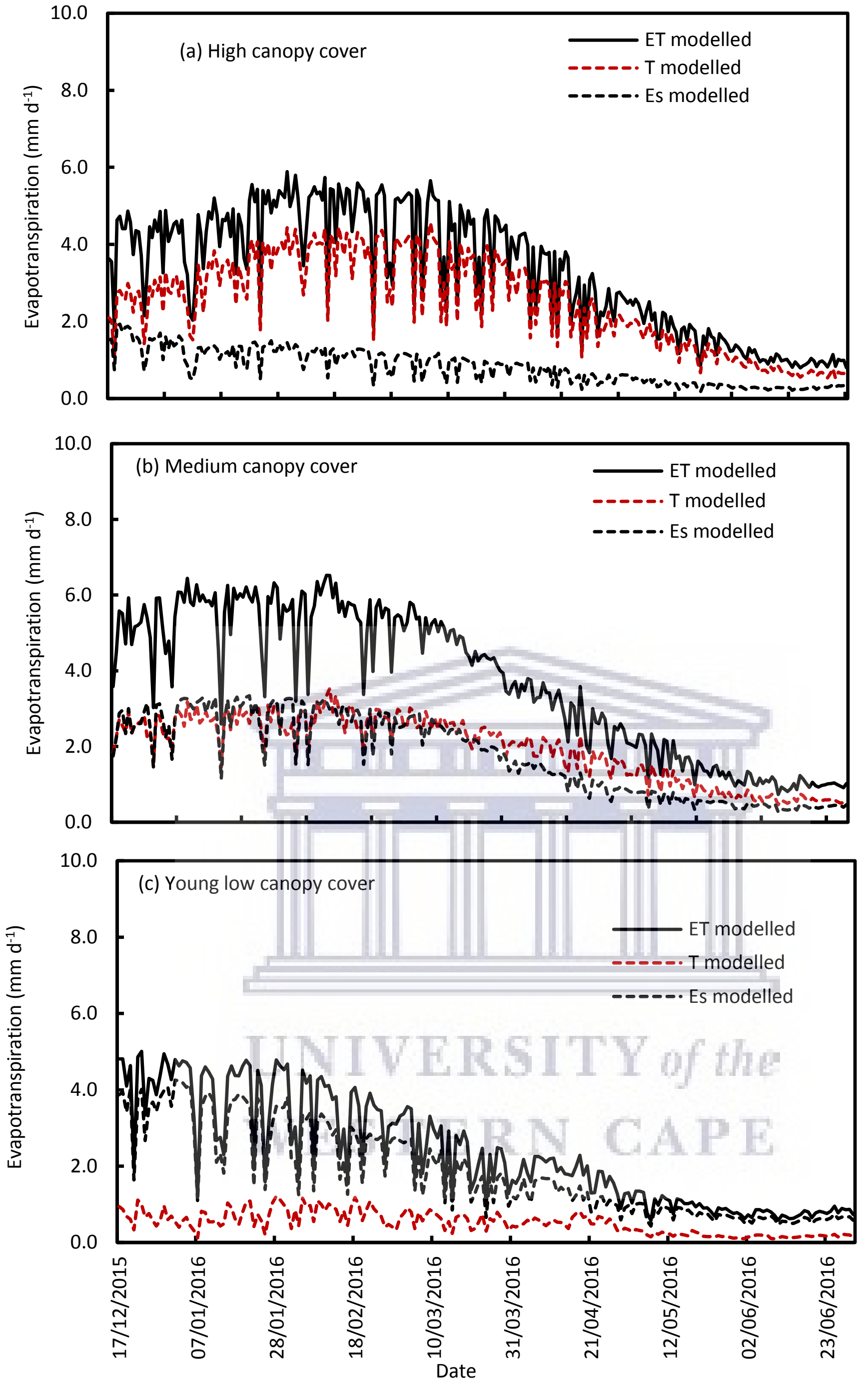

Fig. 6.5: Modelled daily evapotranspiration (ET) and its components, transpiration (T), and orchard floor evaporation (Es) for: (a) high, and; (b) medium and (c) low canopy cover compared with the measured ET from the eddy covariance system.

6.4 DISCUSSION

Evapotranspiration generally represents the greatest loss of water from irrigated orchards in semi-arid regions and it is sensitive to changes in the cover of vegetation (Wang and Wang, 2017). Accurate estimates of orchard ET and its components are important for precise irrigation scheduling, irrigation system designs, and optimal on-farm water allocation. This information is particularly important in countries like South Africa where the frequency and severity of droughts is increasing in the major fruit producing regions (Volschenk, 2017). In these regions, models relying on readily available data are valuable given the lack of direct measurements of orchard water use. In this study, we for the first time, adopted, improved and applied the dual source PT-JPL model that requires few inputs data (Fisher et al., 2008) to twelve irrigated apple orchards in a semi-arid environment. To date the model has mainly been validated in natural ecosystems (e.g., García et al., 2013; Zhang et al., 2017; Purdy et al., 2018; Shao et al., 2019; Dzikiti et al., 2019). Few studies have applied the model in crop fields possibly because of the remote sensing nature of the original model that used course spatial resolution satellite imagery. In this study, we used high resolution Sentinel and Landsat images to study the performance of the model in orchards ranging in size from about 3.0 to 6.5 ha. In addition, we also investigated, in detail, the influence of orchard canopy cover on the performance of the model under irrigated conditions.

This study highlights that, for irrigated crops that are sensitive to soil water deficit and to the atmospheric vapour pressure deficit, constraint factors for these stressors should be included for optimal model performance. Besides the present study, Purdy et al. (2018) also investigated the incorporation of soil moisture to constrain soil evaporation and canopy transpiration in the PT-JPL model but in a natural ecosystem. In that study, they used soil moisture data derived from Soil Moisture Active Passive Mission (SMAP) to model ET. The modified model showed reduced errors and increased explanation of variance with the greatest improvements in water limited natural ecosystems. García et al. (2013) also modified the model by working out the soil moisture constraint relying on the concept of apparent thermal inertia (ATI) computed with remotely sensed surface temperature and albedo observations. The modified model yielded satisfactory ET estimates on an open woody savanna in the Sahel and a Mediterranean grassland in the arid regions.

Although a number of studies have showed that the constant Priestley and Taylor coefficient of 1.26 gives accurate ET estimates on some vegetation types (Pereira, 2004; Utset et al., 2004), the present study showed that a variable coefficient was required for orchards with different canopy cover. This is consistent with the findings from other researchers (e.g., Pereira et al., 2007; Agam et al., 2010; Ding et al., 2013; Qiu et al., 2019) that indicated that α had a large variation over the whole growing season, especially for daily time scales. The main reported factors affecting α include mulching method, green canopy fraction, air temperature, soil moisture availability, relative humidity, etc. (Ding et al., 2013; Yao et al., 2013; Ershadi et al., 2014; Ai and Yang, 2016). In this study the P-T coefficient was not constant, it varied with the size of canopy cover for apple orchards, with α_s and α_c values relatively larger in young open canopy orchards (LAI ~ 1.0) as compared to mature high canopy orchards (LAI ~ 3.0). These results suggest that the modified PT-JPL model could accurately estimate evapotranspiration of irrigated apple orchard from planting until they reach full-bearing age in the semi-arid region of Western Cape on a daily time scale.

6.5 CONCLUSIONS

An accurate estimate of ET is essential especially in semi-arid regions where there is limited amount of water being competed for by different users. Different ET models of varying complexities and data input requirements are available, and their applicability in different climatic regions and scales is consistently under scrutiny. In this study, we adopted, modified and applied PT-JPL evapotranspiration model in orchards with varying canopy cover. Our findings showed that the modified PT-JPL model performance was 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 were most reliable, but uncertainties are higher with the orchard ET estimates given the difficulties to accurately model the orchard floor evaporation fluxes. It appears that there was a significant loss of water from the orchard floor in medium and young low canopy cover orchards amounting close to 43 and 78% of the orchard ET, respectively. There is therefore a need to reduce the orchard floor losses especially given the increasing frequency of droughts that will put further strain on the already limited water resources.

CHAPTER 7: GENERAL CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

The water use rates of fruit tree species are highly variable and affected by several factors including changes in weather and orchard management practices. In this study the water use rates of two apple cultivars with varying canopy cover under semi-arid conditions were measured to test some of the models used to estimate water use in these orchards. This information is important as growers need a better understanding of how much and to what extent irrigated water is transpired by crops in order improve the management of increasingly limited water resources worldwide.

The first chapter focused investigated the water use rates of two cultivars grown in pots. This was done to understand how the cultivar type influenced the transpiration dynamics of apple trees. The results show that water use rates were not influenced by cultivar type. Daily average water uptake of well-watered apple tree calculated based on sap flow measurement ranged between 1.0 to 2.0 l day^{-1} tree^{-1} for the Golden Delicious cultivar and 1.0 to 3.0 l day^{-1} tree^{-1} for the Cripps' Red cultivar. There was substantial utilization of water stored in the stems for both cultivars. The stored water was used primarily in the morning to replace transpiration losses and was subsequently replaced by water uptake from the soil during the remainder of the day and at night.

Chapter 4 investigated the water use of 12 apple orchards with varying canopy cover over three growing seasons in two production regions in the Western Cape, South Africa. While both regions are located in the winter rainfall area, they do have some differences in their microclimate. The findings showed that canopy cover rather cultivar type had an effect on the transpiration dynamics (sap flux density, transpiration per unit leaf area and whole orchard transpiration) for all twelve measured orchards. Mature high canopy cover orchards had the highest water use rates followed by medium canopy cover orchards, and young low canopy cover orchards. Although the type of cultivar did not have a significant effect on the transpiration dynamics, mature high canopy Golden Delicious cultivar orchards had the highest water use rates in both production regions compared to the Cripps' Pink cultivar. Therefore, canopy management is critical for water saving. This can be done by pruning and spraying shoot growth retardants such as Regalis® especially for red cultivars. This is done to expose the fruit to solar radiation for anthocyanin synthesis to occur and promote the development of the red fruit colour. For the Golden Delicious/Reinders® orchards, the trees can be grown under shade nets and maintained with open canopies on dwarfing rootstocks, since the fruit is susceptible to sunburn. Thus, the hypothesis that different apple cultivars respond differently to environmental factors causing variations in water use and productivity was rejected in this study. The study also showed that plant based midday xylem water potential was a good predictor of water stress in orchards with varying canopy cover. However, this was not monitored throughout the growing season as this is laborious and time consuming. Therefore, two transpiration reduction coefficients, one based on sap flow (K_{sf}) and the other based on soil water depletion (K_S) (FAO-56 Penman-Monteith approach) were evaluated against the midday xylem water potential in all the orchards to provide a continuous indication of water stress throughout the growing season. The sap flow derived stress coefficient (K_{sf}) was strongly correlated to the midday xylem water potential in all the orchards and was able to detect plant stress.

Chapter 5 aimed to improve the Allen and Pereira (2009) method of estimating crop coefficients. This approach uses readily available information such as the fractional vegetation cover and tree height to estimated K_{cb} and K_c. The method was evaluated in 12 apple orchards with varying canopy cover using actual measured field data over a range of fractional canopy cover, cultivars, and microclimates. Crop coefficients are known to vary widely between fields even for the same crop type due to a range of factors. These include the fractional vegetation cover, size of the wetted area, orchard management practices, e.g. cover crops, mulching. Because each orchard requires unique values of crop coefficients, it was important to adopt this approach to accurately estimate the K_{cb} and K_c taking into account the conditions of each specific orchard. The results showed that there were significant errors in both the K_{cb} and K_c estimates which are consistent with results obtained in other studies. Acceptable agreement between measured and estimated K_{cb} and K_c was achieved by adjusting the ratio rl /100 in the transpiration reduction function (F_r) given by Allen and Pereira (2009). The annual crop resistance value (= 100 s m^{-1})

recommended by Allen and Pereira (2009) was replaced with unstressed canopy resistance for apple trees of 37 s m^{-1} estimated using measured stomatal conductance data. Following this modification, the estimated K_{cb} and K_c values were able to match the K_{cb} and K_c values determined from sap flow and eddy covariance measurements over 12 orchards. This approach also provided acceptable seasonal estimates of transpiration and evapotranspiration. Thus the improvement made can be used for irrigation planning and water allocation in apple fruit tree orchards.

In Chapter 6 a dual-source (PT-JPL) evapotranspiration model was adopted and modified to estimate the water use rates of 12 apple orchards with varying canopy cover. Dual-source ET models take into account tree transpiration and soil evaporation from under the canopy and between the tree rows. The modified PT-JPL model simulated ET well when compared with the observed values based on eddy covariance method, as indicated by the coefficient of determination which varied from 0.54 to 0.75 for apple orchards with varying fractional cover. The estimation errors were small with RMSE varying from ±0.60 mm/d to ±1.99 mm/d, while MAE varied from ±0.49 mm/d to ±1.91 mm/d. The predicted transpiration rates matched the observed values quite well. The results showed that soil evaporation was an important component of ET at the beginning of the growing season for all orchards. However, when the trees started developing foliage, soil evaporation became minimal and tree transpiration was the main component of ET especially in mature orchards with high and medium canopy covers. The study has shown that the quantification of the components of ET is important in designing management strategies for improving water use efficiency of irrigated apple orchards.

7.2 RECOMMENDATIONS FOR FUTURE RESEARCH

Due to lack of adequate knowledge on the water use of apple tree in South Africa, this study has provided an improved understanding of how water use rates of apple cultivars with varying fractional cover differ. This was achieved by measuring the water use during three years in 12 apple orchards in two production regions. The data were subsequently used to parameterize and validate some models for estimating orchard water use. The canopy size rather than cultivar type was the main driver of water use rates in apple orchards from planting to full-bearing age.

Therefore, canopy management is critical to achieving water savings. Further studies are recommended in summer rainfall regions where weather parameters are different from the Western Cape Province, to come up with a clearer picture of how the water use of these orchards differs in order to save limited water resources. The study for this thesis was conducted in well-watered and not water-stressed apple trees. Thus, there is a need for similar studies for apple orchards grown under water-stressed conditions.

Given that water use rates were higher in mature Golden Delicious orchards than mature Cripps' Pink which had small and more open canopies, options to improve water use of Golden Delicious orchards include:

1. growing 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 to reduce canopy cover and to lower water use rates.

The FAO-56 crop coefficient proposed by Allen and Pereira (2009) as suggested in this study may be able to assist famers in planning irrigation effectively throughout the season. This would prevent orchards from being under or over irrigated and farmers will avoid water wastage mainly due to leakages. Although this approach gave accurate estimates of crop coefficients and water use after some improvements, validation studies should be conducted in other apple growing regions. Emphasis should be placed on adjusting the ratio rl /100 in the transpiration reduction function (F_r) as this can introduce significant uncertainties in the crop coefficients and water use estimates.

Lastly, this study adopted and improved a dual ET model for the purposes of scaling up the results of the present study to other apple growing regions. Although the overall performance of the model was satisfactory, further calibration and validation in a wide range of growing conditions to improve its accuracy is still needed.

It was observed from this study that evaporation from the orchard floor was fairly high in orchards with medium and low canopy cover, approaching 43 and 70%, respectively. Therefore, it will be ideal to reduce orchard floor evaporation e.g., through:

1. using shorter range micros, conventional or sub-surface drip in medium and low canopy cover young orchards;
2. using mulching to reduce soil evaporation;
3. 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.

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APPENDIX A.

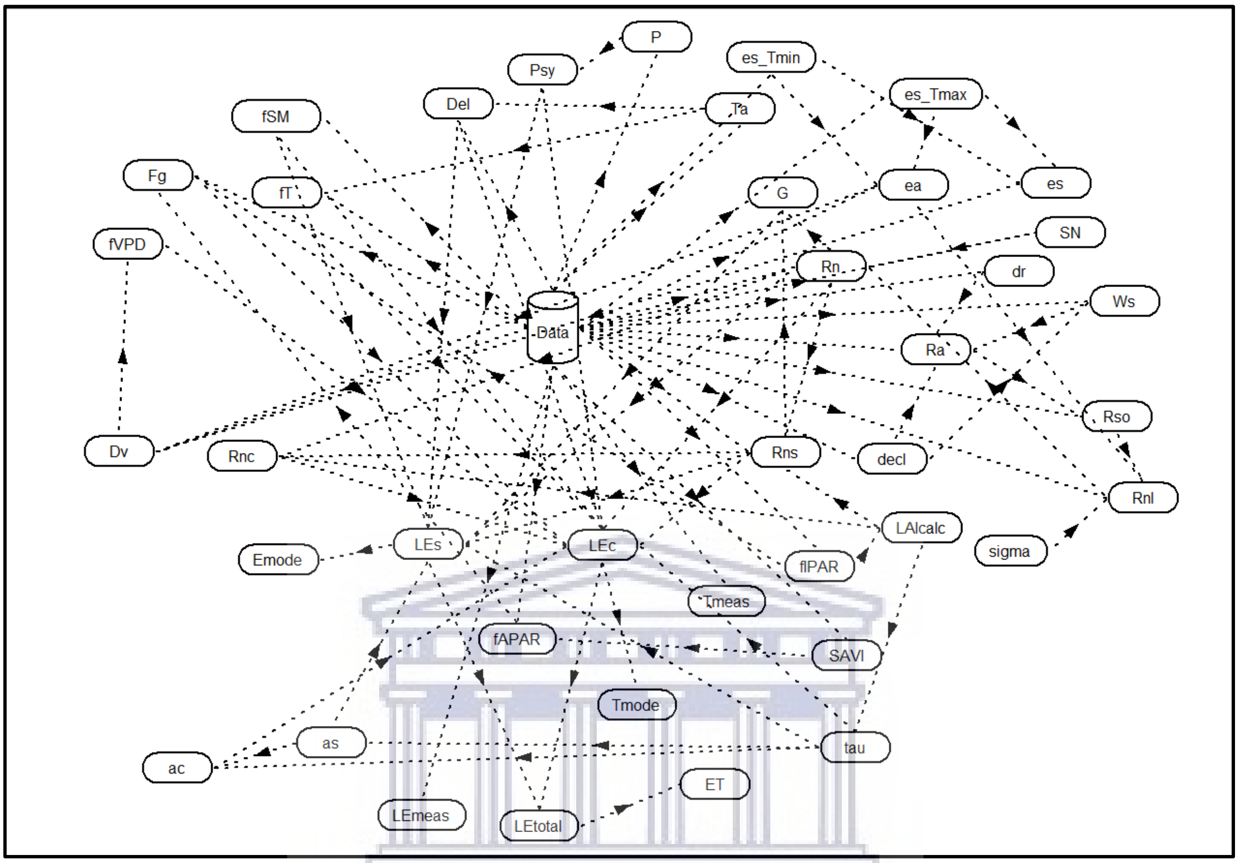

Fig A1. Structure of the modified PT-JPL model in the ModelMaker software.

APPENDIX B. MODEL DESCRIPTION

Main

ac Unconditional

ac = (Alpha-as*tau)/(1-tau)

Alpha 1.26 0

as Conditional

as =

1 for tau<=tau0

Alpha-((Alpha-1)*(1-tau))/(1-tau0) by default

b1 -0.048 0

b2 -0.02 0

Beta 1 0

decl Unconditional

Solar declination (in radians)

decl = 0.409*sin(2*pi*DOY/365-1.39)

Del Unconditional

Slope of saturation vapour pressure curve

Del = 4098*(0.6108*exp((17.27*Ta)/(Ta+237.3)))/(Ta+237.3)^2*1000

dr Unconditional

Relative earth-sun distance

dr = 1+0.033*cos(2*pi*DOY/365)

Dv Unconditional

kPa

Dv = (es-ea)

ea Unconditional

Daily mean actual vapour pressure in kPa

ea = (es_Tmin*RHmax/100+es_Tmax*RHmin/100)/2

Emode Unconditional

modelled soil evaporation

Emode = LEs/2.45

es Unconditional

Daily average saturation vapor pressure (in kPa)

es = (es_Tmax+es_Tmin)/2

es_Tmax Unconditional

Saturation vapor pressure at minimum air temperature (kPa)

es_Tmax = 0.6108*exp((17.27*Tmax)/(Tmax+237.3))

es_Tmin Unconditional

Saturation vapor pressure at minimum air temperature (kPa)

es_Tmin = 0.6108*exp((17.27*Tmin)/(Tmin+237.3))

ET Unconditional

Evapotranspiration (mm/d)

ET = LEtotal/2.45

fAPAR Unconditional

PAR fraction absorbed by green vegetation

fAPAR = m1*NDVI+b1

Fg Conditional

fractional vegetation cover

Fg =

1 for fAPAR/fIPAR>1

fAPAR/fIPAR by default

fIPAR Unconditional

fraction of PAR intercepted by total vegetation cover

fIPAR = m2*NDVI+b2

fSM Conditional

Soil moisture stress factor

fSM =

1 for (SWC-SWCmin)/(SWCmax-SWCmin)^0.6>1

(SWC-SWCmin)/(SWCmax-SWCmin)^0.6 by default

fT Conditional

Plant temperature constrait

fT =

1 for exp(-(Tmax-Topt)/(Topt)^2)>1

exp(-(Tmax-Topt)/(Topt)^2) by default

fVPD Unconditional

fVPD = exp(-kvpd*Dv)

G Unconditional

Soil heat flux (W m-2)

G = 0.01*Rns

Gsc	0.082	0
kPAR	0.5	0
kRn	0.6	0
kVPD	0.2	0

Data

t Control

Sd Controlled by: t

Linear interpolation

Tmax Controlled by: t

Linear interpolation

Tmin Controlled by: t

Linear interpolation

RHmax Controlled by: t

Linear interpolation

RHmin Controlled by: t

Linear interpolation

RH_ave Controlled by: t

Linear interpolation

VPD Controlled by: t

Linear interpolation

Albedo Controlled by: t

Linear interpolation

SWC Controlled by: t

Linear interpolation

SWCmax Controlled by: t

Linear interpolation

SWCmin Controlled by: t

Linear interpolation

NDVI Controlled by: t

Linear interpolation

DOY Controlled by: t

Linear interpolation

Lat Controlled by: t

Linear interpolation

Elev Controlled by: t

Linear interpolation

LEm Controlled by: t

Linear interpolation

Tm Controlled by: t

Linear interpolation

LAIcalc Unconditional

Leaf area index

LAIcalc = -ln((1-fIPAR))/kPAR

LEc Conditional

Transpiration

LEc =

0 for ac*Fg*Ft*Fsm*fVPD*Del/(Del+Psy)*(Rn-Rns)<0

ac*Fg*Ft*Fsm*fVPD*Del/(Del+Psy)*(Rn-Rns) by default

LEmeas Unconditional

Measured evaporanspiration (W/m2)

LEmeas = LEm

LEs Conditional

Bare soil evaporaion

LEs =

0 for as*Del/(Del+Psy)*(Rns-G)<0

as*Del/(Del+Psy)*(Rns-G) by default

LEtotal Conditional

Latent heat of vaporization

LEtotal =

0 for LEc+LEs<0

LEs+LEc by default

m1   1.3632   0

m2   1   0

P Unconditional

Atmospheric pressure

P = 101.3*((293-0.0065*elev)/293)^5.26

pi   3.142   0

Psy Unconditional

Psychrometric contant

Psy = 0.665*10^-3*P*1000

Ra Unconditional

extra terrestrial radiation

Ra = 24*60*Gsc/pi*dr*(Ws*sin(lat*pi/180)*sin(decl)+cos(lat*pi/180)*cos(decl)*sin(Ws))

Rn Unconditional

Net radiation (MJ m-2/d)

Rn = SN-Rnl

Rnc Unconditional

Net radiation for canopy (W m-2)

Rnc = Rn*(1-exp(-kRn*LAIcalc))

Rnl Unconditional

Net longwave radiation (MJ/m2/d)

Rnl = sigma*((Tmax+273)^4+(Tmin+273)^4)/2*(0.34-0.14*sqrt(ea))*(1.35*Sd/Rso-0.35)

Rns Unconditional

Net radiation to the soil

Rns = Rn*exp(-kRn*LAIcalc)

Rso Unconditional

Clear sky radiation (in MJ/m2/d)

Rso = (0.75+2*10^-5*elev)*Ra

SAVI Unconditional

SAVI = NDVI*0.45+0.132

sigma Unconditional

Stefan-Boltzmann constant (in MJ/K-4/m2/d) sigma = 4.903*10^-9

SN Unconditional

Daily net shortwave radiation (MJ/m2/d)

SN = Sd*(1-albedo)

Ta Unconditional

Average air temp (deg C)

Ta = (Tmax+Tmin)/2

tau Unconditional

tau = exp(-kRn*LAIcalc)

tau0   0.2   0

Tmeas Unconditional

Measured Transpiration (W/m2)

Tmeas = Tm

Tmode Unconditional

Transpiration

Tmode = LEc/2.45

Topt   25   0

Ws Unconditional

Sun hour angle (in radians)

Ws = arccos(-tan(lat*pi/180)*tan(decl))