UNIVERSITY of the
WESTERN CAPE

The partitioning of evapotranspiration in apple orchards from planting until full-bearing age and implications for water resources management

By

Zanele Ntshidi

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy in the Department of Earth Science, University of the Western Cape

October 2021

Supervisors:

Prof. D. Mazvimavi
Dr S. Dzikiti

DECLARATION

I declare that '***The partitioning of evapotranspiration in apple orchards from planting until full-bearing age and implications for water resources management'*** is my own work, that it has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

Zanele Ntshidi

Full name

Signature

14 October 2021

Date

DEDICATION

I would like to dedicate this thesis to my late mother, Nolitha Mavis Ntshidi, whose resilience, love and thirst for knowledge gave me the strength when I needed it the most. Her love for education and always encouraging us to empower ourselves with education is what we shall pass on to future generations. She was still alive when I started working on this thesis and its completion comes exactly four years after her passing. When I told her that I would be pursuing this degree she assured me that if anyone can do this, it's certainly me. When times got tough, her faith in my abilities kept me going, *enkosi Ntombi ka nomMhini, Qhubeka uphumle ngoxolo*. I will always hold your name high and say it with pride wherever I go. You were such a strong force that moulded me to be the person that I am today, your prayers sustain me till this day, all glory to God. Thank you for being resilient, yet always approaching every life situation with kindness, love, and respect. You were a force to be reckoned with, the epitome of a nurturer, and a true definition of '*imbokodo*'. You are missed every day and will never be forgotten Ma*Gangatha, MaMbiko, MaBhala, Mlom' unesibhamu, MaKhathula (C'Khathu weethu) sasiingayini na uba wawungazange ubekho!*

May this work also be a source of inspiration for anyone in my family that still needs to go through school, my children, nephews, nieces, and even younger siblings!

ACKNOWLEDGEMENTS

"*Ask and it shall be given*" …Matthew 7:7. All glory be to the sovereign Lord. Throughout this journey, I constantly prayed for strength and progress with belief that the Lord would grant it. Reaching this level is the manifestation that "*His promises are Yes and Amen*" 2 Corinthians 1:20. I am forever grateful for the ability invested in me and the spirit of never giving up. It is not by my wisdom, but it is by the grace of God that is sufficient for me!

To my supervisors Prof D. Mazvimavi and Dr S. Dzikiti, thank you for your encouragement, and your patience with me. Thank you for endlessly keeping your doors open for discussions and your many kind words of wisdom, that helped me persevere till this thesis took the shape we all envisioned from the onset. I am forever grateful to you gentlemen, this world is a better place with leaders like you, *tatenda!*

A word of gratitude to all the different farmers that allowed us to conduct experiments in their farms, making all this work possible, thank you for allowing us into your space. To the Council for Scientific and Industrial Research (CSIR), thank you for all the funds and all the opportunities since undergrad; I literally grew up at CSIR as a young researcher. National Research Foundation (NRF), Department of Science and Technology (DST), Water Research Commission (project no. WRC K5 2394//4), CSIR Young Researcher Establishment Fund (YREF), thank you for all the funding that helped in the running of this project. I am grateful to the Agricultural Research Council (ARC) and South African Weather Services (SAWS) for always availing weather data whenever our systems failed!

To my colleague Dr N.T Mobe, thank you for the words of encouragement, for all the field work, the data analysis, the publications, the works. Most importantly thank you for the sisterhood, even being involved in detail such as choosing map colours with me, thank you for being there, research is so much bearable when you are around; *kea leboga ausi*!

To my siblings, Ncumisa, Vuyokazi and Noluvuyo, thank you for always believing in me and encouraging me to be the best version of myself, thank you for all the support. To my husband JKas and beautiful daughter Lunje, thank you for always keeping each other company and letting me be busy with my schoolwork. For organizing play dates away from me so that you can leave me to do my work, even though you wished I joined you. *Merci pour tout le soutien, cette thèse n'aurait jamais été possible sans votre soutien et vos encouragements constants, merci.* To my beautiful baby girl Alitha, thank you for being so kind inside my womb as I finalized this work, every sweet kick kept me going!

To my friends and family, if I could mention all of you by name, it would take half this thesis. I appreciate each one of you, thank you for being proud of me for even attempting this degree. To my fellow comrades, who have literally become family, thank you for your insights on my work. The debates, stimulating conversations, you have challenged me in beautiful ways, and our debates on different topics have shaped this thesis to what it became, *enkosi maqabane, aluta continua!*

KEY WORDS

Canopy cover

Exotic cover crops

Gravimetric

Heat Ratio Method

Indigenous grasses

Irrigation

Leaf water status

Orchard floor evaporation

Reference evapotranspiration

Sap flow

Soil evaporation

Stomatal conductance

Transpiration

Transpiration model

Water use

LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
ARC	Agricultural Research Council
AWS	Automatic Weather Station
CSIR	Council for Scientific and Industrial Research
CP	‘Cripps’ Pink’
CTR	Control
CV	Common Vetch
CWR	Crop Water Requirement
EGVV	Elgin/Grabouw/Villiersdorp/Vyeboom
Era	Eragrostis
FB	Full-Bearing
FC	Field Capacity
Fig	Figure
FJ	Fuji
GD	‘Golden Delicious’
GDP	Gross Domestic Product
GMT	Greenwich Mean Time
GR	‘Golden Delicious Reinders’
G_S	Stomatal Conductance
HPV	Heat Pulse Velocity
HRM	Heat Ratio Method
IRGA	Infrared Gas Analyser

KBV	Koue Bokkeveld
KKY	Kikuyu
LAI	Leaf Area Index
LAIc	Cover Crop Leaf Area Index
LP	Lupine
LWP	Leaf Water Potential
MB	Medium-Bearing
NB	Non-Bearing
NWRS	National Water Resource Strategy
PAR	Photosynthetically Active Radiation
P-M	Penman Monteith
P-T	Priestley and Taylor
Rhode	Rhodes grass
R(i)	Radiation interception
RYE	Rye grass
SAI	Sapwood Area Index
SW	Shuttleworth and Wallace
SWB	Soil Water Balance
SWC	Soil Water Content
TCs	Thermocouples
TF	Tall Fescue
TSS	Total Soluble Solids
USA	United States of America

ROMAN SYMBOLS

A	Leaf area (m^2)
e_a	Actual vapour pressure of the air (kPa)
E_{eq}	Equilibrium evaporation term ($kPa\ k^{-1}\ MJ\ m^{-2}d^{-1}$)
E_s	Soil evaporation ($mm\ h^{-1}$)
ET	Actual evapotranspiration ($mm\ h^{-1}$)
ET_o	Reference evapotranspiration ($mm\ d^{-1}$)
Fs	Sap flux density ($cm^3\ cm^{-2}\ d^{-1}$)
K	Extinction coefficient (-)
K_c	Crop coefficient (-)
K_{cb}	Basal crop coefficient (-)
L_d	Downwelling longwave radiation incident on orchard surface ($MJ\ m^{-2}d^{-1}$)
L_{up}	Longwave radiation emitted by orchard surface ($MJ\ m^{-2}d^{-1}$)
LAI_c	Leaf area index of the cover crop (-)
RH_x	Maximum relative humidity (%)
RH_n	Minimum relative humidity (%)
R_n	Net radiation ($MJ\ m^{-2}d^{-1}$)
R_{nc}	Net radiation at tree canopy ($MJ\ m^{-2}d^{-1}$)
R_{ng}	Net radiation on orchard floor ($MJ\ m^{-2}d^{-1}$)
R_{ns}	Net radiation at soil surface ($MJ\ m^{-2}d^{-1}$)
R_s	Solar radiation ($MJ\ m^{-2}d^{-1}$)
SAI	Sapwood area index ($m^2\ m^{-2}$)
SF	Sap flow ($cm^3\ h^{-1}$)

T	Transpiration (mm h^{-1})
T_a	Average air temperature (°C)
T_c	Cover crop transpiration (mm h^{-1})
T_n	Minimum air temperature (°C)
T_x	Maximum air temperature (°C)
T_R	Transpiration Reduction Coefficient (%)
T_{ds}	Cover Crop Transpiration for drought stress treatment (L m^{-2} d^{-1})
T_s	Surface temperature (K)
U	Sap flux density (cm^3 cm^{-2} d^{-1})
U_2	Mean wind speed (m s^{-1})
Vh	Heat pulse velocity (cm h^{-1})
VPD	Vapour pressure deficit of the air (kPa)

GREEK SYMBOLS

Δ	Slope of the saturation vapour pressure vs air temperature curve (kPa K^{-1})
γ	Psychrometric constant (kPa K^{-1})
α	Priestley and Taylor coefficient (-)
α_c	Priestley and Taylor coefficient applied to cover crop canopy (-)
α_{so}	Priestley and Taylor coefficient applied to the soil layer (-)
σ	Stenfan-Boltzmann constant (MJ $K^{-4}m^{-2}d^{-1}$)
ε_a	Emissivity of the air (-)
ε_s	Emissivity of the surface (-)
ψ_x	Xylem water potential (MPa)
$\boldsymbol{\lambda}$	Latent heat of vaporization (J kg^{-1})

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ABSTRACT

The partitioning of evapotranspiration in apple orchards from planting until full-bearing age and implications for water resources management

Z. Ntshidi

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

Orchard evapotranspiration (ET) is a complex flux which has been the subject of many studies. It often includes transpiration from the trees, cover crops and weeds, evaporation from the soil, mulches, and other orchard artefacts. Studies of evapotranspiration in orchards often quantify tree water use and soil evaporation, treating the water use from the understorey vegetation on the orchard floor as negligible. Therefore, there is a paucity of information; first about the water use of cover crops in general, and secondly about the contribution of cover crops to whole orchard ET. This information is important, especially in semi-arid regions like South Africa where water resources are already under great strain and the situation is predicted to worsen in future due to climate change. This information is even more crucial in the agricultural sector which is considered as an inefficient water user as more than 30% of the water allocated to the sector is lost through leakages, inefficient irrigation scheduling, to name a few. Accurate quantitative information on water use partitioning can help the sector identify opportunities to save water especially during droughts whose frequency and severity is increasing. To address this challenge, this study was divided into two sections. The first section is a greenhouse study which looked at the water use of different cover crop species under controlled conditions to understand their water use characteristics with no influence from the trees in the orchard. The second section of the study was done under field conditions. This section investigated the contribution of cover crops to actual ET using six orchards as case studies planted to trees

with different canopy cover (young non-bearing, medium bearing, and mature full-bearing trees). The aims of the greenhouse study were to compare the transpiration dynamics of various cover crop types to identify species with conservative water use rates. Secondly, we sought to also study the water relations of the various species under different water stress regimes. Studied species included two exotic legumes, three exotic grasses and two grasses that are indigenous to sub-Saharan Africa. Transpiration rates were quantified using miniature stem heat balance sap flow gauges and using the gravimetric approach in which the plant pots were manually weighed. Drought stress was imposed by withholding irrigation at selected intervals and the responses were quantified by monitoring changes in the water relations of the plants. The results showed that exotic legumes had the highest daily water use per unit leaf area. These were followed by exotic grasses while indigenous grasses used the least water. From a water use perspective, this study demonstrates that indigenous grass species are more appropriate as cover crops in South African orchards because of their low transpiration rates and the ability to cope with extended periods of water deficit. For the second part of the study, we investigated the contribution of the orchard floor evaporative fluxes to whole orchard ET focusing on the transpiration dynamics of cover crops in field conditions which are currently not well known. Data on the partitioning of ET into its constituent components were collected in apple (*Malus domestica* Bork) orchards with varying canopy cover. Additional comparisons were done in an orchard under drip and micro sprinkler irrigation systems. The study orchards were in the prime apple growing regions in South Africa in the Western Cape Province. The orchards were planted to the ‘Golden Delicious’/’Reinders’ and the red cultivars (such as ‘Cripps’ Pink’/ ‘Royal Gala’/’Fuji’). The ‘Golden Delicious’ cultivar is the most widely planted cultivar in the country while the ‘Cripps’ Pink’/’Royal Gala’/’Fuji’ are high value cultivars occupying a significant planted area. Tree transpiration was quantified using the heat ratio method on mature trees and

the thermal dissipation sap flow techniques on young trees. Cover crop transpiration was measured at selected intervals using micro stem heat balance sap flow gauges calibrated against infrared gas analyser readings. Orchard ET was measured using an open path eddy covariance system while the microclimate, radiation interception, and soil evaporation were also monitored. For the different irrigation systems trial, which was conducted in a mature 'Royal Gala' orchard, the results showed that under micro sprinkler irrigation there was a greater contribution from cover crop transpiration than soil evaporation and vice versa under drip where the cover crop strip was water stressed. Drip irrigated trees produced smaller sized fruit with poor quality, while micro sprinkler irrigated trees produced bigger fruit with good quality. Using the drip irrigation system saves water, but compromises the quality of the fruit, and subsequently overall farm production. In micro sprinkler irrigated young orchards with dense cover crop that covered most of the orchard floor, orchard floor evaporative fluxes accounted for as much as 80% of the measured ET. In these orchards the cover crop transpiration was of the same order of magnitude as the bare moist soil evaporation suggesting that water use by the cover crop was substantial. However, in mature orchards with a high canopy cover (>55% fractional cover), orchard floor water losses were less than 30% of the measured ET. Cover crop transpiration rates were much lower, contributing less than 10% of the whole orchard ET. Significant volumes of water can be saved, especially in young orchards, by keeping the orchard floor vegetation short, reducing the area occupied by cover crop, and by reducing the wetted ground surface area. A simple model to predict the water use of cover crops in orchards was developed and the results showed that it accurately estimated the seasonal cover crop water use (Tc) from apple orchards of different canopy covers. The results from the modelled Tc against the measured Tc yielded correlation coefficients of > 90% (R^2= 0.96).

October 2021

CHAPTER 1: GENERAL INTRODUCTION

1.1 RESEARCH BACKGROUND

Apples are one of the most popular and widely produced fruit in temperate regions throughout the world. China leads the world in apple production volumes, producing more than 40 million tons annually (Hortgro, 2020). Following China is the United States of America producing more than 4 million tons each year. South Africa is ranked at 15th position in the world,but it is the second country in the Southern hemisphere after Chile. Even though apple production is seasonal, they are available on international markets throughout the year due to global export supplies. In South Africa, a variety of deciduous fruit (apples, pears, apricots, nectarines, peaches, plums, and cherries) are exported to various parts of the world. The country's total area planted to deciduous fruit trees is roughly 54 294 ha and apples remain the largest export fruit by volume (>45% of the total planted area). The country is ranked as the 6th largest exporter of fresh apples in the world. The United Kingdom is the largest single country market for South African apple exports, accounting for ~13%. Apples are exported to the rest of the African continent, Asia, Russia, and European Union. (Hortgro, 2020).

The Western Cape Province is the largest traditional apple production region in South Africa and accounts for more than half of the apple production in the country (Meyer and Breitenbach, 2004). The biggest apple producing regions are around the Western Cape's Kouebokkevel (KBV) and Elgin Grabouw Villiersdorp Vyeboom (EGVV) regions. The KBV region consists of towns like Ceres and Wolseley, characterized by cold winters and hot summers, while the main producing towns in EGVV are Elgin and Villiersdorp characterized by mild winters and warm summers. About 20% of the country's apples are produced in the Langkloof region, which is along South Africa's Southern Cape and extends to the border between the Western and the Eastern Cape. Further north in the country, there are also small but growing production areas in the Free State, Mpumalanga, and Limpopo Provinces. Fig. 1.1 shows the map of South Africa and the Provinces and the associated land cover surrounding the KBV and EGVV regions. The inserts also show the location and names of the different farms used in this study.

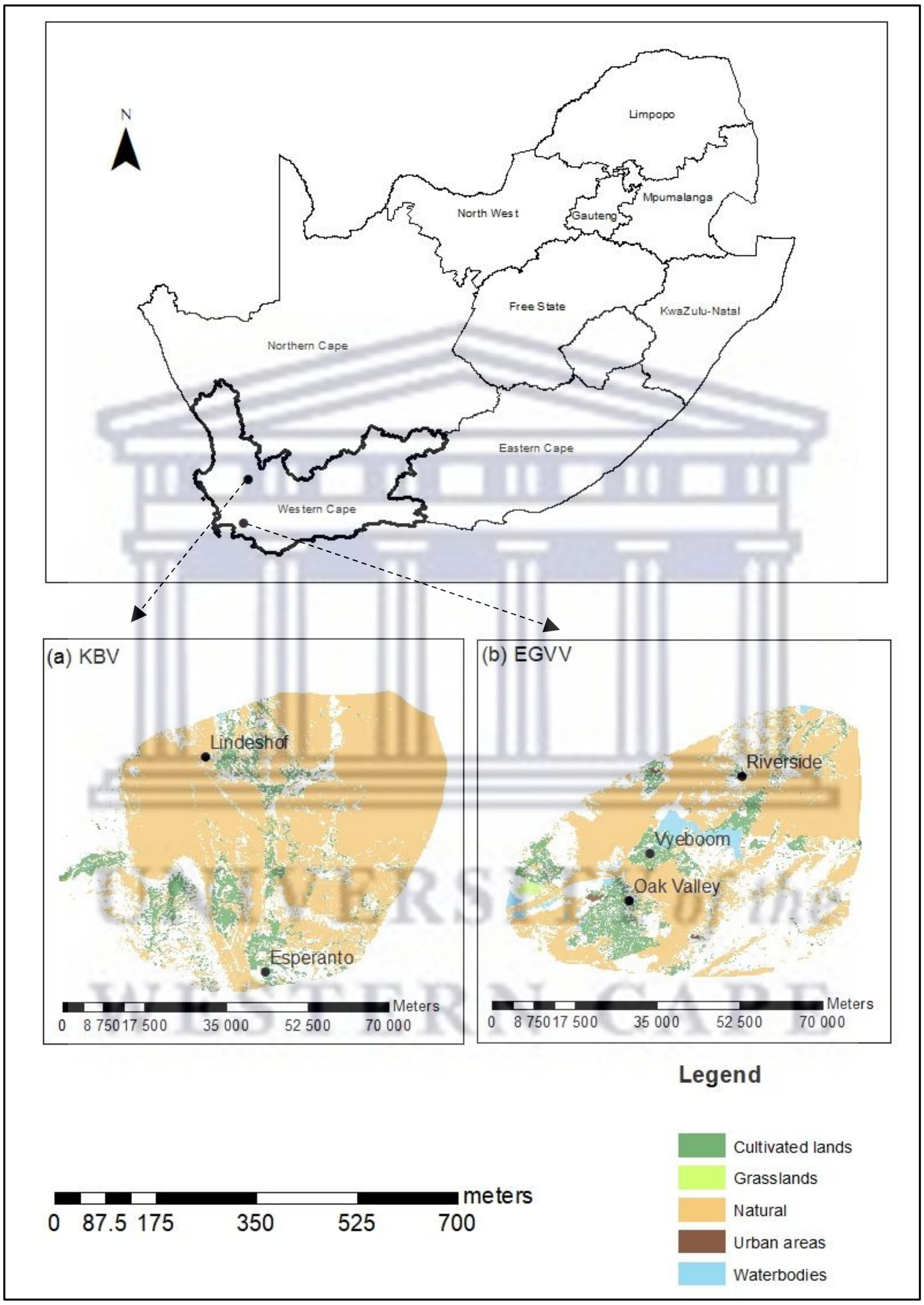


Fig. 1.1: Map of South Africa showing the two study regions (a) KBV and (b) EGVV; the location and names of the different farms used in this study.

During the 2018/19 growing season, the apple industry employed 30 165 workers who in turn supported 120 662 dependents (Hortgro, 2019). This number has increased from the statistics of 2015/16, which reported 27 526 employees that had 110 106 dependents (Dzikiti et al., 2018a). This shows that the sector is an important source of employment even though it does not receive any government subsidies (Dzikiti et al., 2018a).

The Western Cape Province has a Mediterranean-type climate, and the rain falls outside the fruit growing season in winter (May to August), while the apple growing season is from September to March/April (depending on cultivar). Consequently, all the fruit are grown under irrigation yet water resources in the country are under great strain. The province is projected to experience severe water shortages in future due to rising competition between irrigated agriculture, increasing industrial activities, and the rapidly growing population of the Cape Town Metropolitan (Dzikiti et al., 2018a; Gush et al., 2019). Climate change is also projected to exacerbate the water problems by increasing the frequency and severity of droughts and extreme weather events in the region (Midgley and Lotze, 2011).

Sustainable management of irrigation requires accurate quantitative information on evapotranspiration (ET) which is the second largest water balance component in orchards (Villalobos et al., 2013). Many studies have quantified ET in apple orchards (Li et al., 2007; Dzikiti et al., 2018a & b; Ntshidi et al., 2018; Gush et al., 2019; Zanotelli et al., 2019; Mobe, 2020; Mobe et al., 2020a & b). Besides the work by Li et al. (2007) and Wang and Wang (2017), few studies have investigated, in detail, the partitioning of evapotranspiration into its constituent components in apple orchards of varying age groups. Besides whole orchard ET, there is a paucity of detailed information on the transpiration dynamics of cover crops which are often present especially in orchards with non-localized irrigation systems, such as micro-sprinkler, flood, to name a few.

In fruit production, cover crops are plants that are grown in between tree rows for purposes of protecting and enriching the soil (Chamberlain et al., 2020). These crops can manage soil erosion, soil fertility, soil quality, improve water infiltration, control weeds, pests, diseases, biodiversity, and wildlife. Cover crops can also reduce nitrate leaching by maximizing nitrogen (N) acquisition before the drainage period, thereby avoiding groundwater nitrate pollution. The production of biomass by cover crops is also important for soil carbon confiscation (Tribouillois et al., 2015). This in turn results in the reduced use of agrochemicals, mainly pesticides and herbicides that are harmful both to humans and the environment.

Various plant species are often used as cover crops in orchards worldwide. These include both grasses and legumes (Wilson et al., 1982). Fynbos, *a sclerophyllous* shrub dominated by species of the *Proteaceae*, *Ericaceae* and reed-like *Restionaceae* which is endemic to the Cape Floral Regions (Rebelo et al., 2006), is also used in some commercial orchards in South Africa (Johan Burger, pers. comm.). Grasses, rather than legumes are, by far, the most commonly found cover crops species in orchards (Roper, 1992).

A major question surrounding the use of cover crops in orchards revolves around whether the benefits derived from them exceed the losses, particularly of scarce resources such as water and nutrients (Jannoyer et al., 2011). For example, during recent devastating droughts in South Africa (2016-2018), many farmers instinctively removed cover crops supposedly to lower the orchard water use (Wiehann Steyn, pers. comm.). Given that currently no accurate quantitative information exists on the water use of cover crops, these actions beg the following questions: Firstly, how much water do cover crop species use in orchards under semi-arid sub-tropical conditions? Secondly, how does this water use differ between cover crop species? Thirdly, how do orchard management practices such as the use of the cover crops, influence overall orchard water use? An ideal cover crop should maximize the benefits while at the same time it reduces costs, such as, through excessive water use and competition for resources with the orchard trees (Jannoyer et al., 2011).

Little is also known about how the cover crop transpiration is affected by different irrigation systems used in apple orchards, nor how it is affected by canopy cover of apple trees from planting until the trees reach full-bearing age or maturity (full canopy cover). This study therefore seeks to close these important information gaps to gain insights on the role that cover crops play in the water balance of apple orchards under Mediterranean growing conditions.

Understanding the partitioning of ET in orchards is very important, especially in dry countries to quantify the proportion of beneficial water used to produce fruit (Kool et al., 2014; Wang and Wang, 2017). It also gives irrigation managers opportunities to identify and implement practices to reduce orchard floor evaporative fluxes to improve water productivity (Dzikiti et al., 2017; Dzikiti et al., 2018b; Fernández et al., 2018; Ortega-Farias, 2012). In addition, ET partitioning data is also important for evaluating multiple source water use models in agricultural, hydrological and in climate modelling studies (Anderson et al., 2017; 2018,). Few studies have directly measured all the components of ET in crop fields. For example, in a comprehensive review of 52 publications of ET partitioning, Kool et al. (2014) found that 32 of the studies showed that soil evaporation (E_s) contributed more than 30% of ET. Only 20 of the studies independently quantified both E_s and transpiration (T) as well as ET. In this study we, for the first time, extend these measurements by collecting detailed data not only of E_s and T, but also of cover crop transpiration (T_c) which has not been quantified in apple orchards.

In most orchards, the cover crop vegetation is either a single species of exotic cover crops or indigenous vegetation, weeds or complex mixtures of these. Grasses are the most common cover crops planted in South African apple orchards for a variety of reasons. Examples include the tall fescue (*Festuca arundinacea*), kikuyu grass (*Pennisetum clandestinum*) and rye grass (*Lolium*), among others. As much as cover crops bring a host of benefits to apple orchards, there is a strong, and yet unconfirmed, suspicion that they also contribute to an increased orchard water use.

1.2 AIMS AND QUESTIONS

The main aim of this study was to quantify the water requirements of apple orchards and to establish how ET is partitioned into its various constituent components as affected by canopy cover. The novelty of this research project resides in; 1) providing, for the first time, detailed information on the water use characteristics of indigenous and exotic cover crop species grown in South African orchards to minimize orchard floor water losses, 2) the quantification of water use by apple trees under different irrigation systems and how ET is partitioned under these systems; 3) deepening our understanding of how ET is partitioned into the beneficial (water use by plants) and non-beneficial (water used by orchard floor) water uses in apple orchards of different age groups, and; 4) developing a multiple source ET model that incorporates the role of cover crops. The study used apple orchards as case studies although the methods are applicable to other fruit types. This research seeks to answer the following questions:

- How much water do different cover crop species use and how does their contribution to total ET vary with different canopy covers?
- What are the key drivers of water use in apple orchards under different irrigation systems and how does this influence water use partitioning?
- How does the partitioning of ET into tree transpiration and orchard floor fluxes vary in orchards of different canopy covers?

- How can we accurately model the partitioning of water use in orchards with various cover crop species and varying canopy covers?

1.3 OBJECTIVES

Specific objectives of this study are:

- To investigate the water use characteristics and water relations of indigenous and exotic cover crop species used in apple orchards.
- To quantify the dynamics of transpiration and ET partitioning in apple orchards under different irrigation systems.
- To quantify and understand how ET is partitioned into tree and cover crop transpiration as well as orchard floor evaporation and how this varies with orchard age.
- To evaluate the performance of a multiple source ET model in apple orchards.

1.4 STUDY HYPOTHESES

- Indigenous cover crop species use less water than exotic ones thereby reducing overall orchard water consumption.
- Canopy size is the main factor determining orchard water use and its partitioning in apple trees under different irrigation systems.
- Cover crop water use contributes significantly to whole orchard ET, irrespective of age group.
- Multiple source ET models can accurately predict the partitioning of water use in orchards of different canopy covers.

1.5 STUDY APPROACH

To address these hypotheses, the approach to this thesis involved first a detailed study with cover crop species that are commonly planted in South African apple orchards in order to gain insights on how water use and water status varied for different cover crop species subjected to similar environmental conditions in a greenhouse experiment. The cover crop species studied involved a wide range of exotic grasses, indigenous grasses, and exotic legumes. The next step was to scale up the greenhouse studies to the field conditions to study in detail the water use partitioning in apple orchards subjected to different irrigation systems for trees with different canopy cover. This involved detailed data collection in six commercial orchards planted to different apple cultivars, under different irrigation systems, different orchard floor management practices and different age groups. The orchards were planted to the following cultivars ‘Golden Delicious’/’Reinders’ and the red cultivars (‘Cripps’ Pink’/ ‘Royal Gala’/ ‘Fuji’). ‘Golden Delicious’ cultivars are the most widely planted in South Africa accounting for about 22% of the area under apples (Hortgro, 2020), while the red cultivars are high value and high performing cultivars that account for roughly 12% of the total planted area.

The approach followed in this study was quantitative with the following measured variables over a period of three years from 2017 to 2020: 1) site microclimates using an automatic weather station, 2) cover crop transpiration using sap flow sensors and gravimetric method, 3) plant water status using an AP4 porometer and pressure chamber, 4) orchard transpiration rates using sap flow systems, 5) orchard evapotranspiration rates using the eddy covariance system and Soil Water Balance (SWB) approach, 6) tree and cover crop leaf area index (LAI) using LAI meters; 7) soil properties and root zone soil water content using soil reflectometers (CS616 sensors), and 8) irrigation volumes using a flow meter.

1.6 THESIS STRUCTURE AND OVERVIEW

This thesis consists of seven Chapters (Fig.1.2). Chapter 1 gives the background to the research and highlights objectives and hypothesis. Chapter 2 gives a critical review of existing literature in line with the subject matter. Chapter 3 evaluates the transpiration dynamics and water relations of different cover crop species grown under controlled conditions in a greenhouse. Chapter 4 compares the water use and ET partitioning of apple trees under different irrigation systems, while Chapter 5 assesses ET partitioning in apple orchards of different age groups. Chapter 6 focuses on modelling ET using a multiple source model while Chapter 7 summarizes the main study findings and provides recommendations for future research.

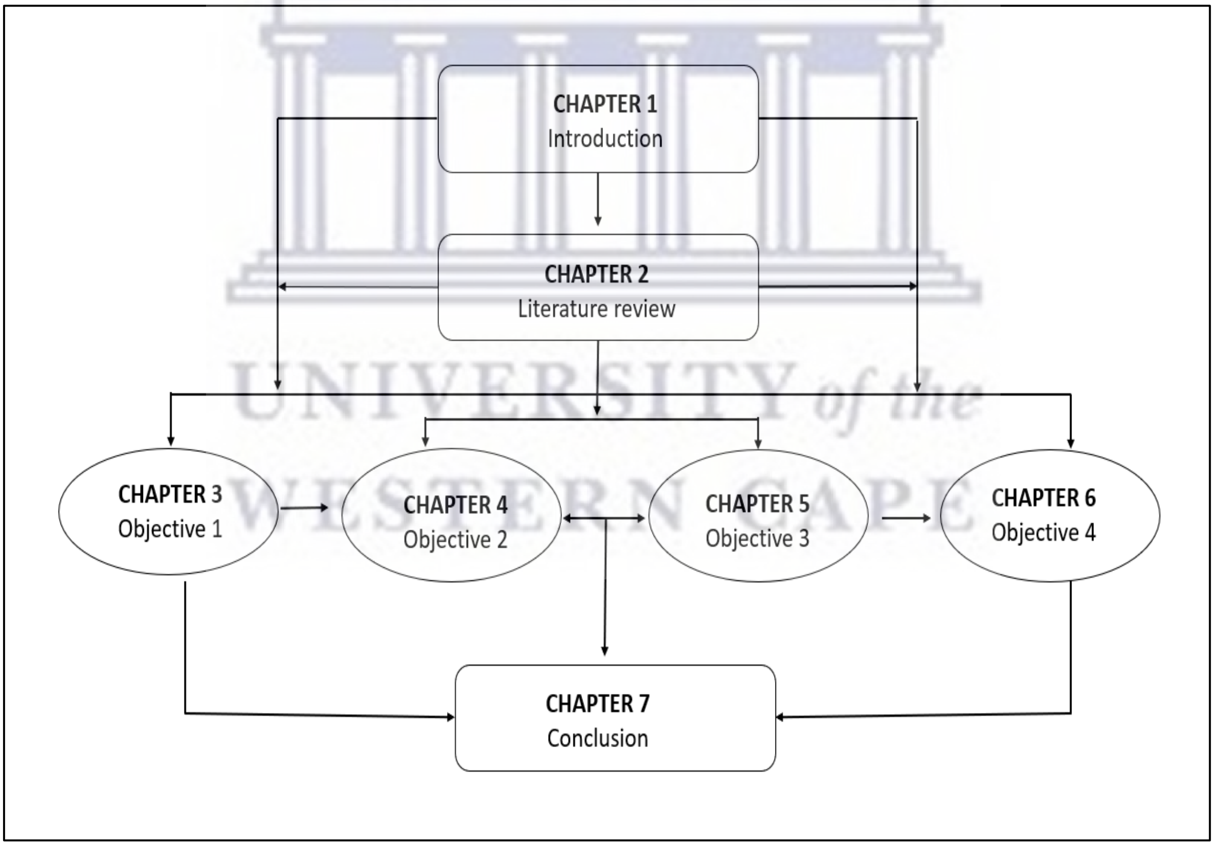


Fig.1. 2: Linkages between thesis chapters.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

This chapter presents the outcomes of the review of relevant literature to the studied topic. Information on what is known about the problem will be presented and gaps in knowledge in the field highlighted. There will be a discussion on theories surrounding apple production in the agricultural sector as well as factors that affect apple production. Furthermore, there will be discussions about water application, role of cover crops in orchards and their water use, evapotranspiration partitioning in apple orchards, monitoring plant water use and modelling orchard floor evaporative fluxes, among others. The information that other researchers have published about similar problems will also be presented. Methods that other researchers have used to address similar problems will be reviewed and advantages and disadvantages of different methods highlighted. Lastly findings from research of both local and international studies surrounding the topic will be elaborated on.

2.2 GLOBAL APPLE PRODUCTION

Apples are one of the most popular and widely produced fruit in temperate regions throughout the world (Table 2.1). China leads the world in apple production volumes, producing more than 40 million tons in years 2016, 2017 and 2019, while it produced just below 40 million tons in 2015 and 2018. Following China is the United States of America producing more than 4 million tons each year. South Africa is ranked at 15th position in the world; however, it is the second country in the Southern hemisphere while Chile is the first. Even though apple production is seasonal, they are available on international markets throughout the year due to global export supplies.

Table 2.1: Apple production around the world showing South Africa being ranked number 15 (Hortgro, 2020).

Rank	Country	Apple production (metric ton)				
		2015	2016	2017	2018	2019
1	China	38 900 319	40 394 483	41 391 451	39 235 019	42 426 578
2	United States of America	4 556 790	5 214 040	5 240 670	4 644 790	4 997 680
3	Turkey	2 569 759	2 925 828	3 032 164	3 625 960	3 618 752
4	Poland	3 168 818	3 604 271	2 441 393	3 999 520	3 080 600
5	India	2 134 000	2 521 000	2 265 000	2 327 000	2 316 000
6	Italy	2 473 608	2 455 616	1 921 272	2 466 990	2 303 690
7	Iran	2 500 000	2 096 749	2 398 831	1 936 697	2 241 124
8	Russian Federation	1 612 700	1 701 100	1 493 600	1 859 400	1 950 800
9	France	1 968 628	1 823 123	1 695 949	1 740 350	1 753 500
10	Chile	1 710 319	1 730 081	1 749 037	1 700 065	1 621 312
15	South Africa	934 375	916 143	929 028	829 636	891 979
	Rest of the world	19 879 580	19 625 598	18 577 575	21 458 253	20 034 197
	Total world	82 408 896	85 008 032	83 135 970	85 823 680	87 236 221
	Yearly change (%)		3%	-2%	3%	2%

By the year 2000, China produced ~40% of the world's apple production, while South Africa produced roughly 4% (Meyer and Breitenbanch, 2004). At the time, it was predicted that by year 2005, China's level of apple production would have increased to more than 50% of the world's production. However, Table 2.1 shows that by year 2019 China produced ~49% of the world apple production while South Africa produced ~1%.

South Africa is ranked number six in the world export of fresh apples (Fig. 2.1). Africa was the largest regional market for South African apple exports by the year 2019, accounting for more than 40%. Nigeria, Zambia, Kenya, and Senegal are some of the African countries that lead in importing fresh apples from South Africa. About 25% of South African apples were exported to Asia, while ~19% went to the European Union and 13% to the United Kingdom, which is the largest single country market for South African apple exports (Hortgro, 2020).

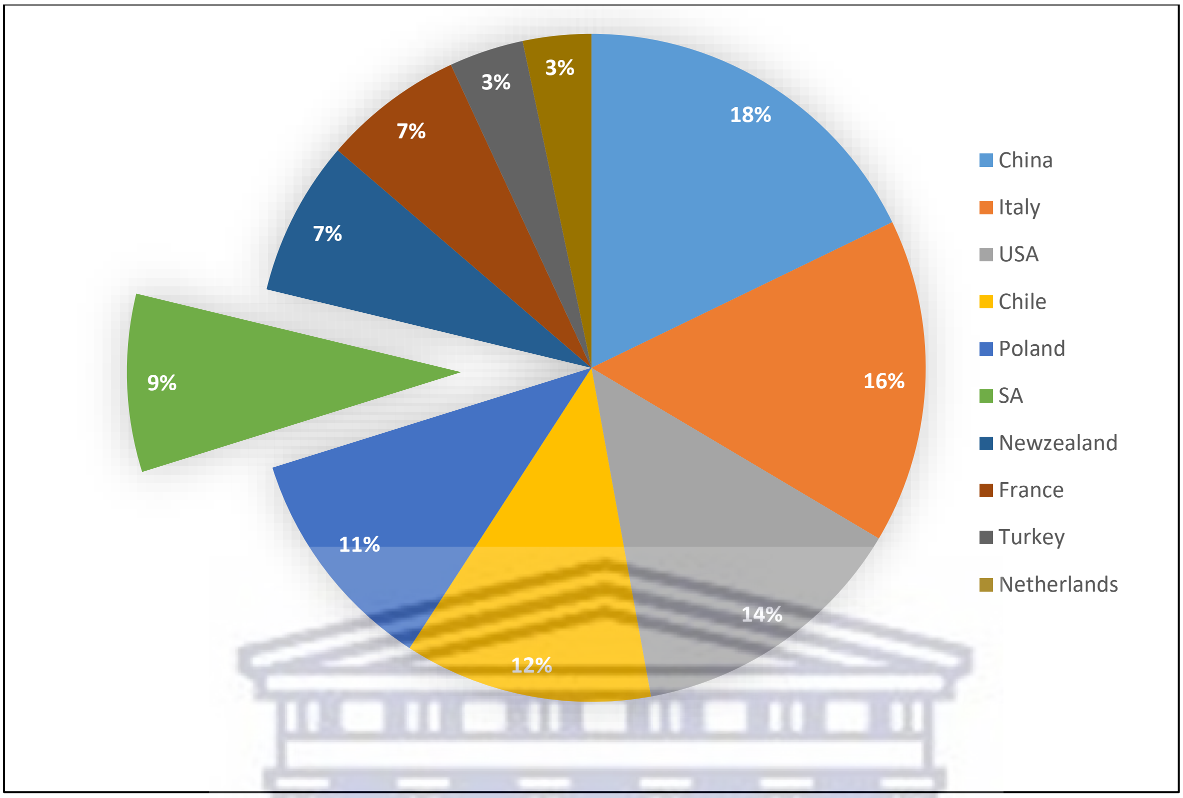


Fig. 2.1: Top 10 fresh apple exporters in the world during the years 2015 – 2020 (Hortgro, 2020)

2.3 APPLE PRODUCING REGIONS IN SOUTH AFRICA

The Western Cape Province is the largest well-known apple production region in South Africa and produces more than half of the country's apples as demonstrated in Fig. 2.2. The biggest apple producing regions surround the Western Cape towns of Ceres, Wolseley, Elgin and Villiersdorp. About 20% of the country's apples are produced in the Langkloof region, which is along South Africa's Southern Cape and extends to the border between the Western and the Eastern Cape. Further north in the country, there are also small but growing production areas in the Free State, Mpumalanga, and Limpopo Provinces. Newer orchards are common in these regions as compared to further south because apple production was not possible before due to the frequent hail experienced in these areas. However, with the introduction of hail nets, apple production has become more viable in these regions. These are the earliest South African production regions as they start producing in late December, they are in high demand during the December holiday season.

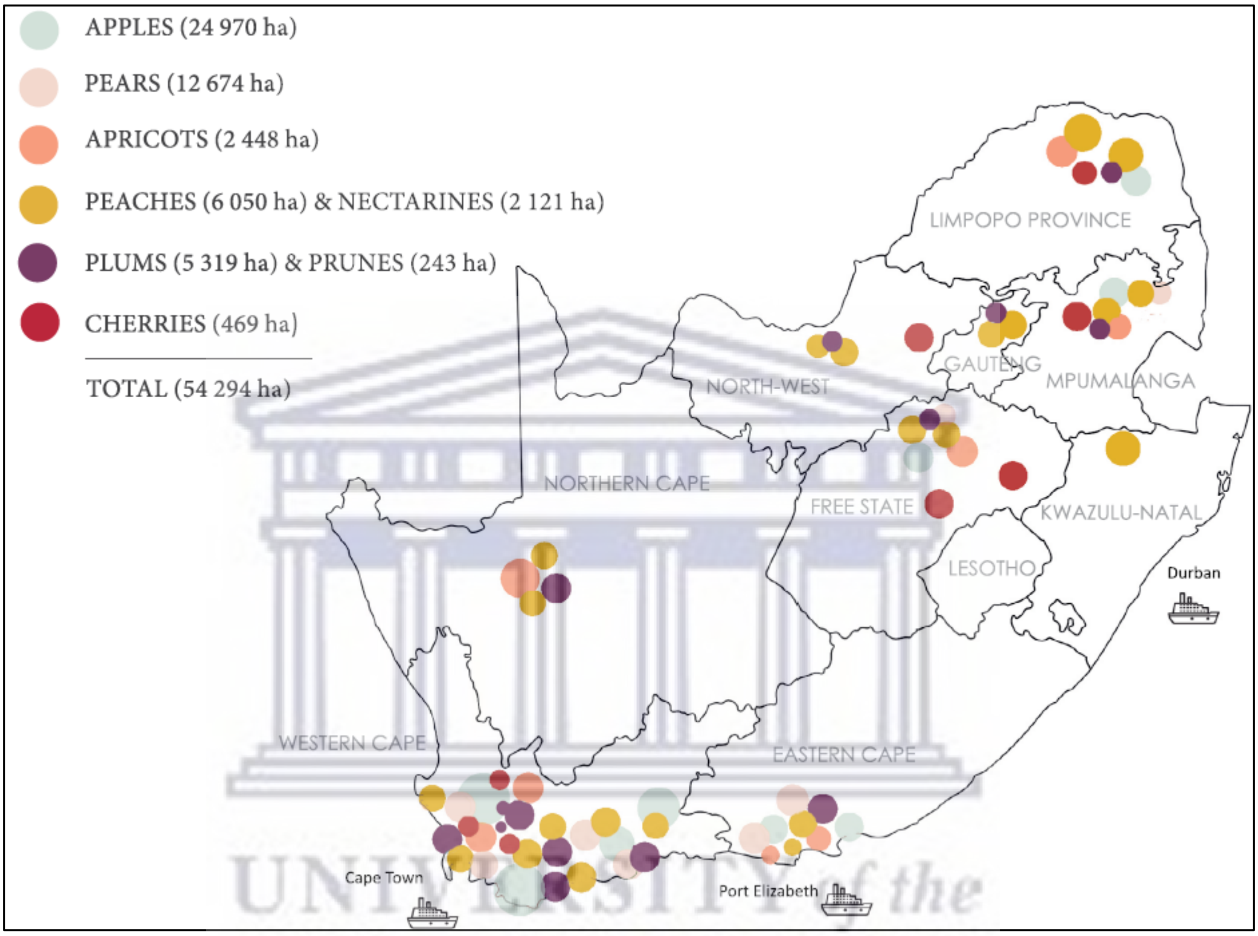


Fig. 2.2: Area under cultivation per deciduous fruit type in South Africa (Hortgro, 2019).

The country’s total area planted to deciduous fruit trees is roughly 54 294 ha and apples occupy about 46% of the total area. Apples have been produced commercially in South Africa since the 1880’s and they have been exported from South Africa to countries such as the United Kingdom since the 1890’s. Primarily, orchards were developed in the Western Cape's deciduous fruit production regions but have over time been produced throughout the country as represented in Fig. 2.2.

During the 2018/19 growing season, the apple industry employed 30 165 workers who in turn supported 120 662 dependents (Hortgro, 2019). This number has increased from the statistics of 2015/16 reported by Dzikiti et al 2018a, which reported 27 526 employees that had 110 106 dependents. The statistics of employment in this sector increases each year, it is therefore important for the livelihoods of South Africans, even though it does not receive any government subsidies (Dzikiti et al., 2018a).

2.5 FACTORS AFFECTING APPLE PRODUCTION IN SOUTH AFRICA

There are many factors that can affect the production of apples. These fruit must be planted in temperate climatic conditions, the soils must contain a Ph of between 6 - 7, it matters what rootstock one choses as it eventually affects yield and plant growth. The availability of water is one of the most important factors to consider when growing apple trees as watering helps the fruit tree to get established. The cultivar that one plants also determines the harvest time and dormancy period as different cultivars reach dormancy at different times, below is an overview of how some of the above-mentioned effects affect apple production.

2.5.1 Climatic conditions

Apples are one of the most widely planted deciduous fruit in South Africa (Fig. 2.2) and the world at large. These fruit grow in a diversity of climates from temperate to semi-arid, subtropical, and even tropical environments with sufficient water supply (Musacchi and Serra, 2018). Apple trees can grow in almost any hardiness zone; however, they grow best in climates that are characterized by cold winters and moderately warm summers with medium to high humidity. In South Africa, apples are mainly grown in the Western Cape Province, this Province is characterized by cool winter temperatures and warm summers. Apple trees can tolerate temperatures as low as -7°C during the colder season. Cold winter temperatures are essential for meeting the chilling requirements of most apple cultivars to induce a phase of dormancy (Rai et al., 2015). The chilling requirements of most apple cultivars are in the range of 800–1000 chill hours (Tharaga, 2016) or temperatures should be at least below 7°C. The optimum temperature for pollination and fertilization in temperate crops like apples is between 20–25 °C (Rai et al., 2015). Rainfall that exceeds 1000 mm in a growing season is most favourable for optimum growth and yields (Li et al., 2018).

2.5.2 Suitability of soils and rootstock effects

Apple trees grow well in deep well-drained sandy and loamy soils; however, they can also tolerate a wide variety of soils as there are numerous rootstocks to choose from (Taylor and Gush, 2014). Soils with poor aeration and prolonged water logging are not ideal as too much water in the root zone can deplete oxygen from the soil, prevent the roots from absorbing necessary minerals, and makes a tree susceptible to rot and infections. The trees perform better to soil pH in the range of 6.0–7.0 (Peryea, 1998). Too low or high soil pH also affects the availability of nutrients to the trees. When a tree is watered, it is important that there is no standing water and soggy roots as this can be as damaging as drought conditions for the apple tree (Yunqiang et al., 2015).

While several hundreds of rootstocks have been developed over the years, Table 2.2 lists some of the most used ones in South Africa and their characteristics. Rootstocks are selected for their ability to grow strong, have persistent root systems and are often characterized as “vigorous” or “dwarfing” depending on the vigour of the scion that grows on them (Cohen and Naor, 2002). Rootstocks also influence crop yields and the time to bearing of newly planted orchards with precocious rootstocks leading to early yields. Increasingly, selection is for precocious and productive dwarfing rootstocks.

Table 2.2: Rootstocks commonly used in South African apple orchards and their characteristics (StarGrow-Africa, 2013; Dzikiti et al., 2018a).

Rootstock name	Characteristic
MM109	100 -110% vigor with a wide adaptability. Thrives in low to medium potential soils and warmer climates
M25	80 - 100% vigor with extremely precocious and high production. Thrives in low to medium potential soils and has a good tree shape to allow for light penetration
M793	80 - 90% vigor with high production and a wide adaptability. Highly recommended for a variety of soils and cultivars
MM106	60 - 70% vigorous with very precocious and high production. Survives in medium to high potential soils. Produces flat crotch angles and good fruit size but can get collar rot in poorly drained soils.
M7	60% vigorous with precocious and high production as well as a wide adaptability. Resistant to collar rot and produces flat crotch angles
M26	40 - 50% vigorous with precocious and high production. Thrives in high potential soils and colder climates and is mainly found in the highveld producing burknots, though susceptible to sunburn.
M9	30% vigorous with extremely precocious and high production. Survives in high potential soils and colder climates as it produces flat crotch angles and large fruit. Has smaller canopy, therefore susceptible to sunburn.

2.5.3 Water availability

The availability of water has a great impact on apple production as plants need water for photosynthesis. The availability of water can improve yields, fruit size, fruit quality, while the lack of it can adversely impact the plant. During times of water scarcity, the available irrigation water supply can be less than the crop water requirements. This can lead to tree water stress and subsequent loss in fruit size and yields in fruit orchards. Water stress can be detrimental to production by reducing growth and net photosynthesis rates per unit leaf area (Landsberg and Jones, 1981; Flore and Lakso, 1989). The amount of radiation intercepted by the canopy, leaf photosynthesis rate and the allocation of assimilates to fruit controls the actual fruit yield (Wünsche, 1993). The partitioning of assimilates to fruit as opposed to vegetative sinks is strongly dependent on radiation distribution in the canopy and on crop load (Wünsche, 1993). Advanced foliar damage and/or leaf senescence caused by water stress can limit carbohydrate availability for growth and development. This in turn has an adverse effect on fruit bud formation, fruit set and fruit size (Wünsche, 1993).

Yield is a function of the number of fruit on trees as well as fruit size. The critical processes to achieve the yield potential of the current year are therefore initial and final fruit set and fruit growth, assuming adequate fruit bud formation and flower density (Wünsche, 1993). Early season water stress of apple trees reduced fruit set, resulted in less fruit per cluster (Powell, 1974) and interfered with flower bud morphogenesis (Landsberg and Jones, 1981), while limiting irrigation increased fruit drop (Assaf et al., 1974, Assaf et al., 1975). The effects of water deficit on yield are more pronounced during budburst and flowering, the beginning of rapid shoot growth and the beginning of fruit fill.

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

2.6 IMPACTS OF CLIMATE CHANGE ON APPLE PRODUCTION

The forecasted climate change is likely to be a major threat to the agricultural sector as it will come with an increase in temperatures while there will be a decrease in precipitation (Kang et al., 2009). This brings a scenario whereby there will be more water leaving the plant in the form of transpiration and a need for more water application to keep the plants cooler and promote the process of photosynthesis. The worst prediction is that the mean temperatures for the Southwestern fruit production areas of the country will increase by an average of 1.5°C in the coastal areas, 3°C inland by the year 2050 (African Climate and Development Initiative, 2016), and the likelihood that these figures may double by the end of the century. These conditions are also likely to be accompanied by a reduction in annual rainfall and a shorter winter season, meaning reduced colder period (Warburton and Schulze, 2005). The existence of cold and warm days is predicted to change, whereby there will be a decrease in colder days frequency while there will be an increase in warmer days by year 2030. The one aspect of tree physiology that is likely to be affected by climate change is the accumulation of winter chills, and this will likely have a major impact on fruit species with chilling requirements such as those of apples (Luedeling et al. 2012). The prediction of reduced winter chills due to climate change are likely to put production restraints in most fruit trees as they will be unlikely to fulfil their chilling requirement for bud break/ dormancy (Baldocchi and Wong, 2008).

2.7 ROLE OF COVER CROPS IN ORCHARDS

Cover crops are plants that are grown in between tree rows in fruit orchards for purposes of protecting and enriching the soil (Chamberlain et al., 2020). These crops can manage soil erosion, soil fertility, soil quality, improve water infiltration, control weeds, pests, diseases, biodiversity, and wildlife. Cover crops can also reduce nitrate leaching by maximising nitrogen (N) acquisition before the drainage period, thereby avoiding groundwater nitrate pollution. The production of biomass by cover crops is also important for soil carbon confiscation (Tribouillois et al., 2015).

Various plant species are often used as cover crops in orchards worldwide, these include both grasses and legumes (Wilson et al., 1982). Fynbos, *a sclerophyllous* shrub dominated by species of the *Proteaceae*, *Ericaceae* and reed-like *Restionaceae* which is endemic to the Cape Floral Regions (Rebelo et al., 2006), is also being used in some commercial orchards in South Africa (Johan Burger, pers. comm.). Grasses, rather than legumes, are by far the most commonly found cover crops species in orchards (Roper, 1992). A major question surrounding the use of cover crops in orchards revolves around whether the benefits derived from them exceed the losses, particularly of scarce resources such as water and nutrients (Jannoyer et al., 2011).

Water use in orchards is driven by factors such as the evaporative demand of the air, available soil moisture (irrigation and rainfall), and management (such as, canopy cover, cultivar, mowing practices, irrigation system, and irrigation frequency.) (Dragoni et al., 2005; Dzikiti et al., 2018a & b; Gush et al., 2019). The water use of grasses has been studied all over the world using different techniques such as sap flow (Erickson et al., 2012; Ramirez et al., 2006; Senock and Ham, 1995), bowen ratio energy balance (Everson et al., 2011), crop coefficient (Shapiro et al., 2015) and neutron probes (Siddique, 2001; Rao and Northup, 2009; Nielsen et al., 2015). Besides the work by Everson et al. (2011) on grasslands in the Kwazulu-Natal Drakensberg in South Africa, and Ntshidi et al. (2021) on grasses and legumes, no comparative studies exist on the water use and drought stress responses of grass and legume cover crops. Detailed quantitative information on the water use of cover crops is required to improve water resources management in orchards. The above-mentioned studies conducted across the globe produced results that show that the water use from different cover crops can vary depending on the type of grass or legume, the environment it grows in and climatic conditions.

2.8 IRRIGATION SYSTEMS USED IN SOUTH AFRICAN ORCHARDS

Irrigation can be defined as the process by which controlled amounts of water are applied to agricultural crops to help them grow and reach their optimal during periods of less than average rainfall (Uphoff, 2019). Crops that rely mainly on direct rainfall and are only grown in rainy seasons are referred to as rainfed-crops (Wani et al., 2009). Several irrigation systems currently exist in South Africa, these include canals, flood irrigation, draglines, pivots, sprinklers, micro irrigation, and drip irrigation. The main irrigation systems currently used in South African apple orchards are micro-sprinkler and drip irrigation (Gush and Taylor, 2014).

Irrigated agriculture plays an important role in establishing food production and security. However, it is also reported to use more than 60% of the country’s available water resources (Mukheibir, 2008). The second National Water Resources Strategy of South Africa (NWRS 2, 2013) cites irrigated agriculture as one of the most inefficient industries when it comes to their use of water resources. It is estimated that between 30 and 45% of water allocated for irrigation is wasted through leakages, poor irrigation scheduling and other causes.

To increase agricultural water productivity, it is recommended that information on crop water use under different production practices is acquired and precise irrigation technologies are adopted (NWRS 2, 2013; Dzikiti et al., 2018a). According to Dzikiti et al. (2018a) the irrigation infrastructure is already modernized in South African apple orchards and most fruit are produced under the high-pressure irrigation systems mainly micro-sprinkler. Water saving practices such as mulching are the norm in the deciduous fruit industry and several growers use shade nets with the aim of saving as much water as they possibly can.

2.9 MEASUREMENTS OF CROP WATER USE

Crop water use can be measured using several techniques that are either ground based measurements or remotely sensed estimates. The hydrological approaches include (lysimetry and soil water balance-based techniques), micrometeorological methods (Bowen ratio, eddy covariance and surface renewal techniques), remote sensing (remote sensing energy balance and satellite-based crop ET using vegetation indexes) and plant physiology approaches (sap flow techniques and chamber systems). All these techniques have their own advantages and disadvantages, and are subject to unpredictable degrees of uncertainty, intricacy, and require specialized expertise to setup and maintain (Monteith and Unsworth, 1990; Allen et al., 2011; Burba, 2013; Arriga et al., 2017). The micrometeorological techniques have been reported to be generally costly (not easily affordable), they require a lot of time to setup by trained experts in the field who also do not come cheap (Allen et al., 2011; Burba, 2013; Arriga et al., 2017; Mobe, 2020). Despite all the constraints, these techniques have been used and yielded valuable information on the water requirements of apple orchards in South Africa and around the world (Table 2.3).

One technique of measuring tree transpiration that has been reported to be the most accurate is the weighing of lysimeters and because of this, it has been used in several studies as shown in Table 2.3 and many other studies (Ayars et al., 2003; Payero and Irmak, 2008). However, this technique also comes with its own disadvantages, for one, it is very expensive to install in existing orchards and is not easily maintained (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). Another method that researchers have shown great confidence in is the sap flow technique, these sensors have been used in several studies especially in recent years (Table 2.3). Sap flow offers several advantages including the measurements of the water stream within the plant, a potentially high number of replicates, continuous and long monitoring of tree 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) which is suitable for any stem sizes >10mm, ii) thermal dissipation (TDPs) (Granier, 1985) suitable for stems in the range of 50-125 mm, and iii) stem heat balance (Sakuratani, 1981) stem range (2–150 mm). All these methods 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).

Table 2.3: Summary of apple water use measurements in different parts of the world

Cultivar	Rootstock	Age	Technique	Results	Country	Reference
‘Golden Delicious'	Not specified	4	Lysimetry	4.7 l/d	Germany	Blanke, 1996
‘Red Delicious'	MM105	10	Sap flow	25 l/d	New Zealand	Green et al., 1989
‘Golden Delicious'	M9	10	Sap flow	571 mm/season	Israel	Li et al., 2002
‘Splendour'	Not specified	14	Sap flow	4.4 mm/d	New Zealand	Green et al., 2003
‘Royal Empire'	M9	8	Sap flow	5 mm/d	United States	Dragoni et al., 2005
Not specified	Not specified	8	Sap flow & Lysimetry	6.1 - 6.5 mm/d	China	Gong et al., 2008
‘Golden Smoothee'	M9	7	Lysimetry	6 mm/d	Spain	Girona et al., 2011
‘Yellow Delicious'	M9	8	Lysimetry	3.82 mm/d	Spain	Auzmendi et al., 2011
‘Golden Smoothee'	Not specified	9	Sap flow	5 mm/d	Spain	Villalobos et al., 2013
‘Cripps' Pink'	M793	12	Sap flow	638 mm/season	South Africa	Dzikiti et al., 2018b
‘Cripps' Pink'	M793	12	Sap flow	683 - 691 mm/season	South Africa	Gush et al., 2019
‘Cripps' Pink'	M793	12	Sap flow	3.9 mm/d	South Africa	Mobe et al., 2020

2.9.1 Heat Ratio Method (HRM)

The heat ratio method (HRM) of the heat pulse velocity (HPV) technique is a scientific principle for measuring the flow of sap (sap flow/ water use) in plants. This method was developed in the late 90's by scientists from the University of Australia in response to limitations in sap flow techniques that existed at the time. This principle was developed by Burgess et al., (2001) and validated by Bleby et al., (2004). The technique is underlain by the theory of thermal conductance (diffusivity/conductivity) and convection (sap movement or flow). This method consists of a line heater and two thermocouples (temperature sensors) inserted radially into the xylem to determine the heat pulse velocity. The heat pulse is 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 differences at defined locations around the heater (Fig. 2.3).

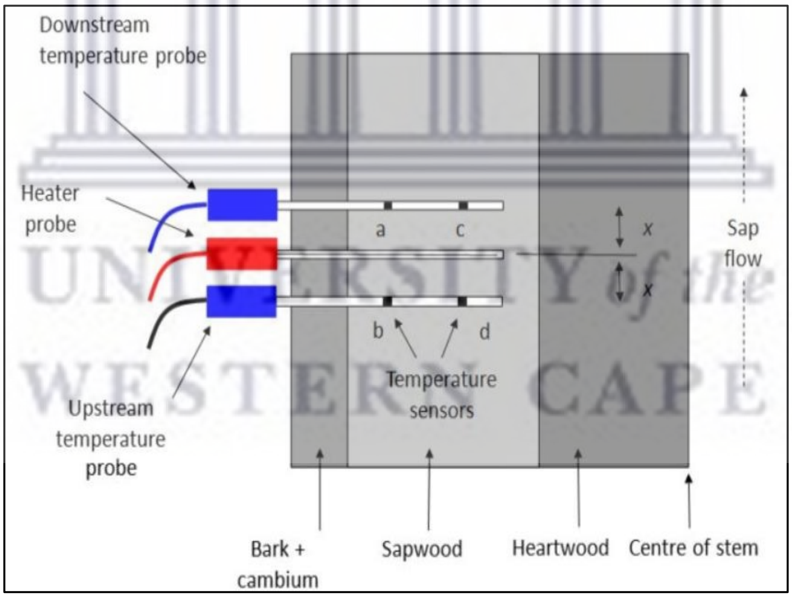


Fig. 2.3: Schematic diagram of the Heat Ratio Method, also showing the different parts of the instrumented plant, adopted from ICT international.

The velocity of the heat pulse (Equation 2.1) is determined by recording the ratio of increase in temperature (relative to ambient sap temperature) measured by the upstream and downstream thermocouples, following the release of a heat pulse by the line heater (Marshall, 1958). The ratio of increase in temperature at the thermocouples (TC) is calculated for TC measurements taken between 60 and 100 seconds after the heat pulse is released. Sap velocity is logarithmically related to the ratio of temperature increases and is calculated as:

$$V_h = \frac{K}{X} In\left(\frac{V_1}{V_2}\right) 3600 \qquad (2.1)$$

Where V_h is the heat pulse velocity (cm/h), k is the thermal diffusivity of the wood (it is assigned a nominal value of 2.5 x 10^{-3} cm^2/s as described by Marshall (1958), x is the distance (cm) between the heater and either temperature probe, v_1 and v_2 are increases in temperature (from initial temperatures) at equidistant points downstream and upstream, respectively.

The heat pulse velocity data can be corrected for wounding according to the method by Swanson and Whitfield (1981). Whole – tree transpiration in litres per day can be calculated as the sum of the sap flows in four circular rings in the sapwood with flow in each ring calculated as the product of the sap velocity at each probe depth and the sapwood area represented by that probe. Sap flux density (*U*, in $cm^3/cm^2/d$) can be derived as the ratio of the daily sap flow rate of an individual tree and the conducting sapwood area. Stand level transpiration (*T*, in mm/d) can then be derived as the sum of the products of the sap flux density and the stand sapwood area index (*SAI*) for trees in different stem diameter classes such that:

$$T = \sum_{i=1,3} SAI_i \times U_i \qquad (2.2)$$

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

This technique is popular for sap flow measurements due to its relatively low cost, low power requirements, and low maintenance (Forster, 2017). Additionally, many sensors can be deployed across multiple species types or across the growth stages of woody plants 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. Furthermore, 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.

The Heat Ratio Method (HRM) being an improvement of the Compensation Heat Pulse Method (CHPM), the main strength of the HRM is that it can measure high, low, zero and even reverse rates of sap flow (Burgess et al., 2001). Many researchers have published using this method and have outlined its advantages which supersedes any disadvantages associated with it (Green et al., 1989; Burgess et al., 2001; Li et al., 2002; Bleby et al., 2004; Dragoni et al., 2005; Clearwater et al., 2009; Gush and Taylor 2014; Miner et al., 2017; Dzikiti et al., 2018b; Mobe et al., 2020a & b; Ntshidi et al., 2020; Mobe et al., 2021).

2.9.2 Thermal Dissipation Probes

The thermal dissipation probe (TDP) method has been widely used for sap flow measurement globally due to its simplicity, reliability, and relatively low cost (Steppe et al., 2010). This method was developed by Granier (1985) based on the work of Vieweg and Ziegler (1960). It is based on the detection of convective heat transport, which is heat that moves with the sap stream (Fernández, 2017). Using the TDP method, transpiration rates are determined based on the temperature difference between a constantly heated probe and a non-heated probe installed in the hydro-active xylem of a tree (Fig. 2.4). 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 as shown in Fig. 2.4 below.

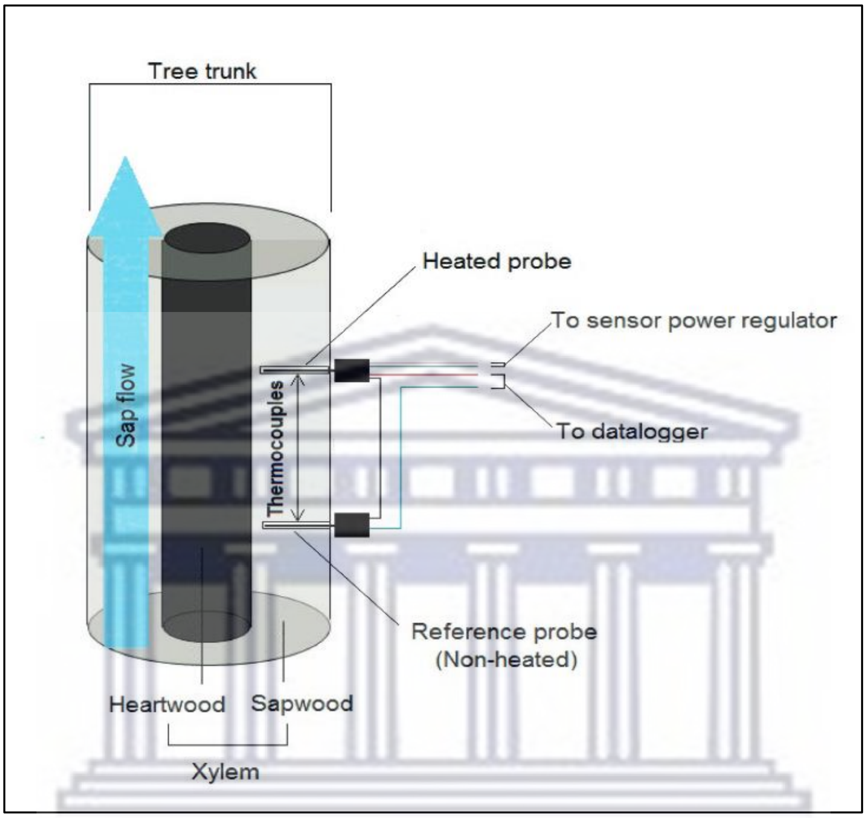


Fig. 2.4: Schematic diagram of the Thermal Dissipation Probe (TDP) sap flow gauge detailing the technical components of the sensor, adopted from Ehsani et al., 2017.

From Granier (1987) average sap flow velocity V (cm/s) may be empirically determined by the exponential expression:

$$V = 0.0119 * K^{1.231} \qquad (2.3)$$

where the parameter K is defined as:

$$\mathrm{K} = \frac{\mathrm{dTM} - \mathrm{dT}}{\mathrm{dT}} \qquad (2.4)$$

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

$$Fs = \mathrm{As} * \mathrm{V} * 3600 \qquad (2.5)$$

where Fs is the sap flux density (cm^3 /h), As 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 may include 1) the effect of the ambient thermal gradient, 2) the underestimation of the night-time sap flow, and 3) the deficient thermal contact between the probe and tree body. The TDP method provides continuously uninterrupted measurements of sap flow while it is also easy to use and less costly (Do and Rocheteau, 2002; Coelho et al., 2012; Reder et al., 2014; Lopez-bernal, 2017).

2.9.3 Stem Heat Balance

The Stem Heat Balance (SHB) method is customarily used on stem sizes in the range of 2 -125 mm in diameter. This technique comprises a partially flexible heater that is wrapped around the crop stem. In this technique, a known constant power, P_{in}, is applied to the plant segment encircled by a small flexible heater, typically a few centimeters in width, wrapped around the organ where sap flow is to be measured (Smith and Allen, 1996).

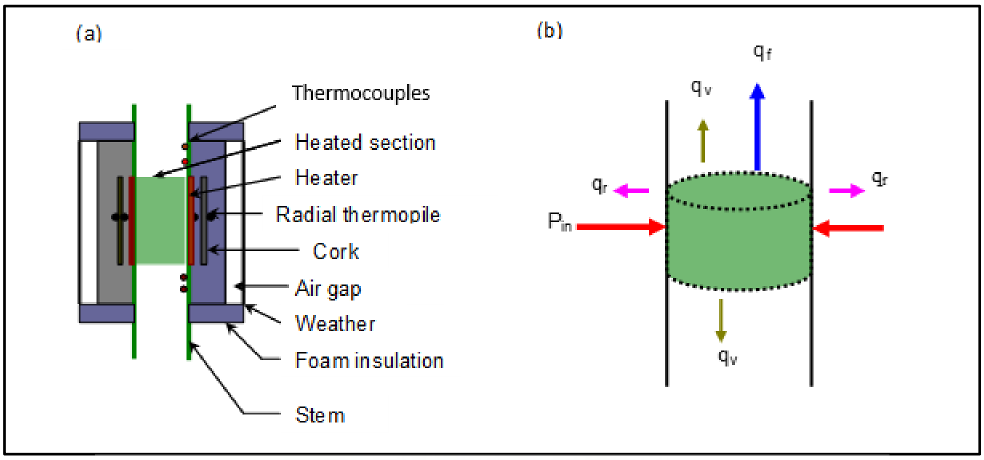


Fig. 2.5: Descriptive representation of the stem heat balance (SHB) sap flow gauge. (a) Vertical cross section through the SHB sap flow gauge. (b) Energy balance components of the SHB sap flow sensor connected to a plant stem. Symbols are referred to intext.

The energy balance equation for that segment is then solved for the amount of heat taken up by the moving sap stream under steady state conditions. This energy carried by the sap stream (Watts) is then utilized to calculate the mass flow of sap (kg/h). Given the need for steady state conditions, it is important that the heater is the sole source of energy and thus insulation of the gauge to cut out energy inputs from the environment is crucial. This is usually achieved by using a radiation shield or aluminium foil to ensure steady state conditions around the gauge are achieved.

Assuming the power input to the plant organ (such as the stem in Fig. 2.5) is P_{in}, then the heat balance of the stem according to Sakuratani (1981) and Baker and van Bavel (1987) can be written as:

$$P_{in} = q_v + q_r + q_f \qquad (2.6)$$

where q_v is the rate of vertical heat loss by conduction, q_r is radial heat loss by conduction and q_f is heat uptake by the moving sap stream. The value of q_f is obtained by subtracting q_v and q_r from P_{in} which all can be measured. If ΔT_a and ΔT_b are the temperature gradients measured by the axial thermocouples above and below the heater and ΔT_r is the radial temperature gradient, then applying Fourier's law for one dimensional heat flow, q_v is calculated using the following equation.

$$q_v = A_{st}K_{st}(\frac{\Delta T_b - \Delta T_a}{X}) \qquad (2.7)$$

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.

$$q_r = K_{sh}\Delta T_r \qquad (2.8)$$

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 and stem diameter. This is determined from the energy balance equation during periods when q_f is zero. 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} are the most likely errors as sensor theory assumes that K_{sh} is constant throughout the day, while this is hardly ever the case. The influence of naturally occurring temperature gradients can be another source of error. Insufficient heater power can lead to extremely low differential temperature signals, and the nonsteady state conditions around the gauge are some of the errors that can severely affect these measurements. Despite the possible error precautions, one main advantage of this method is that its heater flexibility allows for better contact between the plant stem and temperature sensors (Lascano et al., 2016; Vellame et al., 2010; Lof and Welander, 2009; Weibel and de Vos, 1994).

2.10 EVAPOTRANSPIRATION MEASUREMENTS

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 et al., 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, such as 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 description of the soil water balance and eddy covariance that were used in this study are below.

2.10.1 SOIL WATER BALANCE

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:

$$ET = \mathrm{I} + \mathrm{P} + \mathrm{CR} - \mathrm{DP} - \mathrm{RO} \pm \Delta S \qquad 2.9$$

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 ΔS is change in soil storage (all in mm/d).

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 (irrigation and rainfall) and losses (evapotranspiration, runoff and drainage) from the orchard. Components such as deep percolation and surface runoff are often ignored when using the water balance method, since 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. Even though 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. This can minimize the effects of water stress on the plants and the impacts of the changing environmental conditions on crop evapotranspiration and yield can be evaluated.

2.10.2 EDDY COVARIANCE METHOD

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 (Ta) and vertical wind speed (ω) at high frequencies, typically 10-20 Hz, and by estimating the covariance between them:

$$\mathrm{H} = \mathrm{p} C_p \sum (\omega - \varpi)(T_a - \overline{T}_a) \qquad (2.10)$$

where, H is the sensible heat flux (energy used to warm up the air), p is the density of air, C_p is the specific heat capacity of air at constant pressure and Ta is the air temperature.

The wind speed ω and Ta 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.

$$\mathrm{Rn} - \mathrm{G} = \mathrm{H} + \lambda\mathrm{E} \qquad (2.11)$$

where, all terms are usually expressed in Wm^{-2}. The Rn 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 Rn-G represents the available energy. Use of Eq. 2.11 assumes surface energy balance closure (Burba and Anderson, 2010), which is not always achieved in practice. Therefore, 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, measured using an infrared gas analyzer (Burns et al., 2014; Kondo et al., 2014; Wu et al., 2015; Pandey et al., 2017).

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 fundamental cause of the energy imbalance is not well known (Reed et al., 2018; Dhungel et al., 2021). Possible causes may include measurement errors (Rannik et al., 2016), an incompletely considered storage term (Hollinger et al., 2005), mismatches between the scales of the energy balance components (Mauder et al., 2020), and the contribution of large eddies to the energy transport not captured by eddy covariance (Foken, 2008; Schalkwijk et al., 2016).

2.11 EVAPOTRANSPIRATION PARTITIONING

Partitioning of evapotranspiration (ET) into soil evaporation (E) and tree transpiration (T) has been reported to be challenging though essential for water allocations especially in arid and semi-arid regions (Kool et al., 2014). Transpiration is regarded as the desired component as the water is used for plant production, while the evaporation from the soil is regarded as non-beneficial water lost through the orchard floor. The magnitude of the water evaporated from the soil is expected to be extremely significant in sparsely vegetated systems, especially in wet systems like surface irrigated crops and wetlands. In such instances, ET partitioning is crucial to accurately monitor system hydrology and to improve water management practices.

2.11.1 EFFECTS OF ORCHARD FLOOR MANAGEMENT ON ET

Understanding the partitioning of ET in orchards is very important as it can give irrigation managers opportunities to identify and implement practices to reduce orchard floor evaporative fluxes to improve water productivity (Dzikiti et al., 2017; Dzikiti et al., 2018b; Fernández et al., 2018; Ortega-Farias, 2012). In a comprehensive review of 52 publications of ET partitioning, Kool et al. (2014) found that 32 of the studies showed that soil evaporation (E_S) contributed more than 30% of ET. Therefore, managing the orchard floor properly and reducing the water use from its evaporative fluxes can potentially improve water resources in the agricultural sector that is already regarded as the most inefficient water user (NWRS 2, 2013). Of the 52 studies from Kool et al 2014's review, only 20 of the studies independently quantified both E_S and T as well as ET. None of the studies looked at the contribution from the cover crop that grows between tree rows, nor the weeds that are seen in micro-sprinkler irrigated orchards. Therefore, the contribution from the orchard floor fluxes is likely more than the 30% reported if the other orchard floor fluxes are also taken into consideration. Properly managing the orchard floor using mulches to suppress evaporation and regularly mowing the cover crop can reduce orchard floor contribution to the total ET (Losciale et al., 2020).

2.11.2 DRIVERS OF ET PARTITIONING

ET partitioning in orchards can be driven by several factors including but not limited to 1) canopy cover (Lawrence et al., 2007; Ringgaard et al., 2012), 2) irrigation system (Dehghanisanij and Kosari, 2011; Yu et al., 2016), 3) drying cycle (Li et al., 2018; Mark-Mensah et al., 2021), 4) cover crop type (presence or absence of weeds), 5) mulching (Zheng et al., 2018; Wang et al., 2019), 6) ridging, and 7) shade netting (Shen et al., 2019). Depending on the size of the canopy cover, the amount of the orchard floor exposed to the incoming incident radiation and subsequently subject to other environmental factors that influence the evaporative demand differs. In an orchard where the irrigation system does not wet the orchard floor,such as drip irrigated orchard, or wets a fraction of it ,such as in short range micro sprinkler, there should not be much contribution to the total ET from the orchard floor as compared to a wide range micro sprinkler irrigated orchard characterized by a bigger wetted safe in-between the tree rows. As the wetted surface dries, there should be lesser contribution from the orchard floor fluxes. Depending on the cover crop used or any vegetation left to grow in-between the tree rows,such as weeds, the contribution from the orchard floor will likely be greatest in poorly managed orchard floors (Granatstein and Sanchez, 2009). The presence of a mulch, proper ridging, shadenets would likely reduce orchard floor contributions to overall orchard water use (Li et al., 2017; Gong et al., 2017; Zheng et al., 2018; Zheng et al., 2021).

2.11.3 QUANTIFYING ORCHARD FLOOR EVAPORATIVE FLUXES

One way to monitor changes in the orchard floor characteristics, is to keep track of how often the cover crop is mowed or if any herbicides are applied and how much bare soil is exposed over a growing season. The leaf area index of the cover crop can be measured through using a destructive approach wherein a sampling grid with well-known dimensions can be used to mark random positions occupied by the vegetation within the cover crop strip. All the vegetation enclosed in the grid can be cut to ground level and their leaf area measured using any model type leaf area meter suitable for grasses or cover crops. To establish the drivers of water-use by the cover crop, the photosynthetically active radiation (PAR) that is intercepted by the cover crop plants can be measured using ceptometers or solarimeters. Evaporation from the bare soil can be measured by applying the water balance method, using micro-lysimeters (Testi et al., 2004), applying the chamber methods, or even by using micrometeorological methods if applied in a large continuous surface (Tezza et al., 2019).

2.12 ORCHARD FLOOR EVAPOTRANSPIRATION MODELLING

2.12.1 Shuttle and Wallace model

Multiple source ET models were developed to estimate ET for heterogeneous vegetative areas like orchards (Shuttleworth and Wallace, 1985; Li et al., 2010). These types of models do not assume complete uniformity throughout the orchards or plantations, but rather account for the heterogeneity in surface characteristics (such as, Shuttleworth and Wallace, 1985; Choudhury and Monteith, 1988). When evaluating irrigation management regimes, such considerations are crucial, as soil evaporation has been reported to contribute quite substantial amounts to the total ET (Kool et al., 2014), especially in spaces with sparse canopies. Many researchers (Oguntunde et al., 2007; Villalobos et al., 2009; Li et al., 2010; Ding et al., 2013) gave examples of multiple source models applied to orchards. However, the Shuttleworth and Wallace (S-W) model has received good feedback and is considered the most accurate model (Stannard, 1993; Zhou et al., 2006; Hu et al., 2009).

The Shuttle and Wallace (S-W) model is a two-source model that is based on two Penman-Monteith models, one for estimating soil evaporation (soil surface model) and the other for estimating transpiration (plant surface model) (Dolman, 1993; Brisson, 1998). The S-W model provides the opportunity to partition ET into plant and soil components using 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 surface and the atmosphere (Farahani and Bausch, 1995). Evapotranspiration ($\boldsymbol{\lambda}E$T, in W m^{-2}) is then estimated as the algebraic sum of the fluxes from transpiration and soil evaporation as:

$$\lambda\mathrm{ET} = \lambda T + \lambda E \qquad (2.12)$$

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

$$\lambda T = C_c \frac{\Delta A + \left\{\frac{\rho c_p D - \Delta r_a^c A_s}{r_a^a + r_a^c}\right\}}{\Delta + \gamma\{1 + r_s^c/(r_a^a + r_a^c)\}} \tag{2.13}$$

$$\lambda E = C_s \frac{\Delta A + \left\{\frac{\rho c_p D - \Delta r_a^s (A - A_s)}{r_a^a + r_a^s}\right\}}{\Delta + \gamma\{1 + r_s^s/(r_a^a + r_a^s)\}} \tag{2.14}$$

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}), cp 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.

Even though 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 to some extent 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. Previous models of water use in orchards (Gush and Taylor, 2014) have assumed that the contribution of cover crops to orchard ET is negligible. This assumption is unlikely to be true given that some cover crops, such as the fescues have vigorous growth habits (Roberts et al., 1988; Hannaway et al., 1999).

2.12.2 PRIESTLEY AND TAYLOR MODEL

The Priestley–Taylor (P-T) equation, which only requires radiation observations as inputs was developed as a substitute to the Penman–Monteith (P-M) equation (Monteith, 1965) to eliminate reliance on observations. The concept that underlies this model is that an air mass moving above a vegetated area with abundant water would become saturated with water (Priestley and Taylor, 1972). In these conditions, the actual evapotranspiration would match the Penman rate of potential evapotranspiration. However, observations revealed that actual evaporation was 1.26 times greater than potential evaporation, and therefore the equation for actual evaporation was found by taking potential evapotranspiration and multiplying it by $\propto$ (P-T coefficient = 1.26). Even though P-M approach has proven to be remarkably accurate and robust for estimating potential ET in a wide range of conditions, its application was limited by the frequent unavailability of meteorological variables. The P-T model does not consider aerodynamic properties and physiological behaviour of the surface and is given by:

$$\lambda ET = \alpha \frac{\Delta}{\Delta + \gamma} (R_n - G) \qquad (2.15)$$

where, λET is actual evapotranspiration, α is a model coefficient that varies according to the degree of dry/wet (Priestley and Taylor, 1972), Δ is the slope of the saturation vapor density curve (kPa K^{-1}), γ is the psychrometric constant (Pa °C $^{-1}$), Rn is net radiation (W m^{-2}), and G (W m^{-2}) 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. Generally, the P-T coefficient ranges from 0 for 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). Nonetheless, various studies (Fisher et al., 2008; Jin et al., 2011; Yao et al., 2015; Hssaine et al., 2018) have emphasized that the P-T coefficient is variable under different surface and atmospheric conditions and therefore, accurate quantification of this parameter is necessary to yield good estimates.

2.13 CHAPTER SUMMARY

The outcomes of the review of relevant literature shows that the water use of apple trees has been extensively studied globally. However, what remains unknown is how this water use is partitioned into its constituent components. Specifically, the water use of cover crops and their contribution to the water balance in orchards remains unknown. Sap flow techniques have successfully been used in many studies and their advantages have proven to outweigh any disadvantages associated with them, as presented in several studies across the world. Meteorological data can be used to model crop water use where continuous measurements may not be feasible. Multiple source ET models have been used to estimate water use for heterogenous vegetation as they do not assume complete uniformity throughout the orchard, but rather account for the heterogeneity in surface characteristics.

CHAPTER 3: WATER USE CHARACTERISTICS OF INDIGENOUS AND EXOTIC COVER CROPS USED IN FRUIT ORCHARDS

Experimental layout in the greenhouse

Parts of this chapter are published as:

Z Ntshidi, *S Dzikiti, D Mazvimavi, NT Mobe, Y Mkunyana (2021). Water use of selected cover crop species commonly grown in South African fruit orchards and their response to drought stress. Physics and Chemistry of the Earth, Parts A/B/C 103070.*

ABSTRACT

Cover crops are widely planted in orchards for a variety of reasons. These include suppressing soil erosion, nutrient cycling, phytosanitary purposes, general orchard aesthetics,to name a few. However, there is a need to balance these benefits against use of scarce resources such as water and nutrients. Currently no information exists on how different cover crop species use water in orchards and how they cope with drought stress. The aim of this study was therefore to compare the transpiration dynamics of various cover crop types in order to identify species with conservative water use rates. Studied species included: 1) two exotic legumes,namely, Lupine (*Lupinus albus* L.), and Common vetch (*Vicia sativa*), 2) three exotic grasses, namely, Tall fescue (*Festuca arundinacea*), Rye grass (*Lolium perenne*), and Kikuyu grass (*Pennisetum clandestium*) and; 3) grasses that are indigenous to sub-Saharan Africa, namely, African Lovegrass (*Eragrostis capensis*) and Rhodes grass (*Chloris gayana*). The crops were planted in pots under controlled greenhouse conditions. Transpiration rates were quantified using miniature stem heat balance sap flow gauges and by manual weighing. Drought stress was imposed by withholding irrigation at selected intervals and the responses were quantified through changes in the water relations of the plants. The study showed that exotic legumes had the highest daily water use which peaked at about 2.4 litres per square metre of leaf area per day (L/m^2/d), followed by exotic grasses at 1.5 – 2.0 L/m^2/d. The indigenous grasses used the least water ranging from 0.8 to 1.2 L/m^2/d. The indigenous grasses largely displayed an isohydric response to drought stress by maintaining their leaf water status with increasing soil water deficit. The exotic species, on the other hand, showed risk taking behaviour (anisohydry) wherein both the transpiration and leaf water status decreased sharply as drought stress increased. Consequently, some exotic species failed to recover when stress was relieved. From a water use perspective, this study demonstrates that indigenous grass species are more appropriate as cover crops in South African orchards because of their low transpiration rates and the ability to cope with extended periods of water deficit.

3.1 INTRODUCTION

In South Africa as elsewhere in the world, cover crops are commonly planted between tree rows in orchards for various purposes. They are important in maintaining the soil structure (Fageria et al., 2005), encouraging water infiltration (Busscher et al., 1996), reducing soil erosion, reducing mud and dust, and maintaining an acceptable surface for moving farm machinery (Hartwig and Ammon, 2002; Panagos et al., 2015). Cover crops can also enhance soil fertility through nitrogen fixation and increasing the organic matter content in the soil (Reicosky and Forcella, 1998; Chen et al., 2003). They also play a role in suppressing weeds, and hosting beneficial natural organisms that control pests and diseases in orchards (Sarrantonio and Gallandt, 2003; Guerra and Steenwerth, 2012). This in turn results in the reduced use of agrochemicals, mainly pesticides and herbicides that are harmful both to humans and the environment.

Various plant species are often used as cover crops in orchards worldwide. These include both grasses and legumes (Wilson et al., 1982). Fynbos, *a sclerophyllous* shrub dominated by species of the *Proteaceae*, *Ericaceae* and reed-like *Restionaceae* which is endemic to the Cape Floral Regions (Rebelo et al., 2006), is also being used in some commercial orchards in South Africa (Johan Burger, pers. comm.). Grasses, rather than legumes, are by far the most commonly found cover crops species in orchards (Roper, 1992). A major question surrounding the use of cover crops in orchards revolves around whether the benefits derived from them exceed the losses, particularly of scarce resources such as water and nutrients (Jannoyer et al., 2011). For example, during recent devastating droughts in South Africa (2016-2018), many farmers instinctively removed cover crops supposedly to lower the orchard water use (Wiehann Steyn, pers. comm.). Given that currently no accurate quantitative information exists on the water use of cover crops, these actions beg the following questions: Firstly, how much water do cover crop species use in orchards under semi-arid sub-tropical conditions? Secondly, how does this water use differ between species? Thirdly, how do orchard management practices, such as use of the cover crops, influence overall orchard water use? An ideal cover crop maximizes the benefits while at the same time it reduces costs, for example, through excessive water use and competition for resources with the orchard trees (Jannoyer et al., 2011).

Water use in orchards is driven by factors such as the evaporative demand of the air (includes available energy, as well as the influence of other climatic factors such as wind speed and relative humidity), available soil moisture (irrigation and rainfall), and by management (canopy cover, cultivar, mowing practices, irrigation system, and irrigation frequency) (Dragoni et al., 2005; Dzikiti et al., 2018b; Gush et al., 2019). Given the large number of cover crop species used in commercial fruit orchards and the complex interactions between the factors influencing their water use, this study focused on a representative selection of cover crop types. These were selected from the major crop groupings such as, exotic legumes, exotic grasses, and grasses that are indigenous to sub-Saharan Africa. Secondly, to gain detailed insights on how the different species respond to specific water use drivers, the study was conducted under controlled conditions in a greenhouse. This allowed the selected species to be exposed to similar environmental conditions and for the influence of specific stressors to be studied independently (Dzikiti et al., 2007). Thirdly, the greenhouse experiments also eliminated the confounding influence of trees in orchards, mostly competition for resources such as light, nutrients, water, and variations induced by uneven irrigation on the orchard floor. In this way effects of specific environmental factors were studied.

The water use of grasses has been studied before using different techniques as summarized in Table 3.1. Besides the work by Everson et al. (2011) on grassland in the KwaZulu-Natal Drakensberg in South Africa, no comparative studies exist on the water use and drought stress responses of grass and legume cover crops. Detailed quantitative information on the water use of cover crops is required to improve water resources management in orchards. The specific objectives of this study were therefore to compare the water use rates of selected cover crop species subjected to similar growing conditions. As most cover crops are often irrigated in orchards, the second objective was to study how the different species responded to drought stress. We use this information to provide recommendations on the most appropriate cover crop species for orchards under semi-arid conditions based on their water requirements and resilience to drought stress.

Table 3.1: Summary of water use measurements in grasses in different parts of the world.

Species	**Measurement method(s)**	**Water use**	**Reference**	**Scale**	**Country**
Tussock grass	Sap flow/ gravimetric/gas exchange/modelling	44.4 - 166.7 mol H_2O $m^{-2}d^{-2}$	Ramirez et al., (2006)	Individual plant	Spain
Prairie grasses	Sap flow	≤ 4 g/h	Senock & Ham, (1995)	Individual plant	USA
Grassland	Bowen ratio energy balance technique	~695 mm/year	Everson et al., (2011)	Stand/catchment	South Africa
Kikuyu grass	Lysimetry	~ 4.41 mm/d	Van Vuuren, (1997)	Stand level	South Africa
Creeping bent grass	Lysimetry	~4.21 mm/d	Van Vuuren, (1997)	Stand level	South Africa
Kikuyu grass	Neutron probes (soil water balance)	~775 mm/year	Marais et al., (2006)	Individual plant	South Africa
Buffel grass	Neutron probes (soil water balance	~782 mm/year	Marais et al., (2006)	Individual plant	South Africa
Bioenergy grass crops	Sap flow	850-1150 mm/season	Erickson et al., (2012)	Individual plant	USA
Perennial Pasture grasses	Neutron probes (soil water balance)	~400 mm/season	Parry et al., (1992)	Individual plant	New Zealand
Turf grass	Crop coefficient	1407 acre feet/year	Shapiro et al., (2015)	Stand	California
Buffalo grass	Crop coefficient	871 acre feet/year	Shapiro et al., (2015)	Stand	California
Legumes	Neutron probes (soil water balance)	266 mm/year	Siddique, (2001)	Single plant	Australia
Warm season legumes	Neutron probes (soil water balance)	19.6 kg/ha/mm	Rao & Northup, (2009)	Single plant	USA
Cover crops	Neutron probes (soil water balance)	~252 mm/year	Nielsen et al., (2015)	Single plant	USA

3.2 MATERIALS AND METHODS

3.2.1 Plant material

Given the wide range of cover crop species planted in commercial orchards, we selected only seven species for practical reasons. These were categorized into three groups namely exotic legumes, exotic grasses, and grasses that are indigenous to sub-Saharan Africa. Two legumes were studied i.e., Lupine (*Lupinus albus* L.), and Common vetch (*Vicia sativa*). Although these are planted in some orchards, they are not widely used in South African orchards. Instead, exotic grasses are more common, and for this study, we selected three types namely Tall fescue (*Festuca arundinacea*), Rye grass (*Lolium perenne*), and Kikuyu grass (*Pennisetum clandestium*). Of these, Tall fescue is more popular among fruit farmers in South Africa for unclear reasons. Indigenous grasses are not planted in most instances. Rather farmers simply manage the natural grasses in the same way as they do the exotic species although the seeds of indigenous species are also sold commercially. Two indigenous grasses were selected namely the African Lovegrass (*Eragrostis capensis*) and Rhodes grass (*Chloris gayana*). The cover crops were planted in pots as seeds sourced from a local hardware outlet.

3.2.2 Experimental layout

The cover crops were planted in 2½ litre pots in a greenhouse at the Department of Agronomy, Stellenbosch University (33°56'30.49" S; 18°51'58.89" E; 330 m asl) in January 2017. The greenhouse measured about 15 m x 5 m x 3 m (Fig. 3.1), and it was covered with a UV stabilised transparent plastic sheeting with a transmittance of about 88%. About 40 seeds were planted per pot for each grass species. These were thinned to 35 plants per pot after emergence. For the legumes, 20 plants were planted per pot as these tended to be bulky. There were five plant pots per species, so data were collected in five replicates. A standard commercially available potting mixture was used as the growing medium. This comprised of garden soil, compost, sand, sphagnum peat moss, coir fibre, composted pine bark, perlite, vermiculite, limestone, and fertilizers in varying proportions. Irrigation was applied to each pot using a drip irrigation system that delivered about 2 litres of water per hour. Each pot received two to three pulses of irrigation per day each lasting about 25 minutes depending on the weather conditions. The plant pots were randomly arranged in the greenhouse (Fig. 3.1).

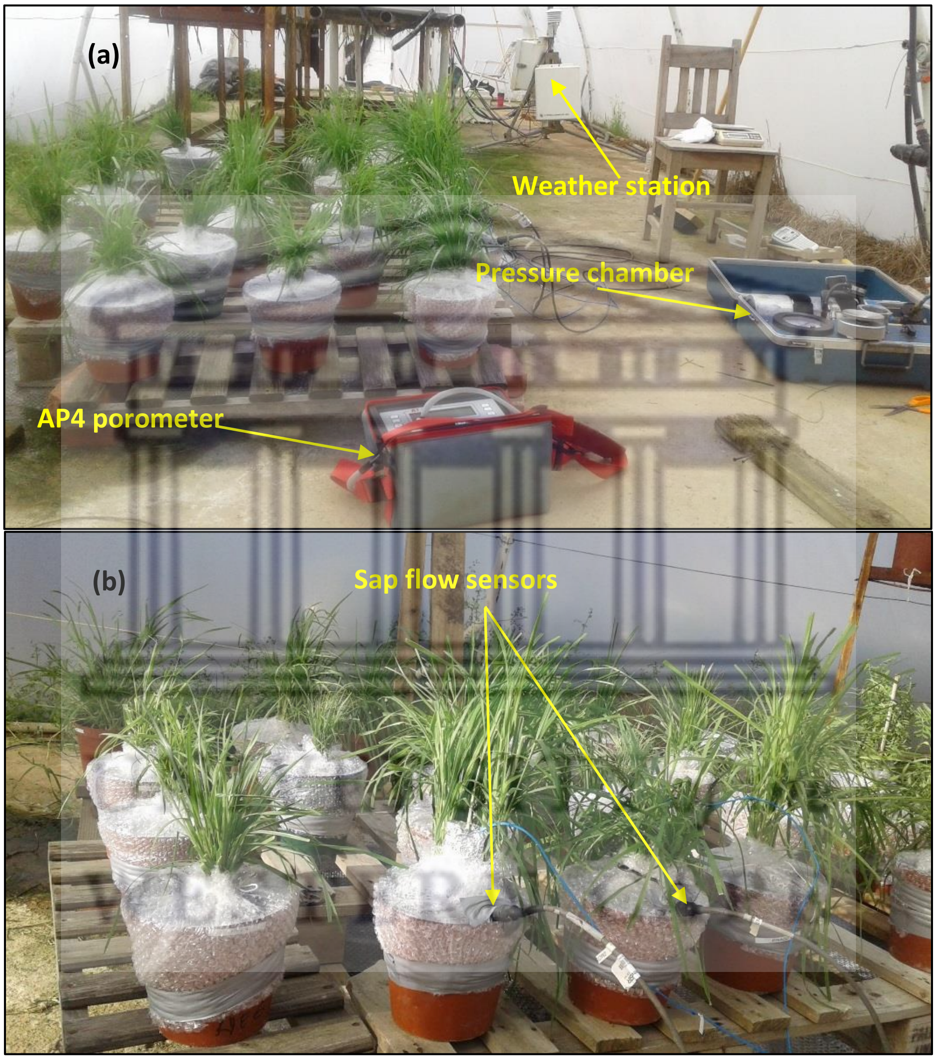


Fig. 3.1: Setup in the greenhouse showing; (a) position of the weather station in relation to the potted plants; (b) sap flow sensors installed in pots wrapped with plastic.

3.2.3 Microclimate and soil measurements

Weather conditions inside the greenhouse were measured using an automatic weather station installed in the middle of the greenhouse (Fig. 3.1a). The equipment comprised a pyranometer

(Model SP 212 Apogee Instruments, Inc., Logan UT, USA) which measured the solar irradiance. The sensor was 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 temperature and humidity probe (Model: HMP60 Campbell Scientific, Inc., Logan UT, USA) installed at a height of about 2.0 m above the ground. The soil water potential was measured using electronic tensiometers (Model: 200SS Campbell Scientific, Inc., Logan UT, USA). All the sensors were connected to a data logger (Model: CR1000 Campbell Scientific, Inc., Logan UT, USA) programmed with a scan interval of 10 s and the output signals were processed at hourly and daily intervals.

3.2.4 Transpiration, stomatal conductance, and leaf water status

To understand the daily water use dynamics of the different cover crop species transpiration was measured using two independent methods. These included gravimetric monitoring in which plant pots were weighed at hourly intervals on selected days (Xin et al., 2008) using a precision balance (Model SNUG III Jadever; Taiwan, China) that measured mass to the nearest 0.1 g. The second method involved using miniature stem heat balance sap flow gauges (Model SGA 2 & 5; Dynamax Houston, USA) (Van Bavel and Van Bavel, 1990) and details are shown in Table 3.2. For the gravimetric method precautions were taken to suppress evaporation from the open soil by wrapping the pots with plastic during measurements (Fig.3.1). Sap flow sensors were used to collect transpiration data over long periods when gravimetric measurements were not practical. At the end of each measurement cycle, all the plants were cut and their leaf area measured using the leaf area meter (Model Li-3000, Li-COR Inc., Nebraska, USA). The transpiration data was normalized with the transpiring leaf area to eliminate bias due to plant size variations. These data, collected over several days, formed the baseline data showing the typical responses of each cover crop species to climatic driving factors when the plants were well-watered.

Table 3.2: Summary of sap flow gauges used to measure water use during the stress trial. CTRL represents the control treatment.

Gauges	**Species**	**Gauge type**	**Heater resistance (Ohms)**	**Input volts**	**Stem diameter (cm)**	**Leaf area (cm^2)**	**Treatment**
Gauge 1	Eragrostis	SGA2	95.1	2.3	2.4	26.85	CTRL
Gauge 2	Eragrostis	SGA2	93.6	2.3	2.2	21.72	Stress
Gauge 3	Lupine	SGA5	180.8	4	4	89.48	CTR
Gauge 4	Lupine	SGA5	177.9	4	3.8	77.64	Stress
Gauge 5	Rye	SGA5	179.6	4	2.6	33.24	CTRL
Gauge 6	Rye	SGA5	186	4	2.5	29.78	Stress

To establish quantitative relationships between leaf water status and the extent of stomatal opening for the various species, the leaf water potential was measured concurrently with the stomatal conductance when the available soil water was not limiting. These data were collected hourly from sunrise to sunset on selected cloudless days. The leaf water potential was measured using a Scholander-type pressure chamber (Model: 615 PMS Instrument Company, Albany, OR, USA) while the stomatal conductance was measured using a diffusion porometer (Model AP4: Delta-T Devices, Cambridge, UK).

3.2.5 Assessing cover crop response to water deficit

The choice of micro sprinkler irrigation system in orchards (whether narrow or wide range) is informed, not only by the desire to encourage the development of an extensive root system, but also to supply water to cover crops and to maintain biodiversity (Jannoyer et al., 2011). Wide range micro sprinklers inevitably use larger amounts of water than narrow range ones (Knox et al., 2012). Therefore, the selection of drought tolerant cover crops is essential in orchards with drip irrigation or narrow range micro sprinklers. To assess the sensitivity of the different species to drought stress, we used plants grown in 20 L containers with higher water storage capacity. One pot of a selected species was well-watered while drought stress was imposed on a second pot by withholding irrigation over a number of days. The transpiration, plant water status, stomatal conductance and soil water potential were measured over drying cycles typically lasting 5 to 6 days. The stress was relieved at the end of the cycle and data collection continued during the recovery phase. We calculated a transpiration reduction coefficient ($T_{R,}$ $\%$) to quantify the impact of water stress on transpiration calculated as:

$$T_R = (1 - {}^{T_{ds}}\!/_{T_c}) \times 100 \qquad (3.1)$$

where T_c is the daily transpiration per unit leaf area (L/m^2/d) for the control treatments, and T_{ds} is the daily transpiration per unit area (L/m^2/d) for the drought stress treatments. Because of the need for continuous data during the drying cycle, the transpiration measurements were taken using the stem heat balance sap flow gauges. Also given equipment limitations, the data were collected on only three species namely Lupine, Rye and *Eragrostis* grass representing each of the three crop groupings.

3.2.6 Statistical analysis of variance (ANOVA)

A one-way analysis of variance (ANOVA) was used to determine whether there were any statistically significant differences in the water use of the different cover crop species. The water use of each species from five different replicates of the same species were used. The differences were compared within the species, also to other species. We tested the hypothesis:

$$Cw1 = Cw2 = Cw3 = \cdots Cw\_z \qquad (2)$$

where: Cw is the average water use for each treatment.

3.3 RESULTS

3.3.1 Climatic factors and transpiration dynamics

The diurnal course of the key climate drivers of water use namely the solar radiation (Rs) and the vapour pressure deficit of the air (VPD) on a typical cloudless day on 20 September 2017 is shown in Fig. 3.2a. Solar radiation peaked at 600 W/m^2 around noon at 12:00 (Local time = GMT + 2 h) while the VPD reached a maximum of about 3.5 kPa about two hours later at 14:00 (Local time = GMT + 2 h). The maximum air temperature recorded on this day exceeded 40 ˚C, typical of greenhouse conditions. Also on this day, all the plants were well-watered, so the transpiration values represent the baseline water use for each species when water availability is not limiting. The transpiration data were collected using the gravimetric method, so each value in Fig. 3.2b is an average of measurements from five plant pots.

The exotic legumes (Lupine and Common vetch) had the highest hourly transpiration rates which exceeded 0.30 L/m^2/h (Fig. 3.2b). This was followed by the exotic grasses at around 0.28 L/m^2/h. Among the exotic grasses, Kikuyu grass that originates from the tropical and sub-tropical climates in East Africa, had the lowest water use rates close to 0.20 L/m^2/h. Overall the indigenous grasses (*Eragrostis* and Rhodes grass) had the lowest transpiration rates that peaked between 0.10 and 0.16 L/m^2/h.

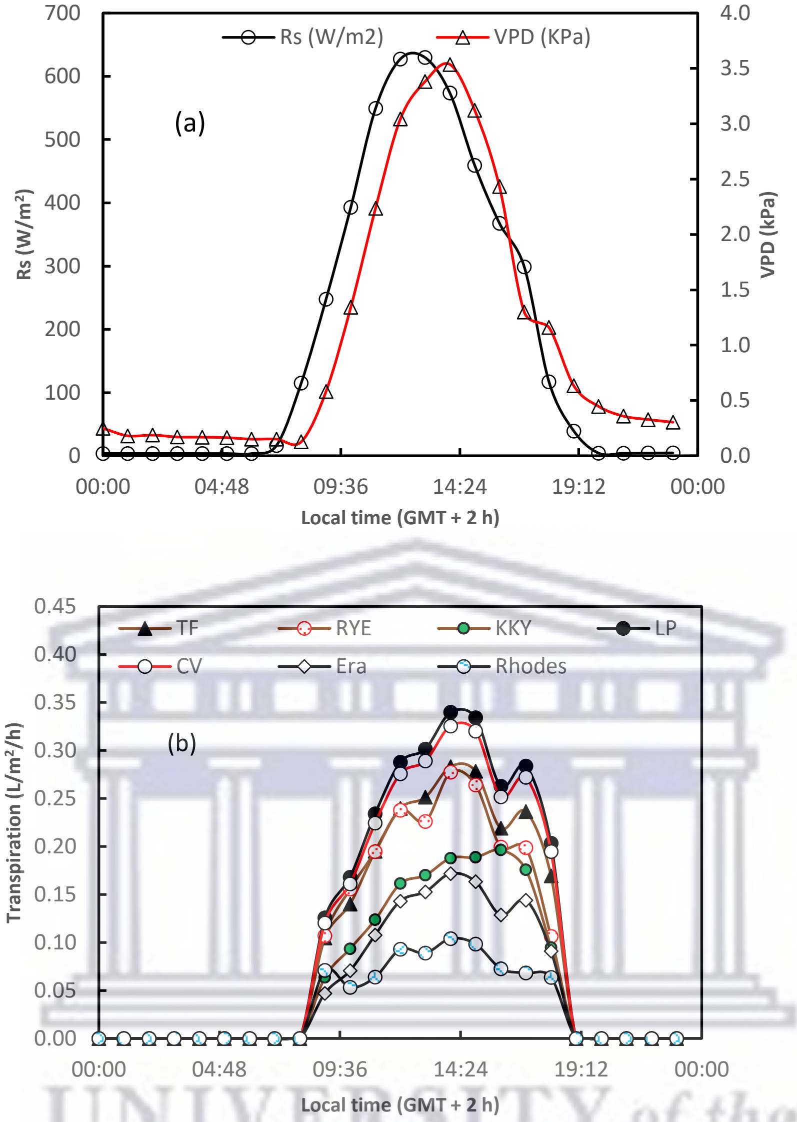


Fig. 3.2: (a) Typical clear day showing the solar radiation (Rs) and the vapour pressure deficit (VPD) of the air in the greenhouse, (b) Different cover crop species' water use, recorded on 20 September 2017. TF (Tall fescue), KKY (Kikuyu), LP (Lupine), CV (Common vetch) and Era (Eragrostis).

The daily total transpiration per unit leaf area summarized in Fig. 3.3 followed the trend described earlier. These ranged from 2.3 to 2.5 L/m^2/d for the legumes, 1.5 to 2.1 L/m^2/d for the exotic grasses and 0.8 to 1.2 L/m^2/d for the indigenous grasses.

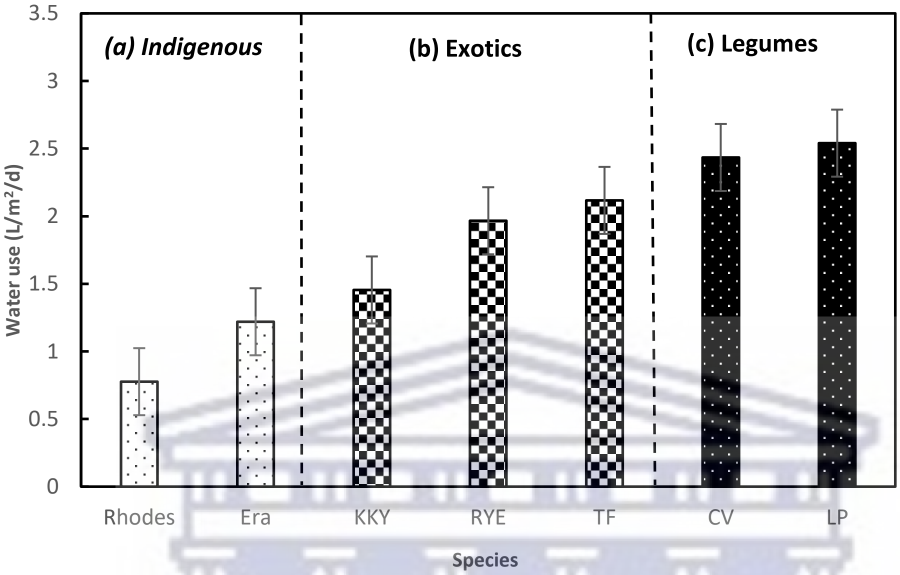


Fig. 3.3: Transpiration rates of different cover crop species.

Water use by plants is driven by the evaporative demand of the air (mainly climatic factors), the available soil water, as well as total leaf area. So, under the well-watered conditions, the solar radiation incident on the crops and the VPD were the main drivers of water use in this experiment. Unlike some irrigated orchard tree species, for example, apple (Dzikiti et al., 2018b) and some citrus cultivars (Gush and Taylor, 2014), the relationship between the hourly transpiration and solar radiation was curvilinear showing a strong hysteresis effect between the morning to midday rise and the midday to sunset decline in transpiration illustrated in Figs. 3.4a, c, e, g, & i. Within each hysteresis loop the coefficient of determination was very high ranging from 0.91 to 0.98. The reasons for the hysteresis effect are unclear, but the capacitance (buffering effect) of the internally stored water controlling stomatal functioning due to changes in leaf water status could be a factor (Steppe et al., 2006a). In contrast, the relationship between the hourly transpiration and the VPD was strongly linear suggesting that the VPD had a very limited effect on the stomatal function. This again contrasts with what has been observed for various tree species in which stomata begin to close when the VPD exceeds values just above 1.0 kPa. The responses to the climate driving variables were similar for all cover crop species.

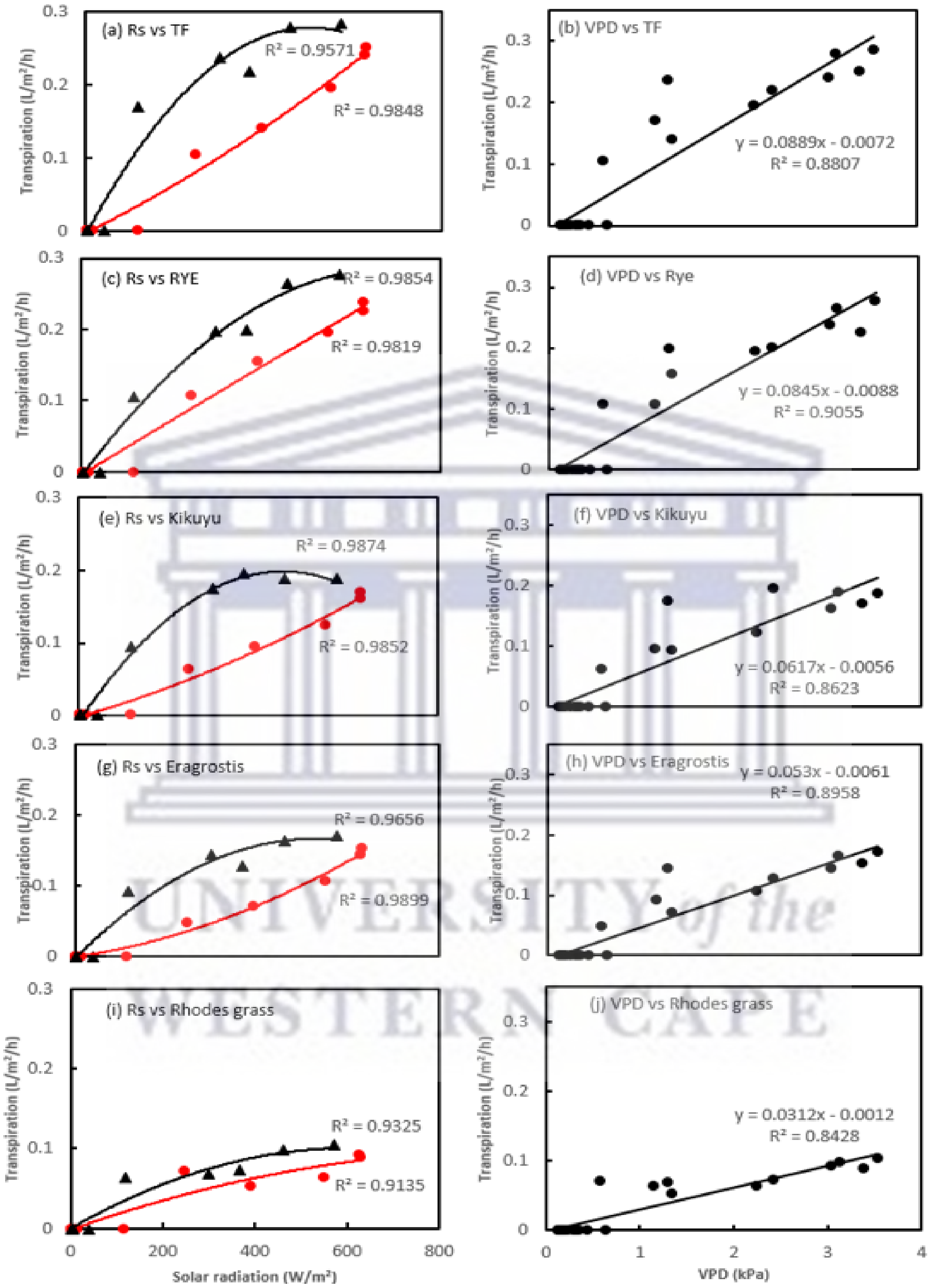


Fig. 3.4: Correlation of cover crop transpiration with weather variables i.e.; (a) Tall fescue (TF) with solar radiation (Rs), (b) TF with VPD, (c) Rye grass (RYE) with Rs, (d) RYE with VPD, (e) Kikuyu (KKY) with Rs, (f) KKY with VPD, (g) Eragrostis (Era) with Rs, (h) Era with VPD, (i) Rhodes grass (Rhodes) with Rs and (i) Rhodes with VPD. The red line shows the morning curve while the black line shows the afternoon curve, demonstrating the hysteresis effect between solar radiation and transpiration.

As expected, the diurnal trend in the stomatal conductance for all the species was strongly related to the transpiration trend, but differences in magnitude between the various species were also quite apparent (Fig. 3.5). However, there was a significant difference in the timelags between stomatal opening (in response to light stimuli) and the commencement of transpiration (in response to the water potential gradient) which was as much as two hours for some species (Fig. 3.6). While this observation is not quite expected for such small plants, it supports the hysteresis observed with the solar radiation (in Fig. 3.3) likely related to the capacitance effects associated with the various species. The ranges of the measured stomatal conductance (Gs) was approximately 0 to 100 mmol/m^2/s for the indigenous cover crops including Kikuyu, 0 to just above 150 mmol/m^2/s for Tall fescue and rye and 0 to close to 200 mmols/m^2/s for the legumes. The stomatal conductance trends were clearly consistent with the transpiration trends.

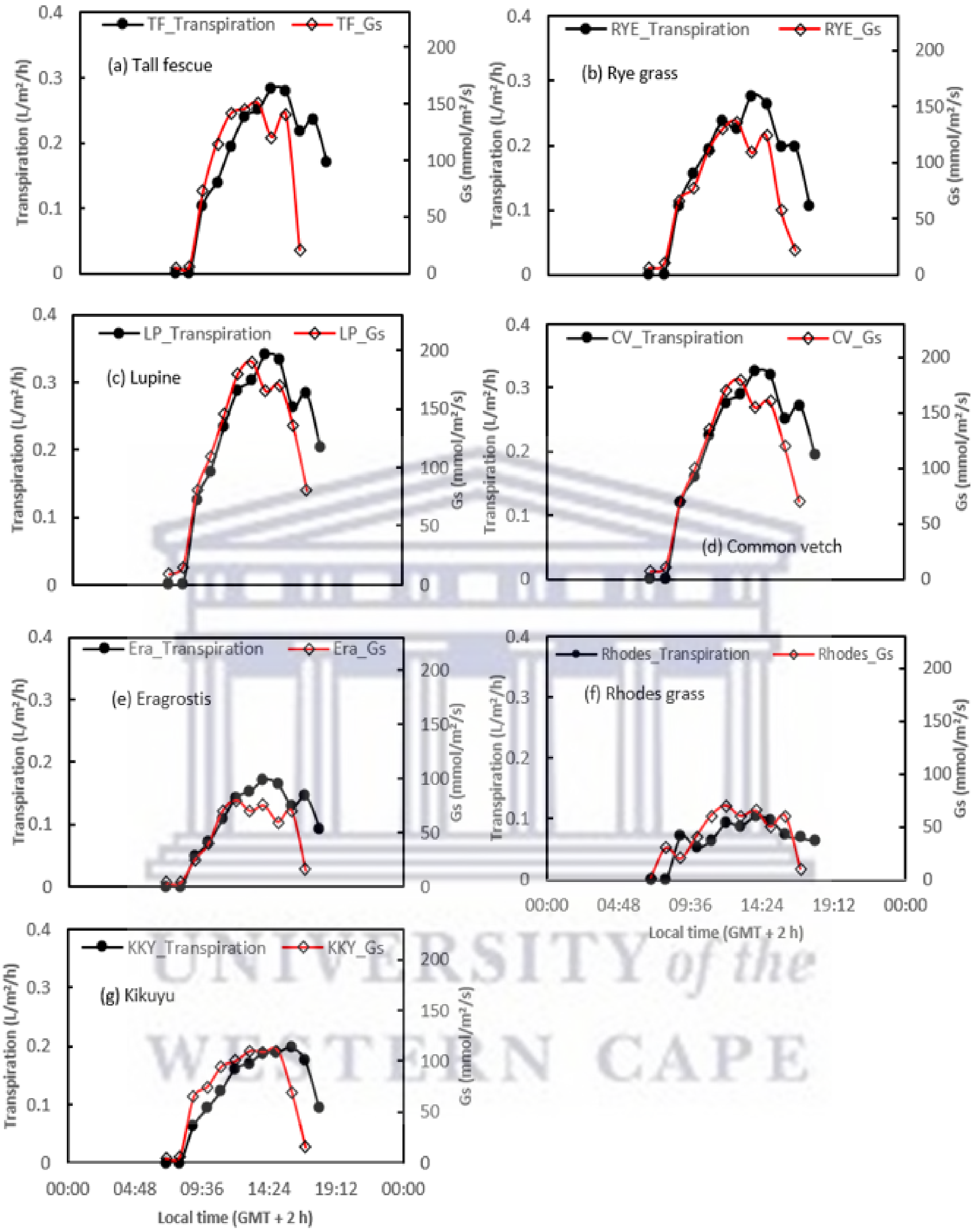


Fig. 3.5: Transpiration of each cover crop species in relation to the stomatal conductance (Gs) presented in the order (a) TF, (b) RYE, (c) Era, (d) Rhodes, (e) Lupine (LP), (f) Common Vetch (CV) and (g) KKY.

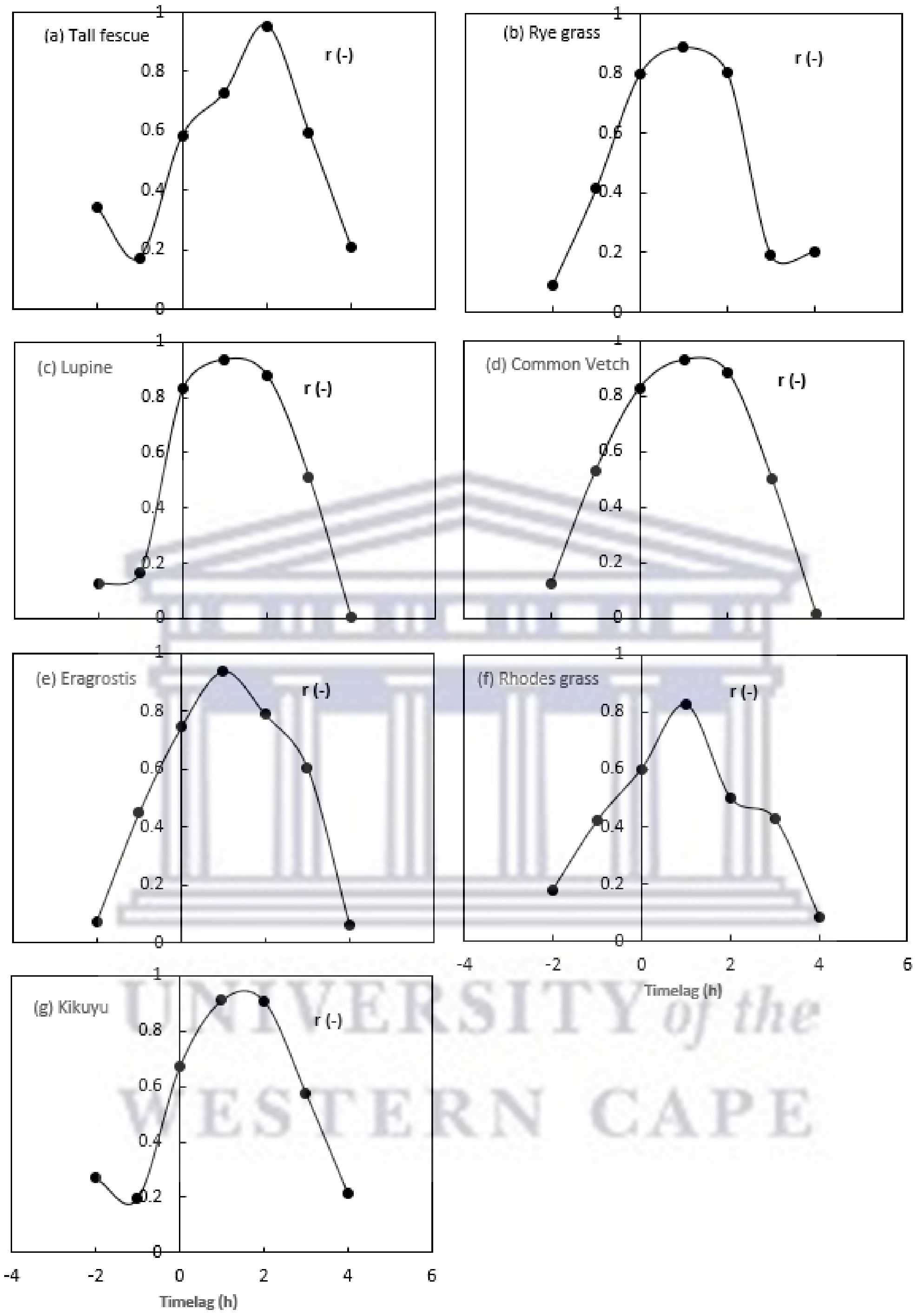


Fig. 3.6: Timelags between stomatal opening and commencement of transpiration for the different cover crop species

The effect of drought stress imposed over a five-day period from 28/11/2017 to 02/12/2017 on the water relations of Lupine, Rye grass and *Eragrostis* are shown in Fig. 3.7. All the days were cloudless except for small patchy clouds on the last day of the drying cycle (data not shown). For the control Lupine (Fig. 3.7a), the stomatal conductance range was fairly consistent over all the days. The same can be said about the leaf water potential which never dropped below -1.5 MPa. However, for the stressed Lupine, some closure of the stomata was apparent although there was a much clear decline in the leaf water status to below -2.0 MPa (Fig. 3.7b). The associated decline in the transpiration rates with increasing soil water tension are illustrated in Fig. 8a and b. Plants that allow their water status to drop with increasing stress or atmospheric evaporative demand, such as Lupine are called anisohydric plants. Rye grass also showed a similar response to Lupine although the minimum leaf water potential for the well-watered control plants was much higher at -0.98 MPa (Fig. 3.7c). The leaf water potential declined to about -1.70 MPa under stress (Fig. 3.7d). The associated transpiration changes for Rye grass for the control and stress treatments are illustrated in Fig. 3.8 c and d.

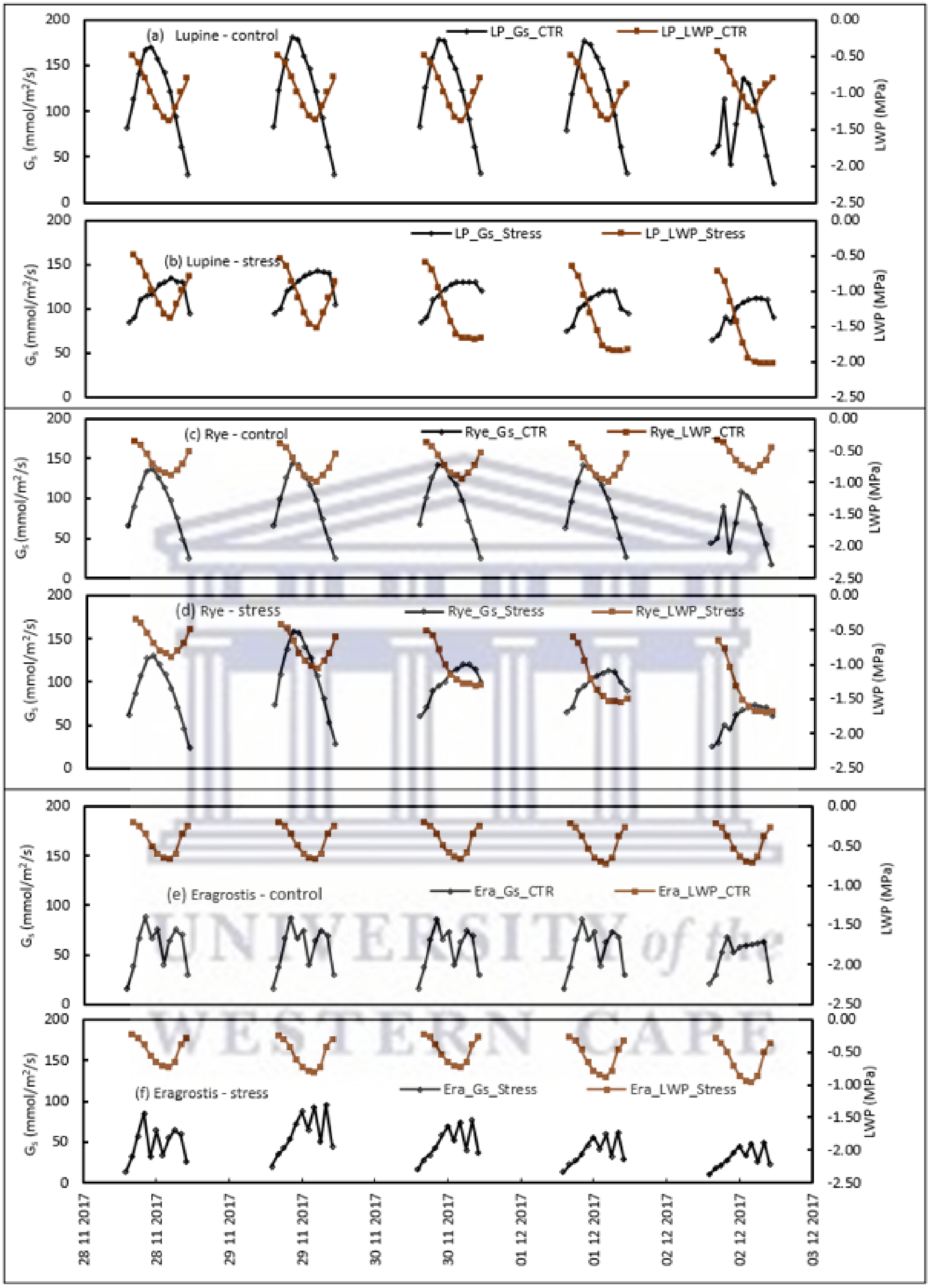


*Fig. 3.7**:** Comparison of stomatal conductance (Gs) with total leaf water potential (LWP) for Lupine (legume), Rye (exotic) and Eragrostis (indigenous), over a wet-dry period from 28/11/2017 to 02/12/2017.*

Although similar treatments were imposed on the indigenous *Eragrostis*, its response was different from that of the exotic species (Figs 3.7 e and f). Firstly, the minimum leaf water potential for *Eragrostis* was much higher dropping to only – 0.70 MPa for the control plants (Fig. 3.7e). Transpiration (Fig. 3.8a) for this species did not vary substantially between days. The reason for this consistent response is because the *Eragrostis* actively regulated its stomatal aperture as shown by the cyclic changes in the stomatal conductance whose trajectory is very different from that of the exotic species. Even if similar levels of water stress were imposed on the *Eragrostis*, it is clear from Figs 3.7 f and 3.8 f that both the leaf water status and transpiration hardly dropped. Plants that actively regulate their stomatal aperture to maintain the leaf water status and minimize transpiration losses like *Eragrostis* are isohydric plants. Under severe drought stress, the leaf water potential for *Eragrostis* did not drop below -1.0 MPa (Fig. 3.7f). Even when the drought stress was relieved, Lupine did not recover from the severe stress as the non-recoverable water deficit threshold had been exceeded.

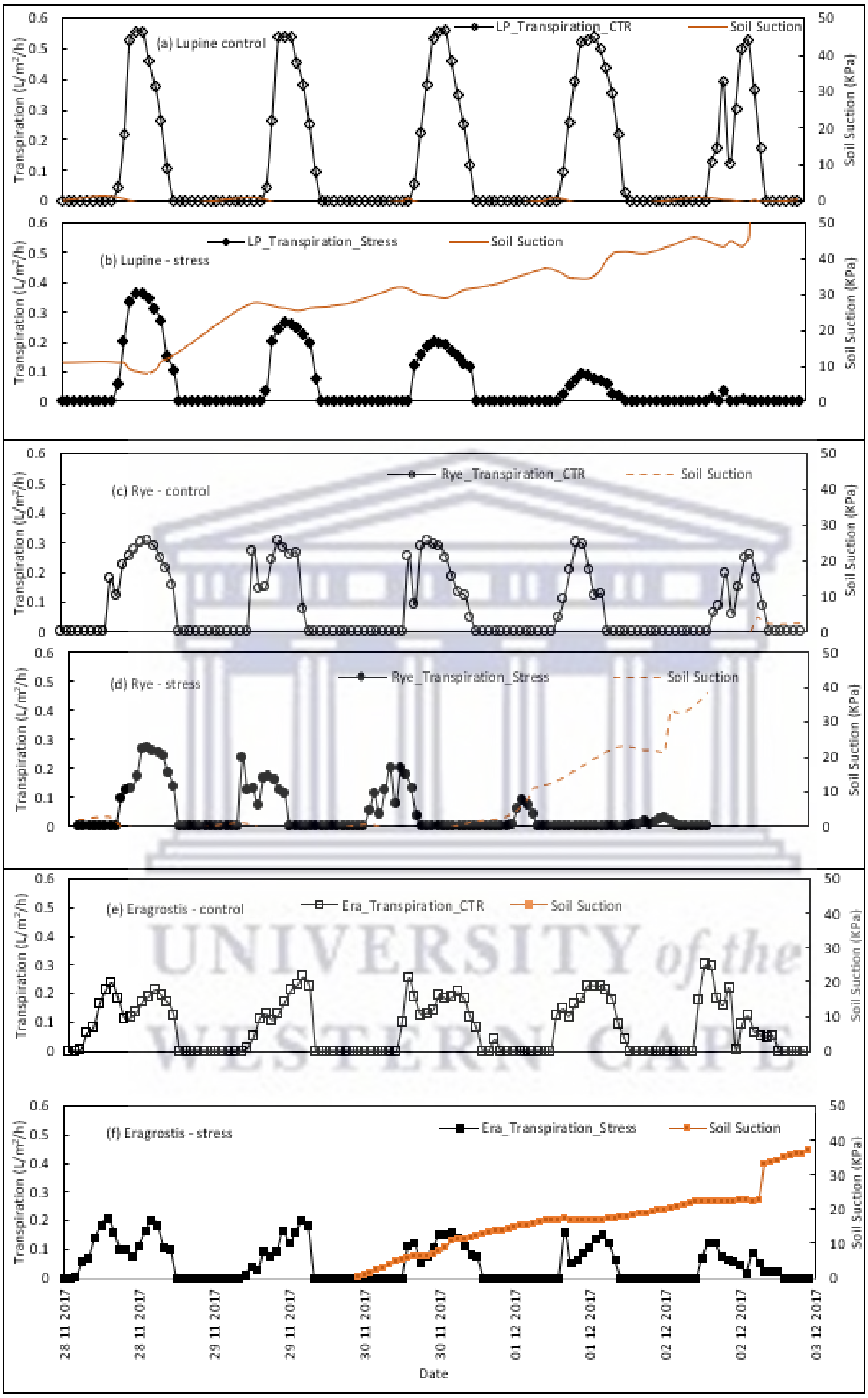


Fig. 3.8: Comparison of transpiration against soil water availability for Lupine (legume), Rye (exotic) and Eragrostis (indigenous), over a wet-dry cycle from 28/11/2017 to 02/12/2017

We calculated the rate of decline of transpiration as a result of drought stress for the three species through a transpiration coefficient and the data is shown in Fig. 3.9. The rate of decline was faster for Lupine while it was slowest for the indigenous *Eragrostis*.

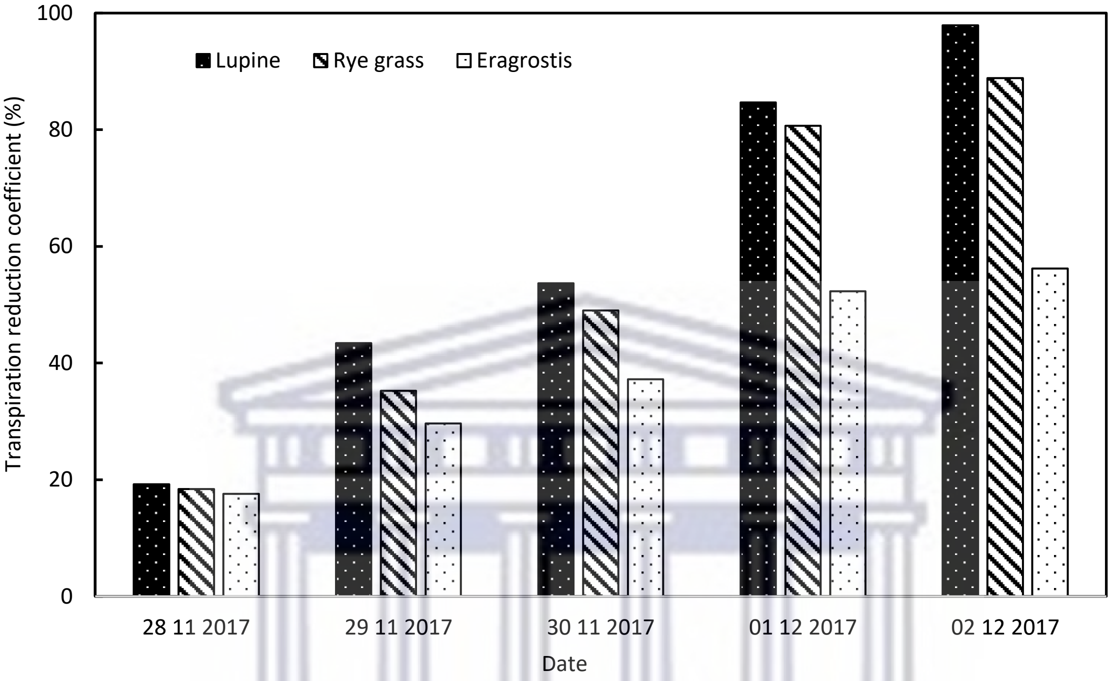


Fig. 3.9: Transpiration reduction coefficient for the three species during the stress cycle.

3.4 DISCUSSION

In this study we, for the first time, compared the water requirements of a range of cover crop species grown in commercial fruit orchards. We also investigated their responses to drought stress. While the benefits of cover crops in orchards are well documented (Reicosky and Forcella, 1998; Chen et al., 2003; Jannoyer et al., 2011), an important information gap exists regarding their impacts on the water resources. Therefore, this study focused on both grasses and legume cover crops, but mostly on grasses which are widely planted in orchards in South Africa and elsewhere. A significant finding from this research is that cover crops that are endemic to sub-Saharan Africa such as *Eragrostis* and Rhodes grass had substantially lower transpiration rates per unit leaf area than their exotic counterparts. In addition, these indigenous grasses also proved to be tolerant to severe drought stress, consistent with observations made on grass species endemic to semi-arid tropics studied by Cardoso et al. (2015). The legumes had the highest water use rates, but they were also most susceptible to water deficit in the root zone. Therefore, this study suggests that legume cover crops are least suited to orchards in water scarce countries such as South Africa, Spain Australia, to name a few. They are more suited to areas where water is not limiting.

The range of water uses by the widely planted exotic grasses lay between that of exotic legumes and the indigenous grasses. Within the exotic grass species, the Tall fescue had the highest water use rates also as reported by Holloway-Philips and Brodrib (2011). These authors focused only on the Tall fescue and Rye grass and they attributed the higher water use rates by Tall fescue to its deep and extensive root system, which is able to supply water to the evaporating sites in the leaves when soil availability is limiting. This study also provided insights on the mechanisms by which the different species responded to stress. For example, the indigenous grasses actively reduced water losses thorough cyclic stomatal oscillations which kept the leaf water status fairly high. Such isohydric responses have also been reported on grasses by Cardoso et al. (2015) and Holloway-Philips and Brodrib (2011). On the other hand, the exotic species displayed the risky anisohydric behaviour wherein the stomata did not actively regulate water losses leading to a precipitous decline in the leaf water potential such that some species, especially the legumes, did not recover from severe drought stress.

Several studies have quantified the water use of grasses under different levels of drought stress (Marais et al., 2006; Koech et al., 2015). However, most of the studies were done under field conditions where the evapotranspiration rather than the transpiration component of water use was measured. So, this study also provides insights on how climatic factors drive water use in the different species. For example, the relationship between the hourly solar radiation and transpiration showed a significant hysteresis effect for all the species. Unlike orchard tree crops whose stomatal movements are sensitive to the atmospheric VPD (Dzikiti et al., 2017, Mobe et al., 2020), this was not the case for the cover crops studied here. The VPD did not cause stomatal closure which was unexpected given the prevalence of this phenomenon in other plant forms. For apple trees for example, the transpiration is linearly related to the solar radiation (Ntshidi et al., 2018). However, for citrus trees, the relationship is curvilinear as illustrated by Dzikiti et al. (2007) and a hysteresis effect was also observed between the transpiration and the solar radiation. The reasons for the hysteresis phenomenon may be related to the hydraulic properties of the plant especially the hydraulic resistance and capacitance (O'Brien et al., 2004; Zhang et al., 2014). Evidence of the high hydraulic resistance in the transpiration stream of the grasses was shown by the time lags between the opening of the stomata and the commencement of water uptake from the soil which was as high as two hours for Tall fescue for example. According to Holloway-Philips and Brodrib, (2011), more than 60% of the hydraulic resistance of grasses resides in the leaves. Therefore, the presence of significant foliage on the cover crops (Fig. 3.1) could have contributed to the hysteresis effect.

3.5 CONCLUSIONS

This study provides insights on how different cover crop species impact water resources in fruit orchards. Exotic legumes for example, had at least three times higher water use than the indigenous grasses under similar growing conditions. Yet the legumes were also most susceptible to water deficit because of their risk taking anisohydric responses to environmental stress. Exotic grasses that are commonly planted in orchards also had high water use rates and a weak response to drought stress, although they were marginally better than the legumes. So, indigenous grasses are more suited as cover crops in the semi-arid tropical and sub-tropical regions because their physiology is more adapted to the harsh growing conditions. They do not need regular irrigation to survive. However, it is important to note that the water saving benefits of the indigenous cover crops demonstrated here should be considered together with other benefits in order to make informed choices when prioritizing species to plant.

CHAPTER 4: EFFECTS OF DIFFERENT IRRIGATION SYSTEMS ON EVAPOTRANSPIRATION PARTITIONING IN APPLE ORCHARDS

Riverside farm v-trellis training system

Parts of this chapter are under review as:

***Z Ntshidi**, S Dzikiti, D Mazvimavi, NT Mobe. (Under review). Effects of drip and micro-sprinkler irrigation systems on tree water relations and water use partitioning in apple orchards in the Western Cape, South Africa. Scientia Horticulturae Science journal.*

ABSTRACT

South African agricultural industry contributes billions of rand to the GDP, thereby sustaining the economy of the country. This industry uses more than 60% of available water for irrigation and farming. There is therefore value in keeping the industry running, but any measures to save water must be taken into consideration. The country receives less than 500 mm of rainfall, making it a dry country considering the many sectors it has that rely on water. More frequent droughts are predicted for the future. Different irrigation systems use water in different ways; where the drip irrigation system has drippers that are under ground, therefore depositing water into the subsurface. Micro sprinkler irrigation systems have their sensors sprinkling water to a wider area on the ground surface. The main aim of this research was to quantify the water use of apple trees and establish how evapotranspiration (ET) is partitioned, in a trial where 20 trees were under micro sprinkler and another 20 trees under drip irrigation in the same row. After determining plant water use, water relations of these trees under different irrigation systems were established, and the weather variables that affect the evaporative demand were also determined. Lastly, the quality of the fruit from these two irrigation systems were recorded. Micro sprinkler irrigated trees used slightly more water compared to drip irrigated trees ($P \leq 0.05$). The drip irrigated trees showed signs of stress and their leaf area index (LAI) was smaller compared to the trees under micro sprinkler irrigation system. The water use was strongly correlated to the solar radiation with $R^2>0.8$. Partitioning of ET showed that under micro sprinkler irrigation there was a greater contribution from cover crop transpiration than soil evaporation and vice versa under drip. Drip irrigated trees produced smaller sized fruit with poor quality, while micro sprinkler irrigated trees produced bigger fruit with good quality. Using the drip irrigation system saves water, but compromises the quality of the fruit, and subsequently overall farm production.

4.1 INTRODUCTION

The agricultural sector is a productive sector with very high demands of water; where more than 60% of all water supplies are used in this sector (Reddick and Kruger, 2019). This sector is under pressure to ensure food production with the most efficient use of the water resources (Silva et al., 2013). Inefficient use of water in the most productive sectors has been putting strain on the availability of water resources (Reddick and Kruger, 2019). The scientifically forecasted changes in climate because of the earth getting warmer (Global warming) are expected to adversely affect the water sector, especially agricultural production (Yildiz and Kadayifci, 2018). The Western Cape Province of South Africa receives winter rainfall (April-August), therefore the growing season for apples (Sept-March) falls outside the rainy period, meaning the apple trees rely solely on irrigation water. It is for this reason that the water application methods need to be looked at very closely in this region. There is a need to use water efficiently, to keep the multibillion-rand sector running smoothly while not straining the water resources. In order to keep the industry competitive in the fruit export market, there is also need to produce good quality fruit. Therefore, water must be used efficiently but the quality of the fruit must also not be compromised in the process. Studies involving the efficiency of water use in the agricultural sector should be considered, and more efficient water using technologies be prioritized (Silva et al., 2013).

A greater percentage of the increased water demand predicted for year 2025 (Kumar and Palanisami, 2010) can be met by increasing the effectiveness of existing irrigation systems. South Africa is characterized by scarce and irregular rainfall, occurring at the same time with the high evaporative demand, and consequently pronounced seasonal water deficits (Nortes et al., 2005). The Western Cape region is projected to experience severe water shortages in future due to growth of the water demand because of the rapidly increasing population, agricultural and industrial activities, and climate change (Midgley and Lötze, 2011). Apple orchards in the Western Cape region previously (before the 2000's) yielded between 60-80 tons/ha, but in recent years (post 2000's) the yield has increased to more than 100 tons/ha for full bearing orchards. As the planted area continues to expand, water availability is negatively affected (Wang et al., 2019). It is therefore necessary to identify irrigation systems and technologies with water saving benefits to keep up with the growing demand in the agricultural sector.

Partitioning evapotranspiration in orchards can give insights on how much water is used to grow the fruit (beneficial water use) and how much can be saved by reducing orchard floor evaporative fluxes (Kool et al., 2014; Wang & Wang, 2017; Ntshidi et al., 2020). The water that is used by the orchard floor (soil evaporation, cover crop/weed transpiration) is not beneficial for fruit production. Therefore, if this water can be reduced, this reduction should be made priority, especially in water scarce regions. Evapotranspiration partitioning information could be useful when developing irrigation scheduling guidelines, particularly during water allocation decision making, and when developing strategies for coping with future droughts (Dzikiti et al., 2018b). Evapotranspiration accounts for more than 90% of the annual water budget in arid and semi-arid ecosystems (Williams et al., 2003). Therefore, an improved understanding of the processes that underlie the availability of water to trees can be explained through the partitioning of ET (Yepez et al., 2003) into water used to produce the fruit and water used by the orchard floor fluxes (Ntshidi et al., 2020).

Proper irrigation management is crucial to obtain high yields of any fruit dependent on irrigation (Santos et al., 2018). Therefore, the main aim of this study was to measure the water use of apple trees planted to a V-trellis training system under two different irrigation systems, namely micro-sprinkler, and conventional drip irrigation systems. Furthermore, we compared this water use based on how it is partitioned into beneficial and non-beneficial uses and compared the water relations of the apple trees under these irrigation systems in order to gain insights on how these differ. Lastly, we compared the quality of the fruit from these two irrigation systems. To our knowledge, these kinds of comparisons have not been done in local orchards and this information has a potential of assisting decision makers during water allocations and farmers when deciding on which irrigation system to use in their farms. This information can also help the fruit industry to find a balance in using water efficiently while not compromising fruit quality. Other researchers (Casadei et al., 2021) have proposed improved irrigation management practices to use water in a more conservative and efficient manner. There may be a large portion of land available to farm, but water remains the most limiting resource for improved agricultural production (Oweis and Hachum, 2006).

4.2 MATERIALS AND METHODS

4.2.1 Study site description

This study was conducted at Riverside farm (33°57’5” S; 019°18’44” E) located about 2.0 km south of Villiersdorp town close to the eastern edge of the Theewaterskloof dam. The study orchard was about 2.36 ha planted to the Royal Gala cultivar on the MM106 rootstock. The orchard was planted in 1998 and the trees were trained with a V-trellis system with about 1 667 trees per ha. The orchard was originally a drip irrigated orchard, but for this experiment, in the middle of the orchard, a row was selected, where the first 20 trees were converted to micro sprinkler irrigation and the rest of the row remained under drip. Irrigation via the drip system had emitters spaced about 0.75 m apart along the length of each drip line. Each emitter delivered about 2.3 L h^{-1}. There were two irrigation lines with one drip line per tree line. Some of the drip lines were buried in places. While for the micro sprinkler irrigated side of the row, each emitter delivered 30 Lh^{-1} and there was one sprinkler servicing two trees at a time. There were no ridges in the orchard which was on flat terrain. The soils were deep sandy soils with no stones. Irrigation scheduling at the farm was done using DFM profile probes. There was an active cover crop which was Tall fescue and Rye grass that mostly grew close to the tree lines that received irrigation. The rest of the inter-row spaces were bare.

4.2.2 Data collection

4.2.2.1 Site microclimate, soil water content, and irrigation measurements

The microclimate of the study site was measured using an automatic weather station which measured components like solar radiation, temperature, relative humidity, wind speed and direction and calculated reference evapotranspiration (ETo) using the Penman Monteith approach (Allen et al., 1998). The station was installed over uniform short grass surface whose attributes resemble the grass reference crop (Allen et al., 1998). Equipment comprised a pyranometer (Model: SP 212 Apogee Instruments, Inc., Logan UT, USA), which measured the solar irradiance, air temperature and relative humidity (Model: HMP60 Campbell Scientific, Inc., Logan UT, USA) installed at ~2.0 m above the ground. A three-cup anemometer and wind vane (Model R. M. Young Wind Sentry Set model 03001, Campbell Scientific, Inc., Logan UT, USA) were used to measure wind speed and direction, respectively at 2.0 m height, while rainfall was recorded using a tipping bucket rain gauge (Model: TE525-L; Campbell Scientific, Inc., Logan UT, USA). All the sensors were connected to a data logger (Model: CR1000 Campbell Scientific, Inc., Logan UT, USA) programmed with a scan interval of 10 s. The output signals were processed at hourly and daily intervals, then monthly totals and averages for different variables were calculated and summarised into table format. The volumetric soil water content was monitored at various depths using time domain reflectometer probes (Model: CS616, Campbell Scientific, USA). The actual volumes of irrigation applied were measured using electronic water flow meters that were installed along the irrigation lines. Actual orchard evapotranspiration was estimated using the soil water balance approach (Rashid Niaghi and Jia, 2019) calculated from data collected with three reflectometer probes placed at depths of 0.25, 0.5 and 1m for each irrigation system.

4.2.2.2 Tree transpiration and tree water status measurements

Transpiration was measured using the Heat Pulse Velocity (HPV) method of the sap flow technique (Burgess et al., 2001). Three trees with varying sizes for both treatments were installed with sap flow sensors. The sap flow rates were measured at hourly intervals throughout the study period. The HPV technique is an internationally accepted method for the measurement of sap flow (water-use) in woody plants and has been extensively applied in South Africa (Dye & Olbrich, 1993; Dye, 1996; Gush & Dye, 2009; Gush & Taylor, 2014; Dzikiti et al., 2018b; Gush et al., 2019; Mobe et al., 2020a&b; Ntshidi et al., 2020). The heat ratio method (HRM) of the HPV technique (Burgess et al., 2001) was used for sap flow measurements for this study. The HRM requires a line-heater to be inserted in the xylem at the vertical midpoint (roughly 5 mm) between two temperature sensors, called thermocouples. Pulses of heat are used as a tracer, carried by the flow of sap up the tree stem. This allows the velocity of individual heat pulses to be determined by recording the ratio of the increase in temperature measured by the thermocouples (TC's), following the release of a pulse of heat by the line-heater. TC's were inserted to four different depths within the sapwood to determine radial variations in sap flow. All drilling was performed with a battery-operated drilling machine, using a drill template strapped to the tree, to ensure that the holes were parallel. CR1000 data loggers connected to AM16/32B multiplexers (Campbell Scientific, Logan, UT) were programmed to initiate the heat pulses and record hourly data from the respective TC pairs.

Heat pulse velocities derived using the HRM were corrected for sapwood wounding caused by the drilling, using wound correction coefficients described by Swanson & Whitfield (1981). The corrected heat pulse velocities were then converted to sap flux densities according to the method presented by Marshall (1958). The data was also corrected for the density and moisture fraction of the wood according to the procedure by Burgess et al. (2001). Lastly, the sap flux densities were converted to whole-tree total sap flow by deriving the sum of the products of sap flux density and cross-sectional area for individual tree stem annuli. Hourly sap flow values were recorded from all the trees and the complete record was then combined into daily, monthly and yearly totals. Individual-tree sap-flow volumes (L/year) were scaled up to a hectare using the tree density to also calculate sap flow (transpiration) totals in mm-equivalents for the year.

To establish the assessable relationships between leaf water status and the extent of stomatal opening for the trees under different irrigation systems, the leaf water potential was measured concurrently with the stomatal conductance when the available soil water was not limiting. These data were collected at hourly intervals from sunrise to sunset on selected cloudless days. The leaf water potential was measured using a Scholander-type pressure chamber

(Model: 615 PMS Instrument Company, Albany, OR, USA) while the stomatal conductance was measured using a diffusion porometer (Model AP4: Delta-T Devices, Cambridge, UK).

4.2.2.3 Soil evaporation and cover crop transpiration

Soil evaporation was measured using at least four micro-lysimeters per treatment, on selected cloudless days. The selected periods coincided with days when all other manual measurements were taken on the treatments to allow comparison. Eight PVC micro-lysimeters were installed at different sun-shade and wet-dry locations on the orchard floor. The changes in the mass of the micro-lysimeters were monitored at hourly intervals using a precision mass balance with a resolution of 0.01 g from sunrise to sun set on selected measurement days. The soil used in the micro-lysimeters was replaced after every 12 h for consecutive measurement days. The whole surface soil evaporation was calculated as the weighted sum of the micro-lysimeter measurements with the area represented by each micro-lysimeter on the orchard floor used as the weights according to the approach by Testi et al., 2004.

Cover crop transpiration was measured using miniature stem heat balance sap flow gauges (Model SGA3, Dynamax Inc., Houston, USA) and details of these micro sap flow sensors are given by Van Bavel and Van Bavel (1990). The cover crop transpiration was also measured during periods when all manual measurements were taken from sunrise to sunset. The sap flow data were measured on between three and four cover crop plants at hourly intervals for a few days. Careful precautions were taken to ensure that the sensors performed optimally according to the manufacturers' recommendations, for example by carefully wrapping each gauge using several layers of reflective aluminium foil to ensure steady state conditions, and cleaning the installation sites on the stems.

4.2.2.4 Tree and cover crop LAI measurements

The orchard leaf area index (LAI) for the trees under the different irrigation systems was measured at roughly monthly intervals throughout the growing season using an LAI- 2000 Plant Canopy Analyser (LI-COR Inc., Lincoln, NE, USA). The data were collected when there was no direct solar radiation either before sunrise or after sunset when the tree leaves behaved like black bodies (Ntshidi et al., 2020).

At the end of each measuring cycle, all the single plants used for the measurements were cut and their leaf area measured manually in the lab using the leaf area meter (Model Li-3000, Li-COR Inc., Nebraska, USA). Cover crop transpiration data was then normalized with the transpiring leaf area to eliminate any bias estimation due to plant size variations. To scale up the cover crop water use to spatial scale, the leaf area index of the cover crop (LAIc) was measured after each extended period of manual measurements. This was done using a destructive approach wherein a 50 cm × 50 cm sampling grid was used to mark four to five random positions occupied by the vegetation within the cover crop strip. All the vegetation enclosed in the grid was cut to ground level and their leaf area measured. The leaf area index of the cover crop strips was then estimated as the ratio of the cover crop leaf area to the grid area (2 500 cm^2), and an average value was calculated.

4.2.2.5 Evapotranspiration measurements using an Eddy Covariance System

Whole orchard ET was measured using an open path eddy covariance system with sensors mounted on a 10 m lattice mast. The sensors comprised a 3D sonic anemometer (Model: CSAT3, Campbell Sci. Inc., Utah, USA), 2) and an infrared gas analyzer (IRGA) (Model: LI-7500A, LI-COR Inc., Nebraska, USA) connected to a CR3000 data logger. Further details on this method are explained in Dzikiti et al., (2018a & b); and Ntshidi et al., (2020).

4.2.3 Fruit quality analysis

A total of 20 fruit from micro and drip setups was harvested and taken to the lab for fruit quality analysis at harvest time (Feb-March) of each growing season. These fruit were analysed for fruit quality indicators such as fruit; 1) firmness, 2) diameter, 3) mass, 4) background colour, starch, and total soluble solids. Fruit quality analysis was done in all three seasons to determine how it would improve or remain the same as the fruit trees adapted to the introduced micro irrigation system.

4.3 RESULTS

4.3.1 Microclimate

During the summer months (Nov – Jan), maximum temperatures reached 38°C while in winter (May- Jul) they dropped to as low as 0.8°C in all growing seasons (Fig. 4.1). Vapour pressure deficit (VPD) of the air picked at 2.8 kPa in summer and dropped to ~0.1 kPa in winter. A summary of the climatic conditions during the three growing seasons (2017/18, 2018/19 & 2019/20) are shown in Table 4.1. The period 2018 – 2020 was a special period for the Western Cape Province as it was starting to recover from the drought that had hit the Province from 2015 – 2017 (Pienaar and Boonzaaier 2018; Ntshidi et al., 2020). Therefore, during the study period, there were no concerns over water availability, the study orchard was irrigated as in normal years. Even if the drought were still ongoing during the time of this study, it would not have affected the results much as very little rain falls during the growing season. During the 2017/18 growing season, the orchard received ~316 mm of rainfall while in 2018/19 it received slightly less rainfall, recording ~ 226 mm/ season and more rainfall was recorded for the 2019/20 growing season (338 mm).

Table 4.1: *Summary of the microclimate at the study site over three fruit growing seasons.*

Date	Tmax	Tmin	RHx	RHn	Rs	U2	Rain	ET0	VPD
	ºC	ºC	%	%	MJ/m2/d	m/s	mm	mm	kPa
2017/18 growing season									
Oct	21.48	6.97	90.99	32.70	23.55	1.54	49.51	125.09	0.76
Nov	23.94	9.63	91.41	34.81	26.70	1.46	56.13	142.57	0.81
Dec	27.06	11.55	90.28	31.34	29.39	1.39	4.57	172.17	1.04
Jan	28.58	13.78	90.68	36.70	27.93	1.30	31.50	169.95	1.06
Feb	28.83	12.74	93.71	29.74	25.79	1.37	20.32	142.60	1.09
Mar	25.45	11.44	93.41	36.33	19.76	1.28	7.86	115.88	0.80
April	23.72	9.74	91.75	35.15	16.06	1.46	37.08	89.34	0.75
May	20.96	9.26	88.64	37.76	10.59	1.51	109.22	60.68	0.67
Total							316.19	1018.28	
2018/19 growing season									
Oct	25.37	10.51	86.83	30.92	22.35	1.53	33.01	133.47	1.04
Nov	25.10	9.00	92.30	29.57	25.36	1.32	29.46	139.92	0.89
Dec	26.69	11.46	93.70	33.19	26.49	1.19	10.66	156.03	0.91
Jan	27.44	12.16	92.02	32.23	27.38	1.40	16.00	162.79	0.99
Feb	29.21	13.85	92.41	34.52	22.74	1.24	7.61	129.26	1.05
Mar	25.51	12.71	95.07	44.06	17.30	1.05	66.55	102.65	0.67
April	23.61	9.78	93.09	37.77	13.96	1.21	10.92	78.39	0.70
May	21.70	7.73	92.69	35.51	10.28	1.35	51.30	61.88	0.68
Total							225.51	964.39	
2019/20 growing season									
Oct	22.34	8.28	92.52	32.08	21.20	1.27	91.19	114.93	0.70
Nov	24.21	9.68	90.95	35.95	24.63	1.31	7.87	135.09	0.85
Dec	25.86	11.19	88.37	32.91	26.57	1.57	16.77	153.73	0.92
Jan	27.08	13.48	93.56	43.55	23.82	1.18	105.66	143.52	0.83
Feb	28.82	14.16	91.32	37.97	23.50	1.40	3.55	142.03	1.00
Mar	26.83	12.25	93.75	39.65	18.23	1.04	1.78	108.00	0.78
April	23.51	8.74	92.22	36.27	13.90	1.12	44.20	74.86	0.72
May	22.50	7.27	91.45	34.58	10.55	0.96	66.80	55.59	0.69
Total							337.82	927.75	
Grand total							879.52	2910.42	

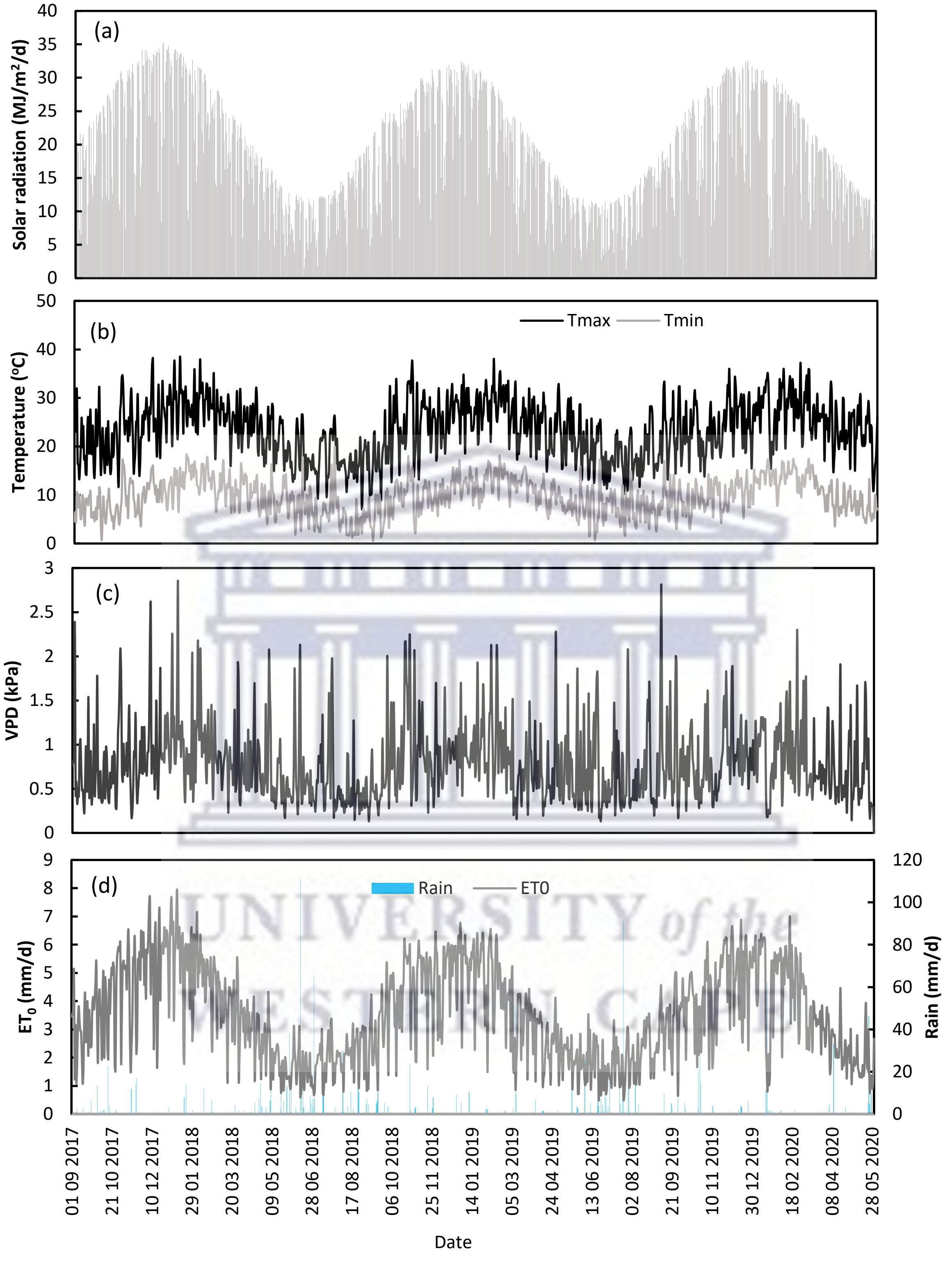


Fig. 4.1: Daily climatic variables during the course of the study (2017-2020) showing (a) Solar radiation, (b) max and min temperatures, (c) vapour pressure deficit (VPD); and (d) short grass reference evapotranspiration and rainfall.

The seasonal total reference evapotranspiration (ETo), which is a measure of the atmospheric evaporative demand was about 1 018 mm for the season 2017/18, 964 mm for 2018/19 and 928 mm for the 2019/20 growing season. In all three seasons the ETo was 3 – 4 times higher than the rainfall. The reference evapotranspiration was calculated using the modified Penman-Monteith equation for a short grass reference according to Allen et al. (1998).

4.3.2 Plant water use and drivers.

Micro sprinkler irrigated trees had a bigger LAI as compared to the drip irrigated trees (Fig.4.2). The effect of reference evapotranspiration (ETo) on tree transpiration from trees under both irrigation systems is shown in Fig. 4.3. The diurnal trends of the tree water use from both setups followed the course of the reference evaporative demand. Micro sprinkler irrigated trees transpired almost 5 mm of water during the hottest summer months and transpiration rates declined to almost zero during the dormant winter months when trees had shed their leaves.

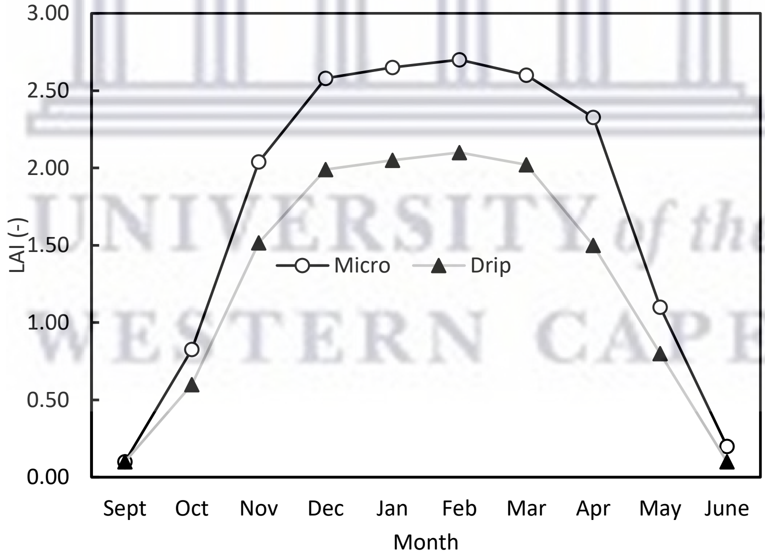


Fig. 4.2: Seasonal changes in the tree leaf area index (LAI) of the Royal gala trees under different irrigation systems.

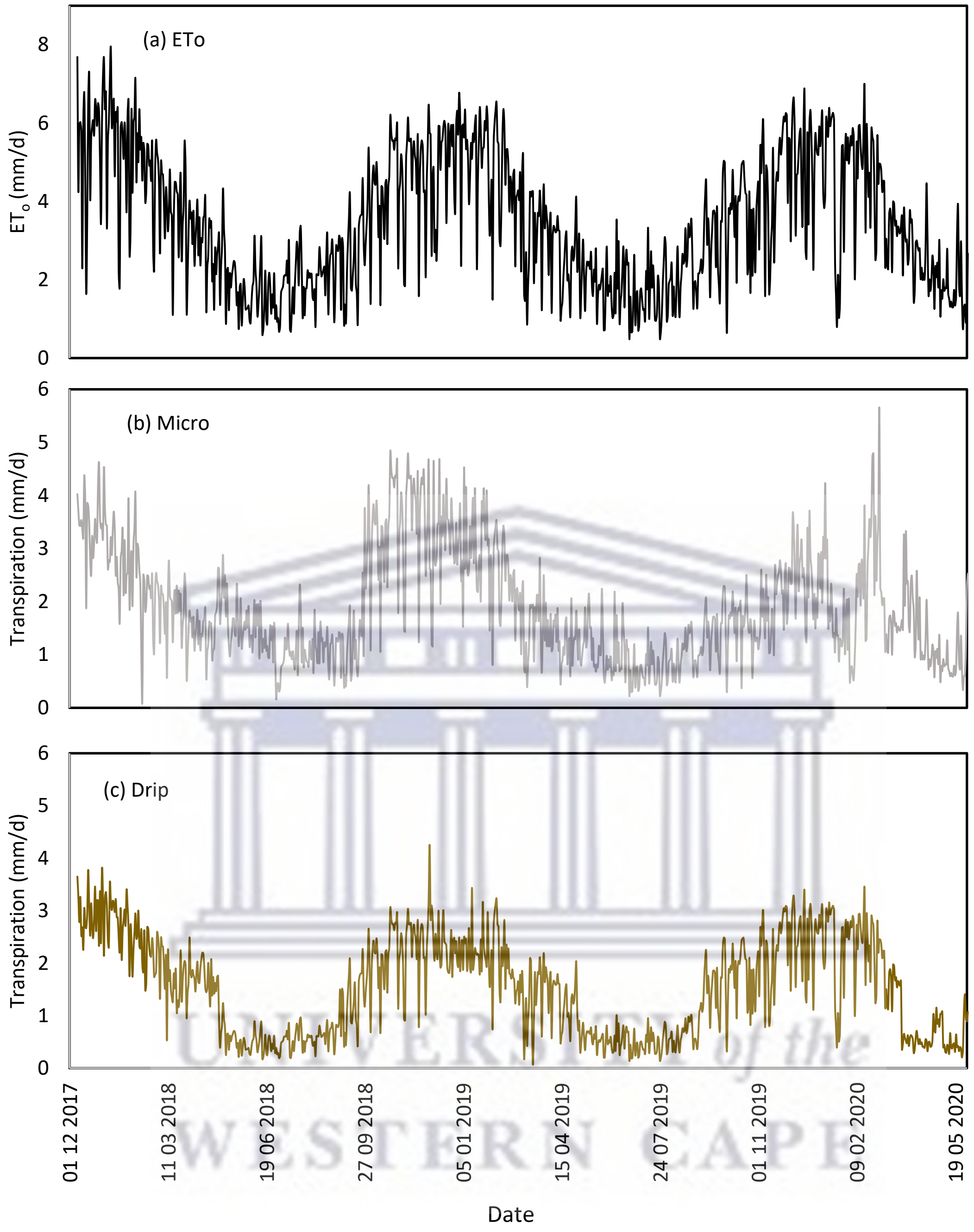


Fig. 4.3: The seasonal course of (a) reference evapotranspiration (b) Water use of micro-sprinkler irrigated trees (c) Water use of drip irrigated trees at Riverside farm in Villiersdorp over the three apple growing seasons (2017/18, 2018/19 and 2019/20).

The same observations were seen with the drip irrigated trees, which transpired roughly less than 4 mm of water per day during summer but declined to almost no transpiration at all in winter. Seasonal totals of ~ 460 mm for drip irrigated tress and ~480 mm for micro-sprinkler irrigation were recorded (Fig. 4.4). Similar trends were observed by Gush et al., (2019) when they looked at the water use of a 12-year-old ‘Cripps’ Pink’ micro sprinkler irrigated orchard over two seasons (2008/09 & 2009/10) in South Africa, and observed ~680 mm. The decline in transpiration rates on both studies over the winter period was expected as the studied trees are deciduous fruit trees that reach dormancy during that period. However, the trees measured by Gush et al. (2019) had a higher plant density as well as a higher LAI as compared to the trees measured in this study, hence their recorded higher water use rates. The main environmental variable that drove the water use of the trees from both set-ups was solar radiation, with a linear correlation coefficient of ~89% for micro and 84% for drip, followed by the ETo with correlation coefficients of 76% for micro and 71% for drip. The VPD of the air showed a logarithmic correlation with both set-ups with an R^2 of 0.64 for micro and 0.65 for drip (Fig.4.5).

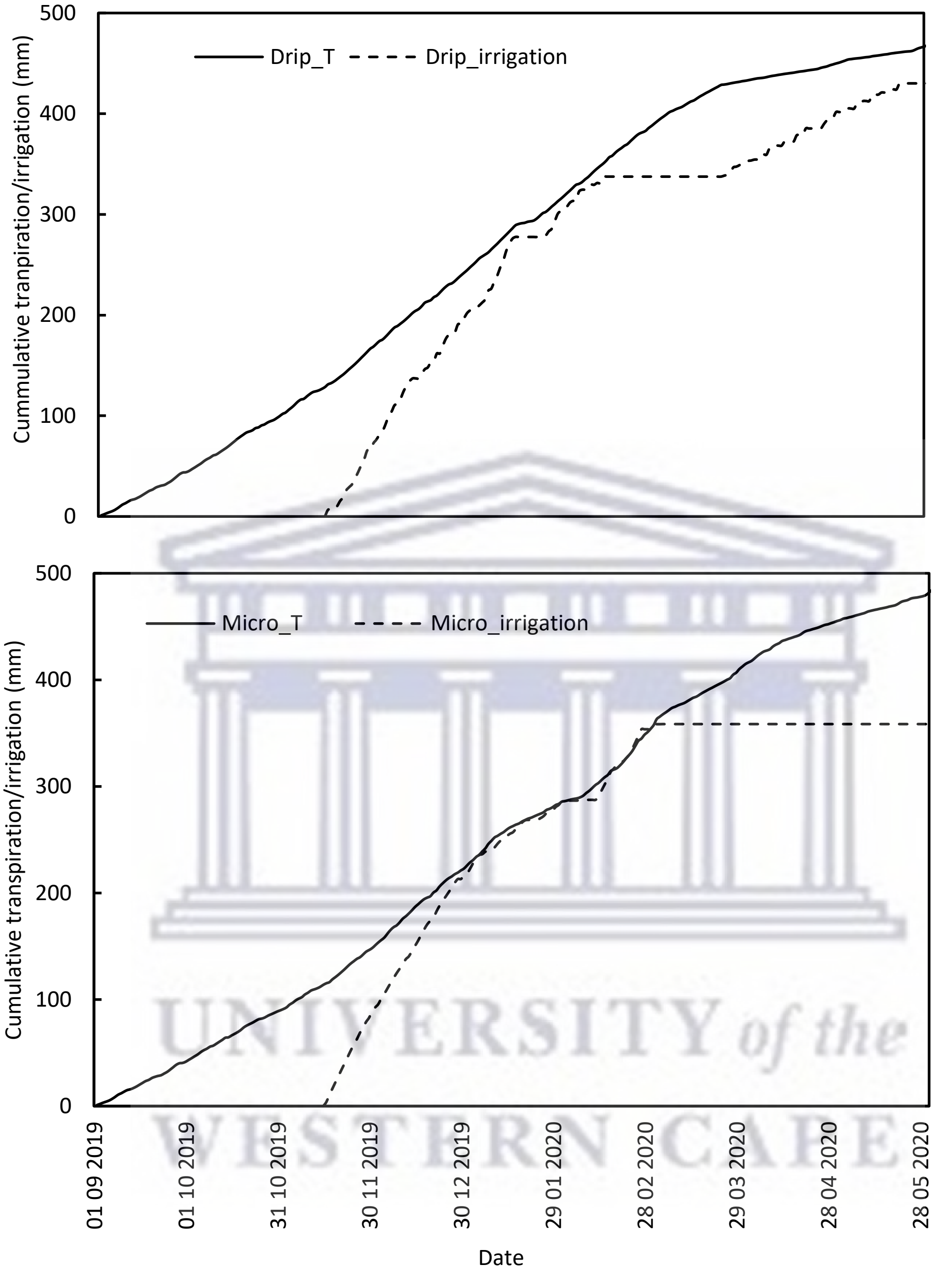


Fig. 4.4: Cumulative transpiration and irrigation of (a) drip irrigated trees and (b) micro-sprinkler irrigated trees.

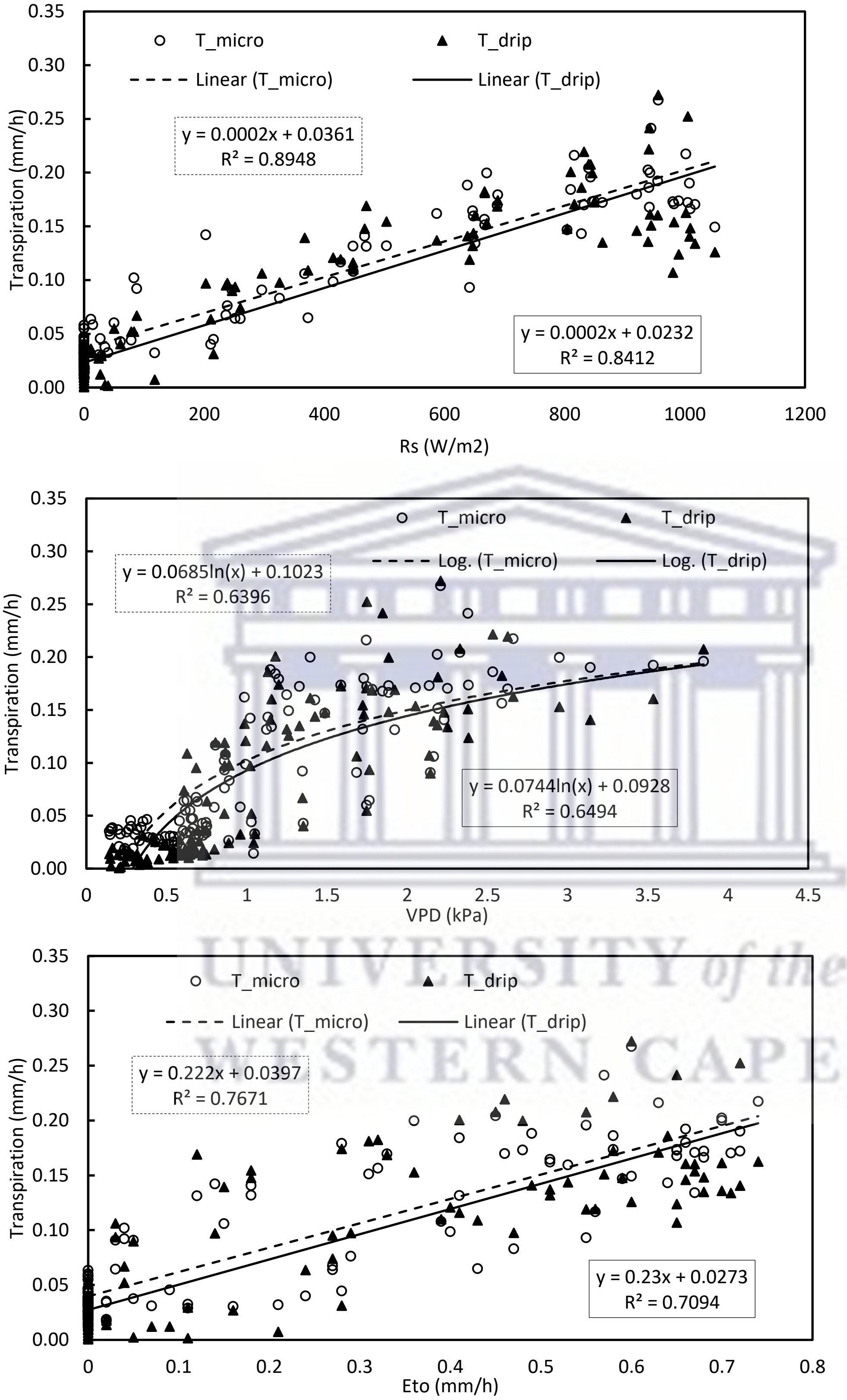


Fig. 4.5: Transpiration response of (a) micro and drip irrigated apple trees to solar radiation, (b) micro and drip irrigated apple trees to Vapour Pressure Deficit (VPD), and (c) micro and drip irrigated apple trees to reference evapotranspiration (ETo)

4.3.3 Evapotranspiration partitioning and soil water content

Partitioning of ET was done over a 4-day period from 22-25 January 2019, during this period Evapotranspiration (ET), transpiration (T), soil evaporation (Es), cover crop transpiration (Tc) were carefully measured. Applied irrigation and soil water content were also monitored carefully as they would influence this partitioning heavily. For the drip irrigated trees, irrigation was applied throughout this period (Fig.4.6a) while for the micro sprinkler irrigated trees irrigation was withheld on day 2 of the measurements (23 January 2019). The reason for withdrawing irrigation from the micro sprinkler was to study the effects of drought on the partitioning and to be able to use the soil water balance approach for calculating the ET as we could not account for drainage. Most of the orchard was under drip irrigation, therefore for drip we could use the total orchard ET obtained from the Eddy covariance system. The integrity of the cover crop transpiration measurements has been tested and calibration of used sensors done with the IRGA as explained in Ntshidi et al., 2020. The partioning from the drip set up shows that tree transpiration contributed the most ~85% of the total ET, while the second highest contribution was from soil evaporation at ~10% and cover crop transpiration only contributed ~5% to the total ET. The micro-sprinkler irrigated side of the orchard showed that tree transpiration contributed ~72% to the total ET, while the cover crop transpiration was the second contributor of ~19% and the least contribution of ~9% was from soil evaporation. These results from both set-ups followed the same magnitude as what Ntshidi et al., 2020 found when they partitioned the water use under mature golden delicious trees and found that in mature trees a greater percentage (65% in their case) was contributed by the trees and the remaining 35% was a contribution from the orchard floor fluxes. After the micro-sprinkler irrigation was switched off on 23 January 2019, there was an immediate decline observed in all the measured fluxes, showing the dependence of all the fluxes on applied irrigation (Fig.4.6d). Soil water content is shown from three different levels on the graphs from the 4-day trial. For the micro set-up, the shallowest sensor was mainly affected by the presence of water showing to have the most moisture (≤ 0.2 cm^3/cm^3), while for the drip set-up, even the deepest sensor was affected by the hourly water application (all sensors recording a soil moisture content of ~2 cm^3/cm^3). The soil moisture content from the three different levels was averaged for the seasonal plots. As expected, the soil water content was affected by the applied irrigation throughout the season on both setups (Fig.4.7).

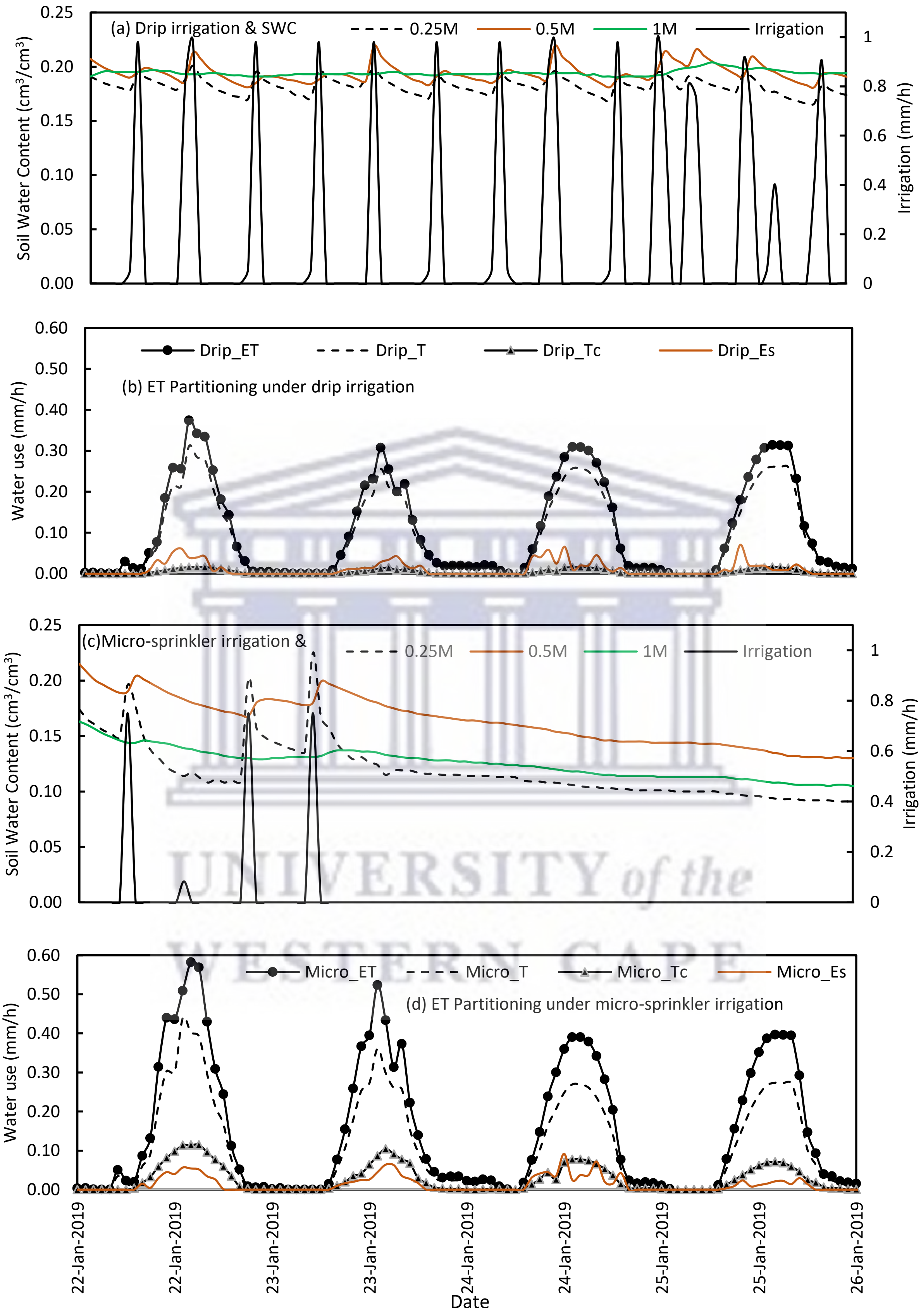


Fig. 4.6: Soil water conditions and ET partitioning under different irrigation systems (a) Drip irrigation and Soil Water Content, (b)ET partitioning under drip irrigation, (c) Micro-sprinkler irrigation and Soil Water Content and (d) ET partitioning under micro-sprinkler over a wet-dry period.

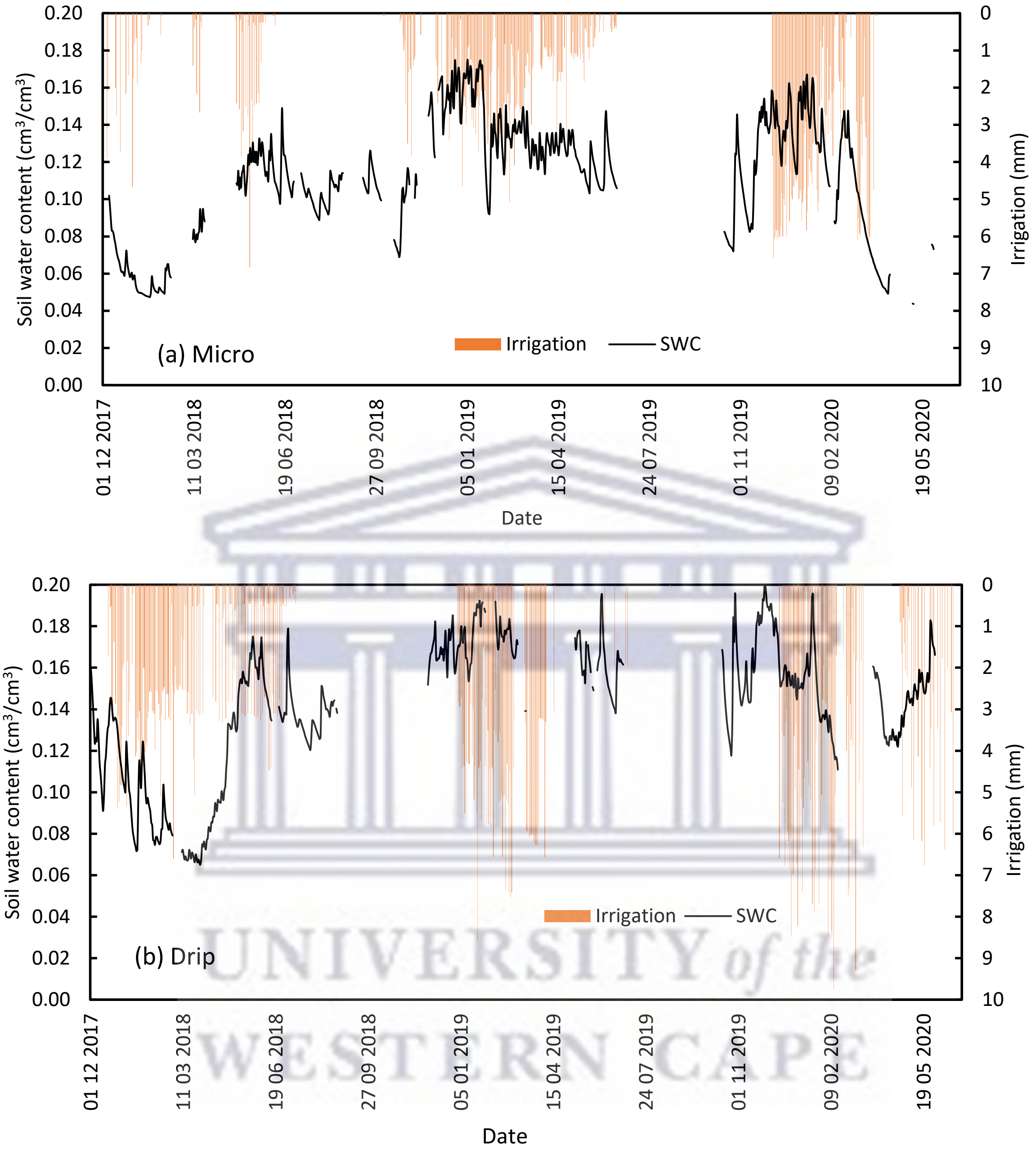


Fig. 4.7: Average soil water dynamics taken from depths of 25, 50, and 100cm with applied (a) micro-sprinkler irrigation and (b) drip irrigation over the three seasons.

4.3.4 Tree water relations

The stomatal conductance of the micro-sprinkler irrigated trees ranged from 0.1 to 0.9 cm/s while that of the drip irrigated trees ranged from 0.02 to 0.5 cm/s (Fig.4.8 a & b). The stomatal conductance was open to its maximum at mid-day while it reduced its opening early mornings and late evenings as the sun sets. This result is similar to what Massonnet et al., 2007 observed when they looked at the stomatal regulation of two apple cultivars grafted on M9 rootstocks in the South of France in 2002. The leaf water potential of the micro-sprinkler irrigated trees ranged from -0.4 to -1.2 MPa (Fig.4.8 c) while that of drip irrigated trees ranged from -0.5 in the morning before the transpiration pull to -1.6 MPa at midday when the transpiration pull was strongest (Fig.4.8d).

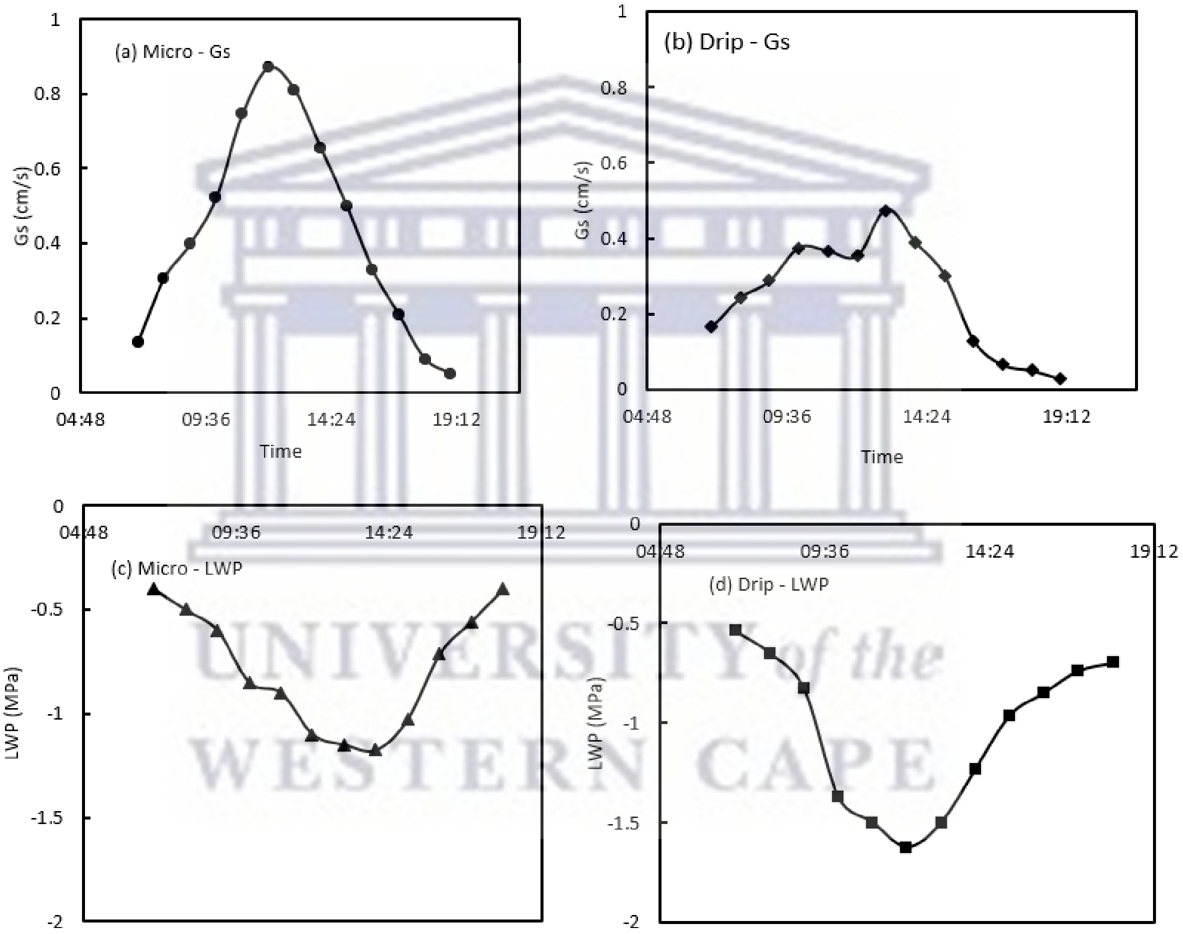


Fig. 4.8: Typical stomatal conductance of (a) micro-sprinkler irrigated trees, (b) drip irrigated trees; also leaf water potential (LWP) of (c) micro trees and (d) drip trees, over a clear day on 24 January 2019 at Riverside farm.

A curvilinear relationship was observed between the diurnal trend in the stomatal conductance and tree transpiration from both set-ups (Fig.4.9 a & b). There was a timelag of roughly an hour between stomatal opening in response to light stimuli and the commencement of transpiration from trees under both setups (data not shown). The stomatal conductance trend was clearly consistent with the transpiration signals, while the drip irrigated trees tended to close their stomata at midday. Many researchers (Tenhunen et al., 1981; Roessler and Monson, 1985; Kamakura et al., 2011; Zhang et al., 2013) have reported that the stomata of the leaves may close during the day if the leaves experience lack of water. This is the case with the drip irrigated trees because they experience more water stress as a result of not having enough water to keep up with transpiration, their stomata resorted to midday closure as shown in Fig.4.8b. Both leaf water potential and stem water potential were affected by the opening of the stomata, as soon as the stomata was open and transpiration started to occur, the plant started to experience water stress. There was a linear relationship between tree transpiration and LWP from both setups, showing correlation coefficients of 69% for micro and 66% for drip irrigated tress (Fig.4.10 a & b). A curvilinear and stronger relationship was observed between the stomatal conductance and LWP form both setups, showing correlation coefficients of 81% and 74% for micro and drip respectively (Fig.4.10 c & d).

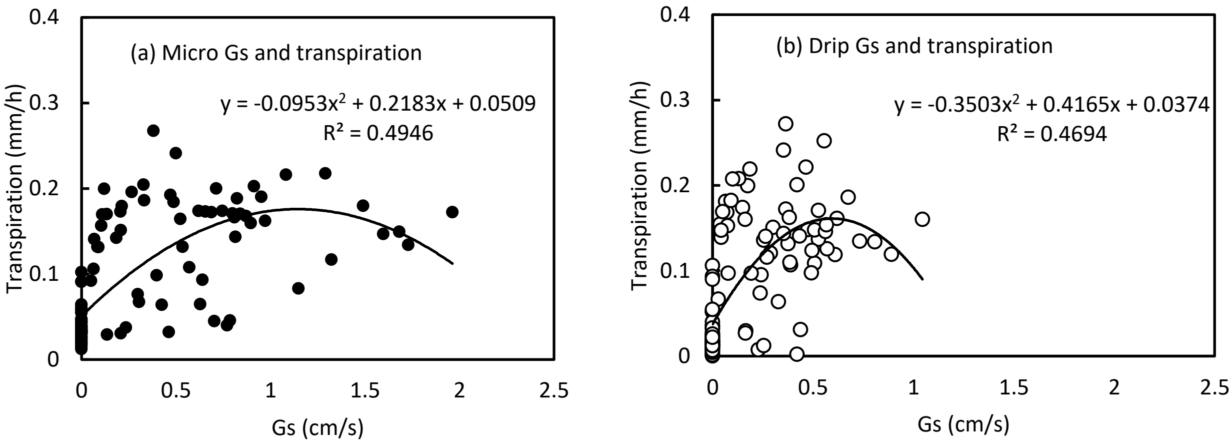


Fig. 4.9: Relationship between stomatal opening and transpiration of (a) micro-sprinkler irrigated trees and (b) drip irrigated trees.

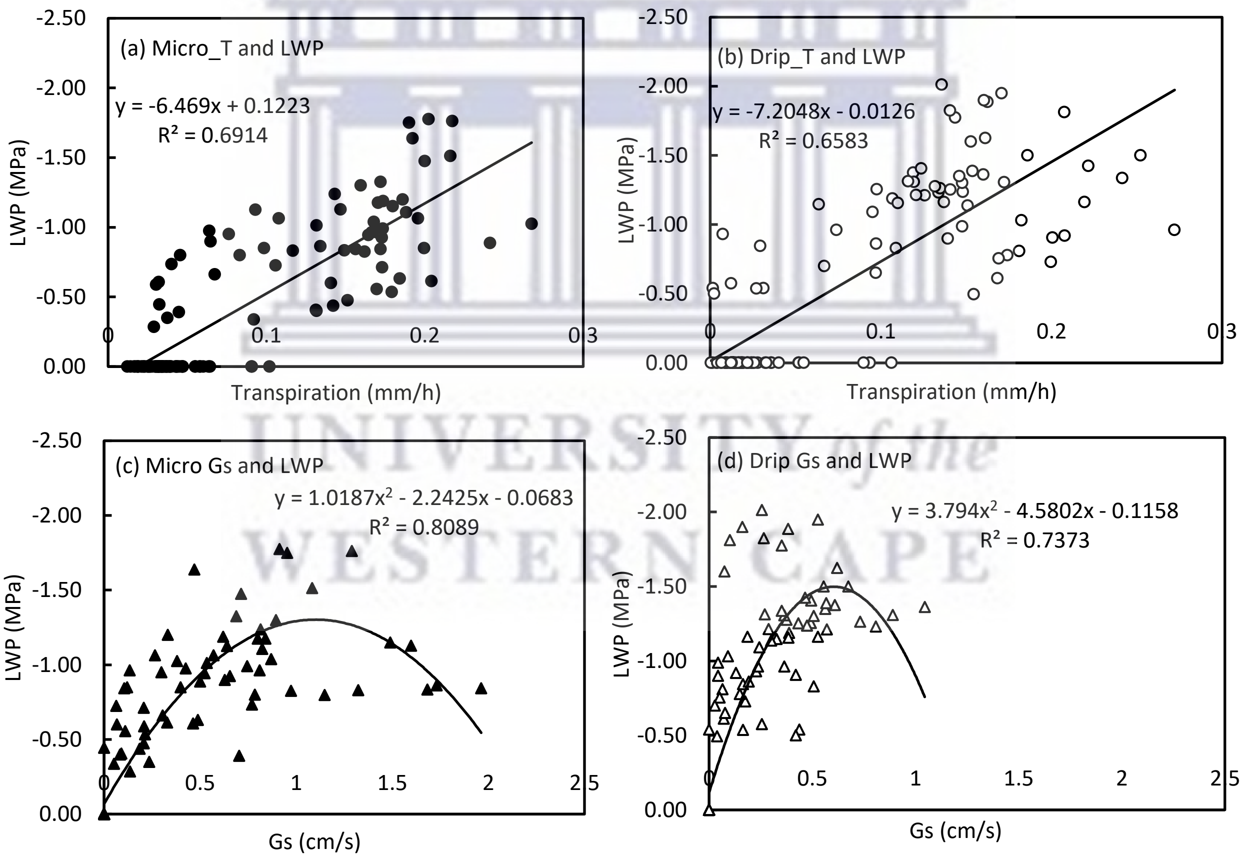
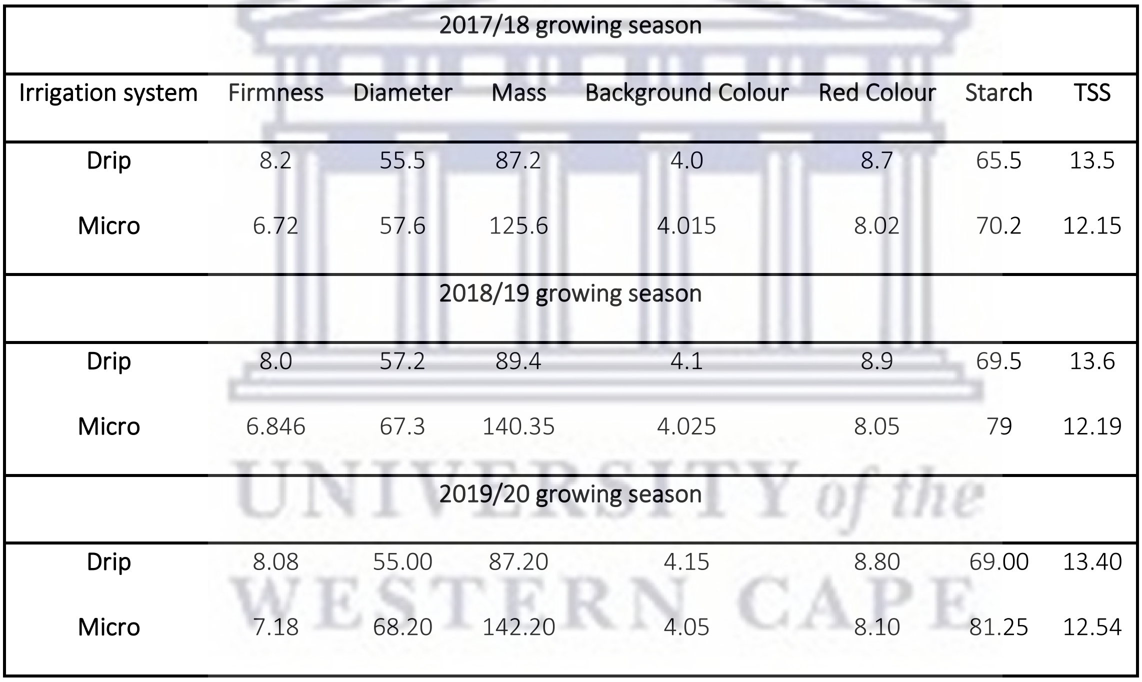


Fig. 4.10: correlations between (a) transpiration from micro-sprinkler irrigated trees and LWP, (b) drip irrigated trees and LWP, (c) stomatal opening of micro-sprinkler irrigated trees and LWP, lastly (d) stomatal opening of drip irrigated trees and LWP.

4.3.5 Fruit quality

The drip irrigated trees produced fruit with an average size of 60 mm throughout the study period, while the micro-sprinkler irrigated trees produced fruit with an average size of ~70 mm. The fruit size and sugars of the micro-sprinkler irrigated fruit showed improvement throughout the years of the study (Table 4.2) possibly due to the trees starting to adapt to the introduced irrigation system. The quality of the fruit from the drip setup was poor as compared to the quality of the fruit from the micro-sprinkler setup.

Table 4.2: Summary of the fruit quality at the study site over three fruit growing seasons.



2017/18 growing season							
Irrigation system	Firmness	Diameter	Mass	Background Colour	Red Colour	Starch	TSS
Drip	8.2	55.5	87.2	4.0	8.7	65.5	13.5
Micro	6.72	57.6	125.6	4.015	8.02	70.2	12.15
2018/19 growing season							
Drip	8.0	57.2	89.4	4.1	8.9	69.5	13.6
Micro	6.846	67.3	140.35	4.025	8.05	79	12.19
2019/20 growing season							
Drip	8.08	55.00	87.20	4.15	8.80	69.00	13.40
Micro	7.18	68.20	142.20	4.05	8.10	81.25	12.54

4.4 Discussion

In this study we, for the first time, compared the water use of apple trees under different irrigation systems within the same orchard, and same row. We further looked at how the water use is partitioned into beneficial and non-beneficial water use, in both wet and dry conditions. Lastly, we looked at the water relations of these trees and how the fruit quality is eventually affected. While the water use of apple orchards is well studied both locally and internationally (Green et al., 1989; Li et al., 2002; Gong et al., 2008; Girona et al., 2011; Liu et al., 2012; Villalobos et al., 2013; Gush and Taylor, 2014; Dzikiti et al., 2018b; Ntshidi et al., 2018; Gush et al., 2019; Mobe et al., 2020a & b; Mobe et al.,2021), an important information gap exists regarding the impacts of different irrigation systems especially within the same environment and how the water relations vary. Water use partitioning has also been studied in apple orchards (Kool et al., 2014; Wang and Wang, 2017; Ntshidi et al., 2020), but a gap still exists on how this water use partitioning changes in different wet-dry conditions, better yet under different irrigation systems. This study focused on all the above-mentioned information gaps.

A significant finding from this research is that while farmers may save water by moving from micro-sprinkler irrigation to conventional drip, they should also carefully consider the impacts on the quality of the final product that they will put in the market for sale. Farmers should investigate ways they can use water saving technologies that can potentially use water more efficiently without compromising the quality of their fruit.

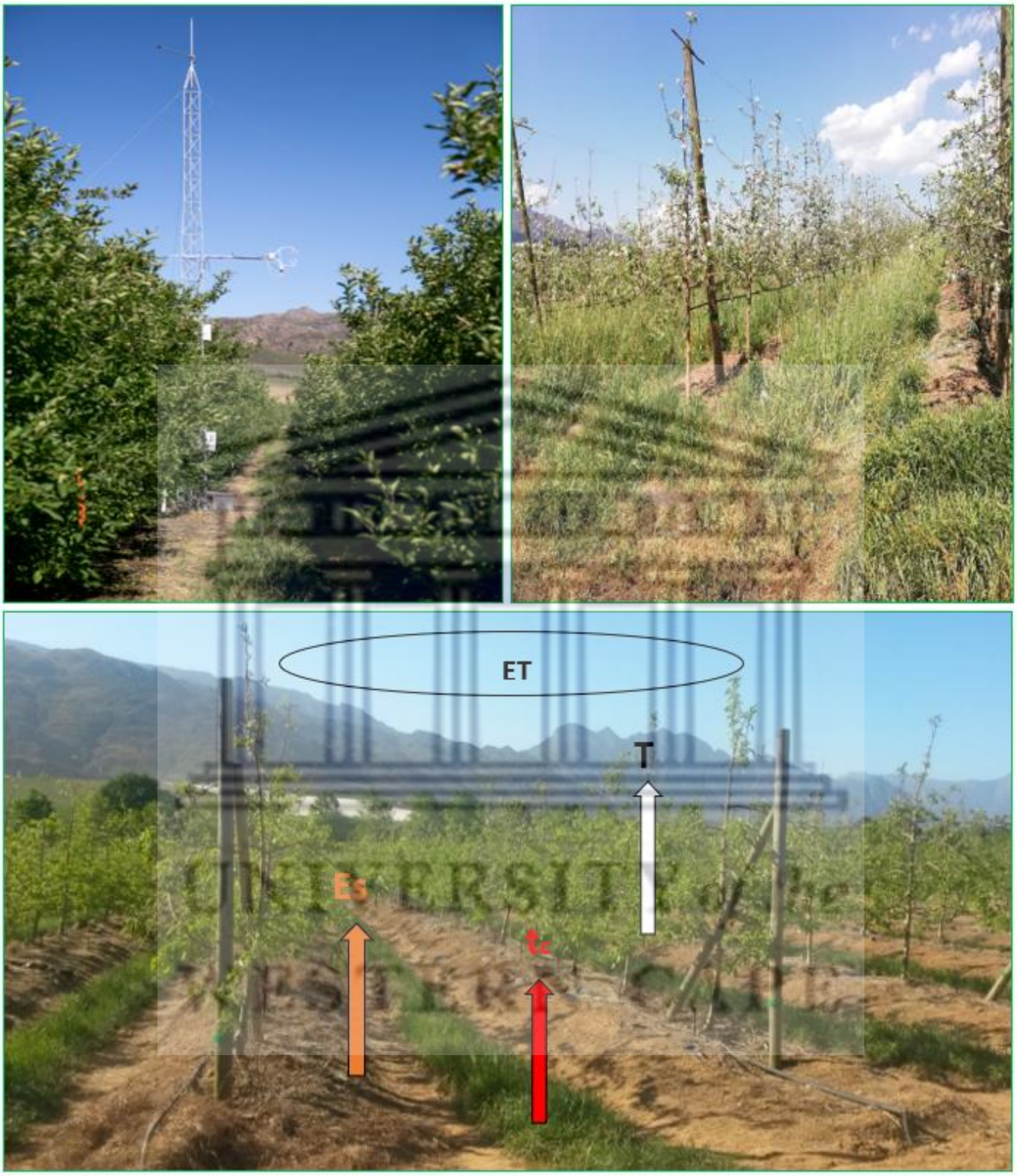
This study also provided insights on the water use partitioning under different irrigation systems. For example, under micro-sprinkler irrigation system, there was a significant contribution from the cover crop water use as compared to soil evaporation, while under drip irrigation there was a significant contribution from soil evaporation as the bare surface area was larger under the drip trees. Furthermore, this study gave insights on how the water use partitioning differed under wet-dry conditions. Findings from this study were no different from what Ntshidi et al., 2020 found, which was that in mature full bearing orchards, a bigger contribution (>50%) to total orchard ET is used by the actual trees (beneficial water use) and less than 50% is contributed by the orchard floor fluxes. This is the case whether the trees are under micro-sprinkler or drip irrigation, whether there is a bigger wetted surface area (under micro) or no wetted surface area (under drip).

Smaller sized fruit with poor quality were observed under the drip irrigation system, while the quality of the fruit observed under the micro-sprinkler irrigated trees improved over the years. According to Lado et al., (2014), the route to the market for fruit is heavily dependent on the quality of the fruit, therefore good quality will equate to good economic returns.

4.5 CONCLUSIONS

Drip irrigated apple trees used less water as compared to micro irrigated trees. However, the drip irrigated apple trees were more stressed and subsequently produced smaller in size fruit with poorer quality as compared to the micro sprinkler irrigated apple trees. Solar radiation was the main climatic driver of water use in these apple orchards. The drip irrigated trees had smaller canopies as compared to the micro sprinkler irrigated trees. Using the drip irrigation system saves water, but compromises the quality of the fruit, and subsequently overall farm production. The partitioning of ET under different irrigation systems proved that in a micro sprinkler irrigated orchard, there is a significant contribution from the cover crop than soil evaporation but an opposite for drip irrigated trees. Farmers who use the drip irrigation system should add more dripper lines on the surface, in order for the top layers of the soil to receive more water, rather than having two drippers that send water straight to the bottom of the soil profile while the apple tree roots are shallow and lateral.

CHAPTER 5: EVAPOTRANSPIRATION PARTITIONING IN APPLE ORCHARDS WITH DIFFERENT CANOPY COVER



Orchards of different canopy covers and age groups.

Parts of this chapter are published as:

Z Ntshidi*, S Dzikiti, D Mazvimavi, Mobe NT (2020). Contribution of cover crop to evapotranspiration partitioning in apple orchards under Mediterranean climatic conditions in South Africa. Agricultural Water Management.245, 106627.*

ABSTRACT

Orchard evapotranspiration (ET) is a complex flux which has been the subject of many studies. It often includes transpiration from the trees, cover crops and weeds, evaporation from the soil, mulches and other orchard artefacts. In this study we investigated the contribution of the orchard floor evaporative fluxes to whole orchard ET focusing on the transpiration dynamics of cover crops which are currently not well known. Data on the partitioning of ET into its constituent components were collected in apple (*Malus domestica* Bork) orchards with varying fractional canopy cover. The study orchards were in the prime apple growing regions in South Africa. The orchards were planted to the ‘Golden Delicious’/’Reinders’ and the red cultivars (‘Cripps’ Pink’/ ‘Royal Gala’/’Fuji’). Tree transpiration was quantified using the heat ratio method and the thermal dissipation sap flow techniques. Cover crop transpiration was measured at selected intervals using micro stem heat balance sap flow gauges calibrated against infrared gas analyser readings. Orchard ET was measured using an open path eddy covariance system while the microclimate, radiation interception, and soil evaporation were also monitored. Orchard floor evaporative fluxes accounted for as much as 80% of the measured ET in young orchards with dense cover crop that covered most of the orchard floor. In these orchards the cover crop transpiration was of the same order of magnitude as the bare moist soil evaporation suggesting that water use by the cover crop was substantial. However, in mature orchards with a high canopy cover (>55% fractional cover), orchard floor water losses were less than 30% of the measured ET. Cover crop transpiration rates were much lower, contributing less than 10% of the whole orchard ET. Significant volumes of water can be saved, especially in young orchards, by keeping the orchard floor vegetation short, reducing the area occupied by cover crops, and by reducing the wetted ground surface area.

5.1 INTRODUCTION

In South Africa, as elsewhere in the semi-arid climates, the availability of adequate water for irrigation is the biggest risk to sustainable fruit production. South Africa is a major exporter of fresh apples (*Malus domestica* Borkh.), being second only to Chile in the Southern hemisphere (Pienaar and Boonzaaier, 2018). The major apple growing region in South Africa is the Western Cape Province which has a Mediterranean-type climate, and the rain falls outside the fruit growing season in winter (May to August). Consequently, all the fruit are grown under irrigation yet water resources in the country are under great strain. The Western Cape region, for example, is projected to experience severe water shortages in future due to rising competition between irrigated agriculture, increasing industrial activities, and the rapidly growing population of the Cape Town Metropolitan (Dzikiti et al., 2018a; Gush et al., 2019). Climate change is also projected to exacerbate the water problems by increasing the frequency and severity of droughts and extreme weather events in the region (Midgley and Lotze, 2011).

Sustainable management of irrigation requires accurate quantitative information on evapotranspiration (ET) which is the second largest water balance component in orchards (Villalobos et al., 2013). Many studies have quantified ET in apple orchards (Gush et al., 2019; Gush and Taylor, 2014; Li et al., 2007; Mobe et al., 2020; Ntshidi et al., 2018; Volschenk, 2017; Zanotelli et al., 2019). Besides the work by Li et al. (2007) and Wang and Wang (2017), few studies have investigated, in detail, the partitioning of evapotranspiration into its constituent components in apple orchards of varying age groups. To our knowledge there is a paucity of detailed information on the transpiration dynamics of cover crops which are often present especially in orchards with non-localized irrigation systems, such as micro-sprinkler, flood, to name a few. Little is also known about how the cover crop transpiration is affected by canopy cover of apple trees from planting until the trees reach full-bearing age or maturity. This study therefore seeks to close this important information gap in order to gain insights on the role that cover crops play in the water balance of apple orchards.

Understanding the partitioning of ET in orchards is very important, especially in dry countries to quantify the proportion of beneficial water used to produce fruit (Kool et al., 2014; Wang and Wang, 2017). It also gives irrigation managers opportunities to identify and implement practices to reduce orchard floor evaporative fluxes to improve water productivity (Ortega-Farias, 2012; Dzikiti et al., 2017; Dzikiti et al., 2018b; Fernández et al., 2018). In addition, ET partitioning data is also important for evaluating multiple source water use models in agricultural and hydrological studies and in climate modelling (Anderson et al., 2017; 2018,). Few studies have directly measured all the components of ET in crop fields. For example, in a comprehensive review of 52 publications of ET partitioning, Kool et al. (2014) found that 32 of the studies showed that soil evaporation (E_s) contributed more than 30% of ET. Only 20 of the studies independently quantified both E_s and T as well as ET. In this study we, for the first time, extend these measurements by collecting detailed data not only of E_s and T, but also of cover crop transpiration (T_c) which has not been quantified in apple orchards.

In most orchards, the cover crop is either single species of exotic cover crops planted between the tree rows or indigenous vegetation, weeds or complex mixtures of these. Grasses are the most common cover crops planted in South African apple orchards for a variety of reasons. Examples include the tall fescue (*Festuca arundinacea*), kikuyu grass (*Pennisetum clandestinum*) and rye grass (*Lolium*), among others. They are used in orchards; i) to reduce soil erosion, ii) for improving the soil health (as living mulches and for nitrogen fixation), iii) for phytosanitary purposes by attracting and feeding beneficiary insects, and; iv) for aesthetic benefits, among others (Jannoyer et al., 2011). However, there is a strong, and yet unconfirmed, suspicion that the cover crops also contribute to an increased orchard water use.

The overall aim of this study is therefore to examine, in detail, the partitioning of evapotranspiration in apple orchards with a special focus on the role of the cover crops. We also investigated how the ET partitioning varies with tree canopy cover which is a function of both the tree age and cultivar. For instance, the red apple cultivars are maintained with more open canopies, and hence, low vegetation cover, to encourage the development of the red colour on the fruit (Wiehann Steyn, pers. comm.). Apple cultivars that are susceptible to sunburn damage such as ‘Golden Delicious’ and ‘Granny Smith’ are usually allowed to develop dense canopy cover (Mupambi et al., 2018) to provide shade for the fruit.

5.2 MATERIALS AND METHODS

5.2.1 Description of study sites

Data were collected over two growing seasons (October to May) of 2016/17, and 2017/18 in five orchards in the prime apple growing regions in the Western Cape Province of South Africa. Detailed descriptions of the study areas are given in Dzikiti et al. (2018a & b) and in Mobe et al. (2020). Two orchards were in the Koue Bokkeveld (KBV) region located about 180 km to the north of the City of Cape Town (Fig. 1.1). The KBV region experiences hot summer temperatures and very cold winters with occasional snow fall over high lying areas. The third orchard was located close to the town of Vyeboom about 90 km to the east of Cape Town, while the other two orchards where close to the town of Grabouw, about 70 km to the southeast of Cape Town (Fig. 1.1). Climate in the Vyeboom and Grabouw areas is mild compared to KBV due to the moderating effect of the nearby Atlantic Ocean.

The selected orchards had contrasting characteristics in terms of tree canopy cover, cultivar, cover crop, and management practices. One orchard in KBV was planted to the five-year-old ‘Golden Delicious’/’Reinders’ apple trees on the M793 rootstock, at Lindeshof farm (hereafter called Orchard 1). The Golden Delicious cultivar is the most widely planted cultivar in South Africa accounting for close to 30% of the area under apples (Hortgro, 2018). In this orchard, the cover crop was patchy comprising of a mixture of the tall fescue cover crop and weeds covering a strip of about 1.1 m wide in the middle of the tree row. Tree spacing was about 4.0 x 1.5 m, giving 1 667 trees per hectare. The second orchard (Orchard 2) in KBV was planted to seven-year-old Cripps’ Pink apple trees on M793 rootstock, at Esperanto farm. This cultivar is a high value and late maturing cultivar under South African conditions. The area under Cripps’ Pink apples is rapidly growing in South Africa due to the high economic returns and reduced sunburn damage (Mupambi et al., 2018). The cover crop in this orchard was a dense mixture of weeds and indigenous grasses mainly the buffalo grass (*Penicum maximum*) and gum grass (*Eragrostis gummiflua*) (Fig. 5.1a). Tree spacing was about 4.5 x 2.0 m giving 1 111 trees per hectare. The cover crop was in the middle of the tree rows but extending over a larger surface area with an average width of about 1.7 m. Apple trees in South Africa typically reach full-bearing age between seven and eight years after planting. Therefore, all orchards between four and seven years old are referred to as “medium bearing” orchards in this study. Soil types for the two KBV sites were deep sandy to sandy loam soils of the Fernwood soil form (Hyperalbic Arenosol) according to the Soil Classification Working Group (1991).

The third orchard (Orchard 3), located in EGVV, was also a five-year-old medium bearing orchard planted to the Golden Delicious/Reinders cultivar on the M7 rootstock, at Vyeboom farm. Tree spacing was 4.0 x 2.0 m giving a density of 1 250 plants per hectare. The cover crop was a dense tall fescue cover crop which grew between the tree rows. However, the cover crop was restricted to a thin strip which was only about 0.75 m wide on average and it was kept lash green by irrigation (Fig. 5.1b). The fourth orchard (Orchard 4) was a mature 26-year-old Golden Delicious apple block in EGVV on M793 rootstock, at Oak Valley farm. Tree spacing was about 4.25 x 2.00 m and the maximum fractional vegetation cover at the midseason stage was about 0.64. The intense shading by the large canopies restricted the cover crop to a thin strip, about 0.50 cm wide on average comprising of the tall fescue species. The last orchard (Orchard 5) was a young non-bearing Fuji orchard which was two years old and located next to the mature Golden Delicious orchard at Oak Valley farm. Tree spacing was about 3.5 x 2.0 m and there was a dense cover crop in the middle of the row with an average width of about 1.9 m (Fig. 5.1c). Fractional vegetation cover of the young trees at the midseason stage was less than 0.20. The soils in the three EGVV orchards were the dark red clayey loam soils of the Kroonstad soil form according to the Soil Classification Working Group (1991). All the five orchards in this chapter were irrigated by a micro-sprinkler system with one sprinkler per tree delivering about 30 litres of water per hour. The wetted area extended between 1.0 and 1.2 m away from the micro-sprinkler. Data collection in Orchards 1 to 3 was done during the 2016/17 growing season while that in Orchards 4 and 5 was collected during the 2017/18 season and Table 5.1 summarizes all the orchard attributes.

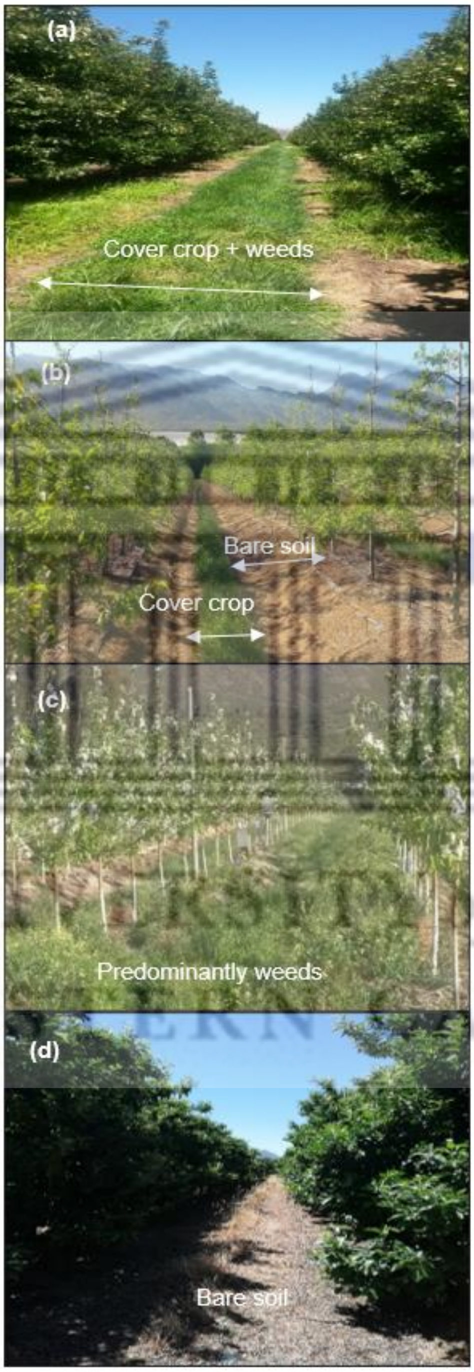


Fig. 5.1: Various orchard floor management practices showing; (a) a wide cover crop strip with a mixture of planted cover crop and weeds; b) a thin single species strip of tall fescue cover crop, (c) a poorly managed orchard floor with a dense cover of weeds and cover crops; and (d) a bare orchard floor typical of drip irrigated orchards.

Table 5.1: Summary of the properties of the five apple orchards of different age groups studied during the period 2016-2018. All experimental orchards had an altitude between 300 – 400 meters above sea level. LAI$_c$ is the recorded peak leaf area index over the cover crop strip.

Region	Orchard number	Cultivar	Age group	Tree density	Orchard size (ha)	Rootstock	Age (years)	Tree height	LAI	LAI$_c$	Fractional cover crop cover	Coordinates
2016/17 SEASON												
KBV	1	Golden Delicious	Medium-bearing	1 667	3	M793	5	3.5	1.5	0.15	0.28	S32°57’01”; E019°12’26”
KBV	2	Cripps' Pink	Medium-bearing	1 111	3.5	M793	7	3.5	2	0.16	0.38	S33°21’55”; E019°19’20”
EGVV	3	Golden Reinders	Medium-bearing	1 250	6	M7	5	3.5	1.3	0.14	0.19	S34°4’5”; E019°6’42”
2017/18 SEASON												
EGVV	4	Golden Delicious	Full-bearing	1 176	5.1	M793	26	4	3.5	0.17	0.12	S34°954’18”; E019°437’2”
EGVV	5	Fuji	Non-bearing	1 667	2.8	M109	2	3	1	0.35	0.54	S34°95’27.6”; E019°43’40.8”

5.2.2 Data collection

5.2.2.1 Site microclimate measurements

Weather data were measured using automatic weather stations located next to the orchards for Orchards 1 and 2. Data for orchards 3, 4 and 5 were collected from the network operated by the Agricultural Research Council (ARC) located less than 3.0 km away. The stations were installed over uniform short grass surface whose attributes resemble the grass reference crop (Allen et al., 1998). Equipment used for Orchards 1 and 2 weather data comprised of pyranometers (Model: SP 212 Apogee Instruments, Inc., Logan UT, USA), which measured the solar irradiance, air temperature and relative humidity probes (Model: HMP60 Campbell Scientific, Inc., Logan UT, USA) installed about 2.0 m above the ground. A three-cup anemometer and wind vane (Model R. M. Young Wind Sentry Set model 03001, Campbell Scientific, Inc., Logan UT, USA) were used to measure wind speed and direction, respectively at 2.0 meters height, while rainfall was recorded using a tipping bucket rain gauge (Model: TE525-L; Campbell Scientific, Inc., Logan UT, USA). All the sensors were connected to data loggers (Model: CR1000 Campbell Scientific, Inc., Logan UT, USA) programmed with a scan interval of 10 s. The output signals were processed at hourly and daily intervals.

5.2.2.2 Sap flow dynamics, leaf area index, and orchard evapotranspiration

In South Africa, the apple growing season is eight to ten months long (September/October to May/June) depending on cultivar. In this study tree transpiration was measured for the entire growing season in each of the five orchards using the heat ratio method (HRM) (Burgess et al., 2001) sap flow sensors installed on between three and six trees in the mature and medium bearing orchards. The HRM systems comprised of heaters implanted into the stems and connected to custom-made relay control modules which controlled the heat application. T-type thermocouple pairs, installed at equal distances (~0.5 cm) up and downstream of each heater probe measured the sapwood temperature. The thermocouples were then connected to multiplexers (Model: AM16/32B Campbell Scientific, Logan UT, USA) which were in turn connected to CR1000 data loggers as described in Dzikiti et al. (2018a). Four sets of sensors were installed in the four cardinal directions around the stem on each of the six trees to account for the azimuthal variations in sap velocity (Lopez-Bernal et al., 2010). The sensors were inserted at different depths into the sapwood to capture the radial variation in sap velocity as described by Wulschleger and King (2000). The HRM data were corrected for wounding due to sensor implantation at the end of the experiment according to the procedure by Swanson and Whitfield (1981). The conducting sapwood area was determined by injecting a weak solution of methylene blue dye into the stems to determine the extent of the active xylem vessels. Whole-tree transpiration was derived as the sum of the sap flows in four concentric rings in the sapwood with flow in each ring calculated as the product of the sap velocity at each probe depth and the sapwood area represented by that probe. In this study, we did not calibrate the HRM sap flow method, so our results represent un-calibrated values. In the young non-bearing orchard with smaller stems, Granier probes (Model TDP 10, Dynamax, Houston, USA) were used. The sensors were installed on trees with different stem sizes to account for the tree-to-tree variation in the water use rates. The Granier probes were calibrated on young apple trees using weighing lysimeters as described by Dzikiti et al. (2018b).

The orchard leaf area index (LAI) for the trees was measured at roughly monthly intervals throughout the growing season using an LAI-2000 Plant Canopy Analyser (LI-COR Inc., Lincoln, NE, USA). The data were collected when there was no direct solar radiation either before sunrise or after sunset when the tree leaves behaved like black bodies.

Evapotranspiration (ET) from the orchards was measured using an open path eddy covariance system with sensors mounted on a 10 m lattice mast. The system was deployed in the orchards during short window periods lasting a few days due to equipment limitations. The sensors comprised a 3D sonic anemometer (Model: CSAT3, Campbell Sci. Inc., Utah, USA) that measured the wind speed in the x – y and z directions. An infrared gas analyser (IRGA) (Model: LI-7500A, LI-COR Inc., Nebraska, USA) was used to quantify the concentration of atmospheric water vapour and carbon dioxide. The sensors were connected to a CR5000 data logger manufactured by Campbell Scientific. Additional sensors to quantify the orchard energy balance included a single component net radiometer (Model CNR1: Kipp & Zonen, The Netherlands) which was installed at about 8.0 m height from the ground. Two clusters of soil heat flux plates (Hukseflux, The Netherlands) were installed at 8 cm depth below the surface to measure the soil heat fluxes under the canopies and between the tree rows. Soil averaging thermocouples (Model: TCAV, Campbell Sci. Inc., Utah, USA) were installed above each set of soil heat flux plates at 2 and 6 cm depths from the surface to correct the measured fluxes for the energy stored by the soil above the plates. The high frequency data, collected at 10 Hz, was stored on a 2 GB memory card. The height of the trees ranged from 3.0 to 4.5 m

(Table 1) while the orchard sizes varied from just under 3.0 ha up to about 6.5 ha. In all the orchards the flux tower was located downwind of the prevailing wind direction to maximize the fetch upwind of the tower. The IRGA and sonic sensors were mounted between 1.3 and 1.6 m above the average canopy height depending on orchard size and data emanating from outside the study area were excluded. The high frequency data were post-processed to correct for air density fluctuations, lack of sensor levelness (coordinate rotation), sensor separation and sensor response times. using the EddyPro v 6.2.0 software (LI-COR Inc., Nebraska, USA). The data were further corrected for lack of energy balance closure using the Bowen ratio method as described by Cammalleri et al. (2010).

5.2.2.3 Cover crop, radiation interception, and soil evaporation

The cover crop management practices varied widely between orchards. To monitor changes in the orchard floor characteristics, we requested the participating farms to record dates when they performed operations such as mowing of the cover crop or application of herbicides throughout the growing season. For example, in the mature orchard (Orchard 4) and medium bearing orchards (Orchard 1 and 3), the cover crop was mowed roughly on a monthly basis using a cutter mounted on a tractor (Fig. 5.2). The medium bearing 'Cripps' Pink' orchard (Orchard 2) was mowed at irregular intervals during the growing season while the young non-bearing 'Fuji' orchard (Orchard 5) was only mowed at the beginning and end of the season.

The leaf area index of the cover crop (LAI_c) was measured at roughly monthly intervals in Orchards 3, 4 and 5. This was done using a destructive approach wherein a 50 cm x 50 cm sampling grid was used to mark four to five random positions occupied by the vegetation within the cover crop strip. All the vegetation enclosed in the grid was cut to ground level and their leaf area measured manually in the lab using the leaf area meter (Model Li-3000, Li-COR Inc., Nebraska, USA). The leaf area index of the cover crop strips was then estimated as the ratio of the cover crop leaf area to the grid area (2 500 cm^2), and an average value was calculated. To establish the drivers of water use by the cover crop, we measured the photosynthetically active radiation (PAR) that was intercepted by the cover crop plants at selected intervals.

These data were measured using a ceptometer (Model: LP-80 AccuPar; Decagon, USA) at six marked positions with different sun-shade exposures on the orchard floor. The fraction of the PAR intercepted by the cover crop was then calculated as the ratio of the average PAR under the canopies to that incident at the top of the tree canopies. The specific dates when these data were collected in each orchard are shown in Table 5.2.

Fig. 5.2: Understory vegetation cutter mounted on a tractor at Oak Valley farm in Grabouw, Western Cape, South Africa

Table 5.2: Dates for the various campaigns to measure water use partitioning in five orchards of different age groups and cultivars.

Region	Orchard number	Cultivar	Age group	Measured variables	Measurement date
KBV	1	GD	MB	ET, T, E_s, Tc & R(i)	13-18 Nov 2016
KBV	2	CP	MB	ET, T, E_s, T_c & R(i)	12-13 Jul 2017
Vyeboom	3	GD	MB	ET, T, E_s, Tc & R(i)	21-24 Feb 2017
Grabouw	4	GD	FB	ET, T, E_s, T_c & R(i)	12-15 Dec 2017
Grabouw	5	FJ	NB	ET, T, E_s, T_c & R(i)	8-10 Nov. 2017

Evaporation from the bare soil was monitored, also for selected days, using micro-lysimeters according to the data collection schedule in Table 5.2. The selected periods coincided with days when the eddy covariance flux tower was operational in the respective orchards. Eight PVC micro-lysimeters were installed at different sun-shade and wet-dry locations on the orchard floor. The changes in the mass of the micro-lysimeters were monitored at hourly intervals using a precision mass balance with a resolution of 0.01 grams from sunrise to sun set according to the schedule in Table 5.2. The soil used in the micro-lysimeters was replaced after every 12 hours for consecutive measurement days. The whole surface soil evaporation was calculated as the weighted sum of the micro-lysimeter measurements with the area represented by each micro-lysimeter on the orchard floor used as the weights according to the approach by Testi et al., (2004).

5.2.2.4 Measurement and modelling of cover crop transpiration

Given the wide range of cover crop which grow in orchards (Fig. 5.1), we did not distinguish between the different species in this study. Instead, we targeted the most common grass species for monitoring. Cover crop transpiration was measured using miniature stem heat balance sap flow gauges (Model SGA3, Dynamax Inc., Houston, USA) and details of these micro sap flow sensors are given by Van Bavel and Van Bavel, (1990). The cover crop transpiration was also measured during periods when the eddy covariance flux tower was deployed in each orchard. The sap flow data were measured on between three and four cover crop plants at hourly intervals for a few days. Careful precautions were taken to ensure that the sensors performed optimally according to the manufacturers' recommendations, which included carefully wrapping each gauge using several layers of reflective aluminium foil to ensure steady state conditions, and cleaning the installation sites on the stems. However, given the proximity of the sensors to the ground, we suspected that strong thermal gradients could affect the quality of the data. So, we calibrated the micro sap flow sensor data against manual transpiration measurements taken using the portable Infrared Gas Analyser (Model: LI-6860, Portable Photosynthesis System, LI-COR Inc., Nebraska, USA). The IRGA data were collected in continuous cycles from sunrise to sunset over a period of two days. The micro sap flow sensor data were normalized with the transpiring leaf area for each instrumented plant. These data were directly compared with that from the IRGA to confirm the accuracy of the sap flow measurements.

5.3 RESULTS

5.3.1 Microclimate

A summary of the climatic conditions during the 2016/17 and the 2017/18 growing season is shown in Table 5.3. The period 2015 to 2018 coincided with one of the worst droughts in living memory in the Western Cape Province which spanned over three consecutive years. However, despite concerns over water availability, the study orchards were prioritized and irrigated as in normal years. Therefore, the drought conditions did not skew the results of this study, particularly given that little rain falls during the growing season.

During the 2016/17 growing season, the Koue Bokkeveld (KBV) sites (Orchards 1 and 2) received only 37.9 mm of rainfall while Orchard 3 in Vyeboom received slightly higher rainfall at 55.0 mm from October 2016 to May 2017. Although most rain falls in winter from May to August, the amounts reported here were much lower than in normal years highlighting the impact of the drought. Therefore, irrigation was critical to compensate for the rainfall deficit. The seasonal total reference evapotranspiration (ET_o), which is a measure of the atmospheric evaporative demand was about 1 443 mm for KBV which was several orders of magnitude higher than the rainfall (Table 5.3), while it was ~1 101 mm in EGVV. The reference evapotranspiration was calculated using the modified Penman-Monteith equation for a short grass reference according to Allen et al. (1998). For Orchards 4 and 5 in EGVV, the seasonal total rainfall during 2017/18 was much higher at about 309.3 mm while the reference evapotranspiration was slightly lower than at the other sites at about 879.9 mm.

*Table 5.3**:** Daily maximum and minimum temperature (T_x and T_n), maximum and minimum relative humidity (RH_x and RH_n), solar radiation (R_s), wind speed (u), rainfall (Rain) and reference evapotranspiration (ET_o) at the Koue Bokkeveld, Vyeboom and Grabouw sites.*

Koue Bokkeveld sites (2016/17 season)								
Month	Rs MJ/m^2/d	Tx °C	Tn °C	RHx %	RHn %	Rain mm	U m/s	ET_o mm
Oct	23.2	31.5	2.6	91.3	9.9	4.6	2.5	134
Nov	28.9	31.9	4.8	91.5	9.5	4.6	2.4	204
Dec	31.3	34.9	8.8	91.1	10.2	6.1	2.8	232
Jan	30.2	34.4	9.3	91.3	8.6	8.1	2.9	234
Feb	28.6	34.9	9.4	89.2	9.9	4.1	2.8	222
Mar	23.2	35.1	8.5	89.8	6.2	0	2.7	187
Apr	17.1	30.7	2.9	91.3	8	5.8	2.6	136
May	13	28.2	3.7	91.9	12.1	4.6	2.4	94
Totals						37.9		1443
	Vyeboom sites (2016/17 season)							
Oct	21.1	36.7	4.1	90.5	8.4	3.3	1.4	131.5
Nov	24.8	36.8	7.4	92.9	13.3	10.9	1.5	153
Dec	27.3	40.4	12.6	89.9	8.8	1	1.6	189.2
Jan	26.4	38.7	12.2	88	10	3.3	1.6	181.2
Feb	25.1	38.6	13.1	89.6	10.5	2.5	1.5	155.8
Mar	19.8	38.9	10	92	9.4	6.1	1.4	137.4
Apr	13.8	34.9	8.2	93.8	15.2	20.5	1.2	89.3
May	10.2	29.9	6.5	94.6	14.6	7.4	0.9	63.7
Totals						55		1101.1
	Grabouw sites (2017/18 season)							
Oct	21.1	22.56	9.06	91.63	40.02	28.56	1.81	114.03
Nov	23.67	22.99	10.3	94.13	45.21	66.8	1.96	120.97
Dec	26.75	26.05	12.28	92.71	40.79	16.3	1.96	151.8
Jan	23.03	27.26	14.18	94.86	46.12	19.9	1.93	138.98
Feb	23.13	27.83	13.51	94.47	38.8	14.6	1.84	126.93
Mar	17.24	24.28	12.35	94.83	47.87	23.9	1.6	98.97
Apr	14.22	23.37	11.1	95.6	46.12	50.9	2.01	76.29
May	9.21	21.08	10.14	92.72	47.89	88.3	2.49	51.97
Totals						309.3		879.9

5.3.2 Radiation interception and cover crop leaf area index

The radiation reaching the orchard floor is essential for driving processes such as transpiration and photosynthesis by the cover crop. Examples of the fractional radiation interception are given in Fig. 5.3 in which three orchards age groups were considered. As expected, the cover crop growing in the young orchard (Orchard 5) with the lowest tree fractional vegetation cover intercepted very high levels of PAR, up to 96% of the incident radiation at midday. In addition, interception levels remained high throughout the day as illustrated in Fig. 5.3. The influence of the high canopy cover was apparent for the medium bearing and the mature orchards. While the peak intercepted PAR at the orchard floor in the medium bearing orchards reached about 70%, this only occurred for a short period when the sun was overhead between 11h00 and 14h00. Outside these times, on average less than 20% of the PAR reached the orchard floor (Fig. 5.3). The peak intercepted PAR by the mature orchard was much lower reaching about 33% around midday. At low sun angles, the fractional PAR intercepted by this orchard was of the same order of magnitude as the bearing orchards. The low PAR reaching the orchard floor partly explained the rather sparse cover crop compared, for example, to younger orchards.

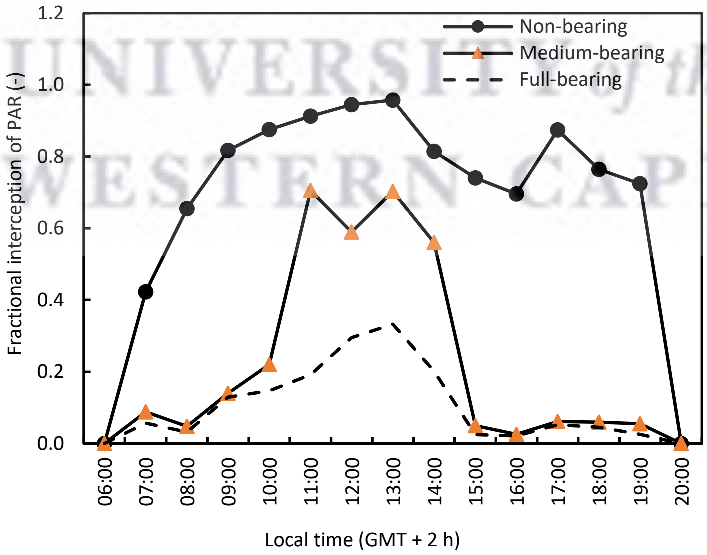


Fig. 5.3: The diurnal course of the fractional PAR reaching the orchard floors for a mature (Orchard 4), medium canopy cover (Orchard 3) and the young non-bearing orchard (Orchard 5).

Fig. 5.4 clearly shows the effect of management on the cover crop leaf area index of the different orchards. Continuous LAI_c data were obtained by linear interpolation between the monthly measurements and using information from the farm on the cutting dates. There was much more intense mowing of the cover crop in the bearing and mature orchards with the peak LAI_c hardly exceeding 0.15. It is not clear why it was a priority to keep the grass short in mature and bearing orchards. Reducing competition for resources between the trees and the cover crop and removing shelter for snakes which could be a hazard for the workers are probable factors. The cover crop in the non-bearing orchard was only cut twice during the whole season, namely at the beginning and at the end of the season (Fig. 5.4). Consequently, LAI_c reached up to 0.35 in the middle of summer. After harvesting (February to March), the cover crop was again allowed to flourish in all the orchards.

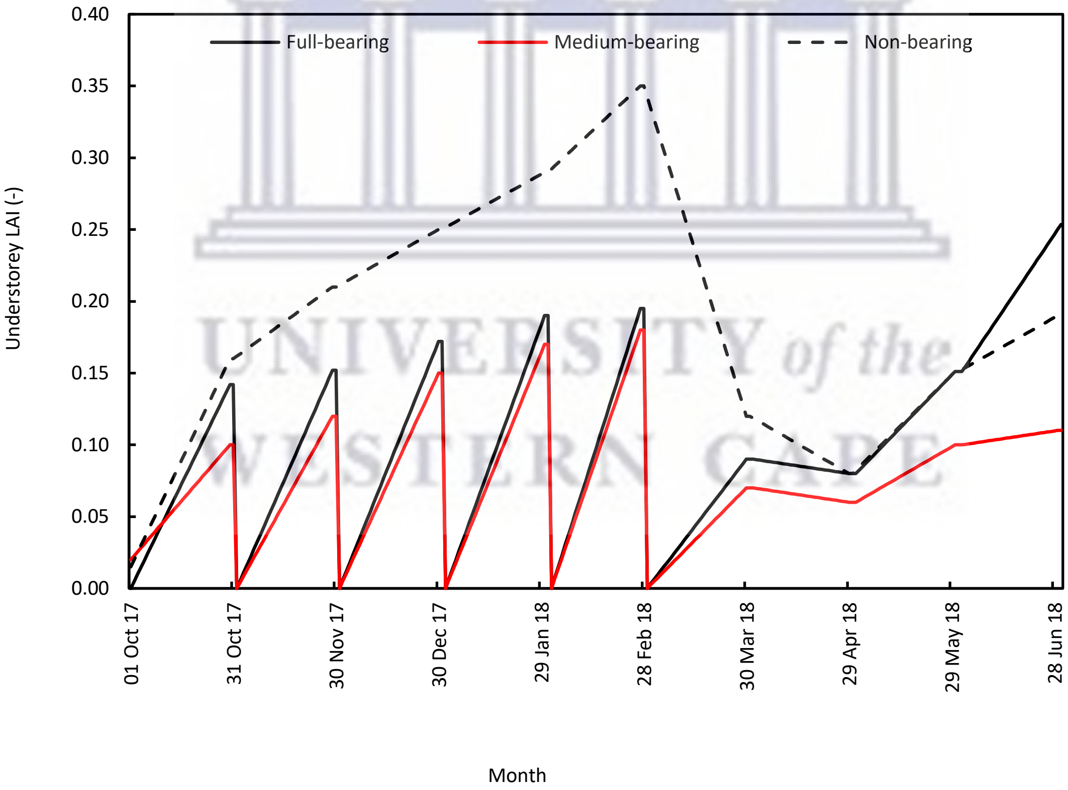


Fig. 5.4: The seasonal dynamics in the leaf area index of cover crop for a mature (Orchard 4), medium canopy cover (Orchard 3) and the young non-bearing orchard (Orchard 5) in South Africa during the 2016 – 2017 growing season. These values are for the cover crop strips only, not expressed over the entire orchard floor.

5.3.3 Cover crop water use dynamics and ET partitioning

While the stem heat balance sap flow gauges have been used on grasses before (Ramírez et al., 2006; Senock and Ham, 1995), the sensors have not been used under natural conditions where thermal gradients are strong (Van Bavel and Van Bavel, 1990). For this reason, we calibrated these sensors under field conditions against the Infrared Gas Analyser (IRGA) and typical results are shown in Fig. 5.5. The micro sap flow sensor readings were of the same order of magnitude as the IRGA readings. However, there was a significant time shift between the sap flow and the IRGA readings suggesting significant capacitance effects due to the stored water (Dzikiti et al., 2007; Steppe et al., 2006b). The area under the curve represents the daily total transpiration and this was similar between the two independent techniques. So, all cover crop transpiration data were subsequently collected using the miniature sap flow sensors which are cheaper, and the measurements could be automated.

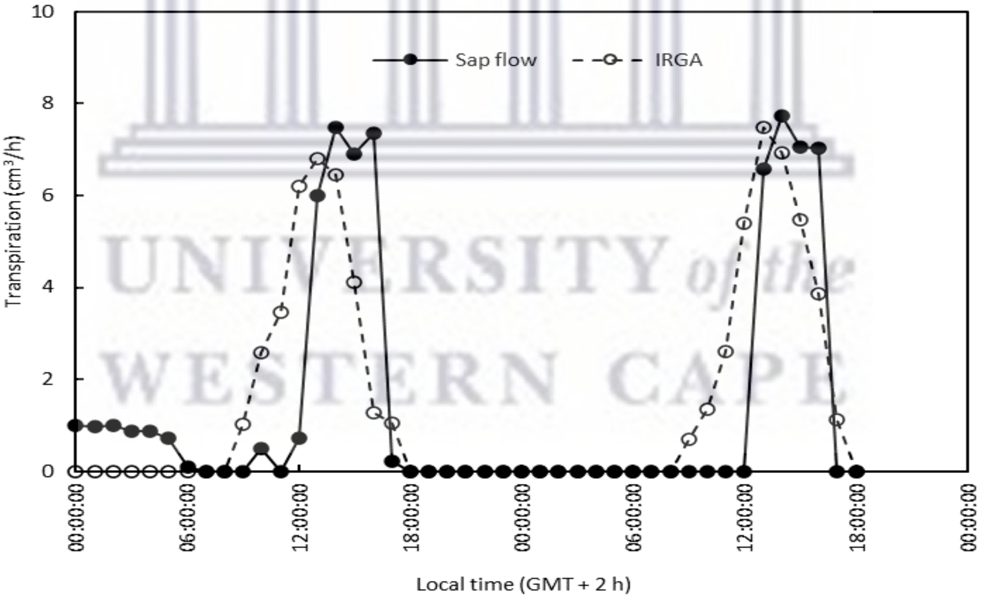


Fig. 5.5: Comparison of the transpiration measured from a single cover crop plant using a micro stem heat balance sap flow sensor and the Infrared Gas Analyser over two clear days.

An example of the time series of transpiration by the cover crop and by the mature apple trees over a five-day period as influenced by the incident PAR at the top of the tree canopies is shown in Fig. 5.6. There is a clear correlation between the tree transpiration and PAR flux while the cover crop transpiration is also influenced by shading by the tree canopies. The contributions of the various orchard floor and tree fluxes to the whole orchard ET on typical clear days are shown in Fig. 5.7 when all the orchards were well-watered. In mature and medium bearing orchards, tree transpiration was the dominant flux while the orchard floor fluxes were the major contributors to ET in young orchards. The stem sap flow derived transpiration shown in Fig. 5.7a is shifted towards the afternoon because of tree capacitance effects and we did not correct for the time lags. In mature orchards, the approximate contribution of tree transpiration, soil evaporation and cover crop transpiration to ET were approximately 65%, 25% and 10%, respectively. The residuals due to lack of closure in the measured water balance components were applied equally to the cover crop transpiration and the soil evaporation. These fluxes have the largest uncertainty due to the uneven wetting of the orchard floor and the variability in the cover crop properties. In the medium bearing orchards, these contributions were 55, 30 and 15%, respectively. In non-bearing orchards, the contributions were 16%, 52% and 32% respectively. There were no mulches in all the orchards studied.

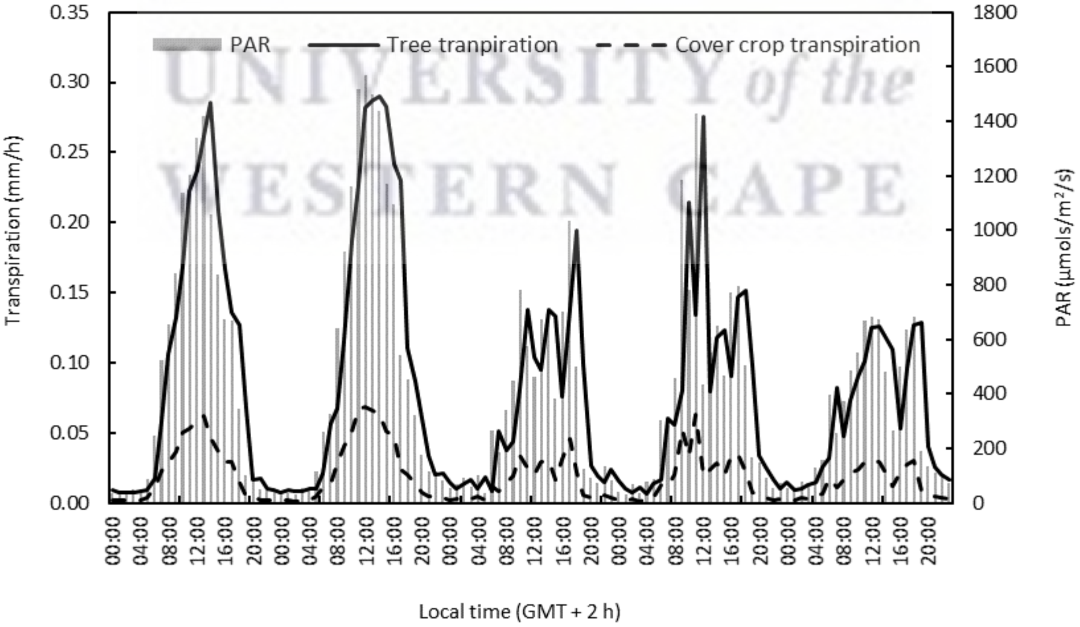


Fig. 5.6: Relationship between the incident PAR, measured tree transpiration in a medium bearing orchard (Orchard 1) and measured cover crop transpiration over five days from 14 to 18 November 2016.

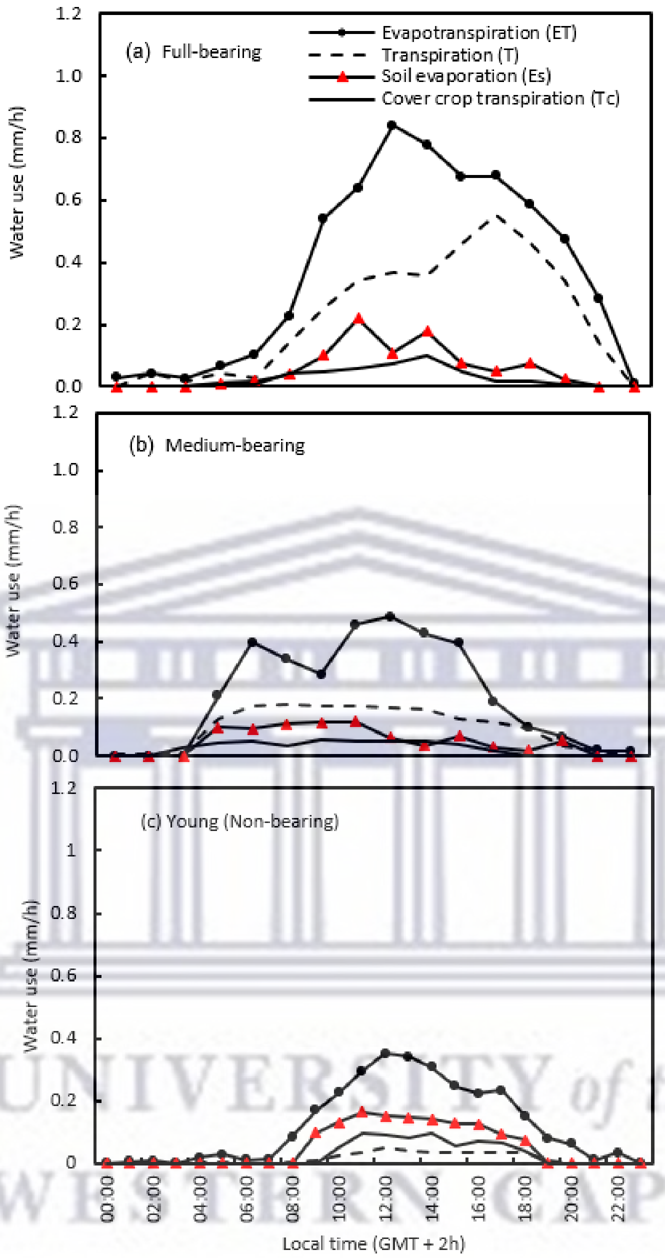


Fig. 5.7: Typical partitioning of evapotranspiration into its constituent components on clear days in micro-sprinkler irrigated orchards that are; (a) full-bearing (Orchard 4), (b) medium-bearing (Orchard 3), and (c) young non-bearing (Orchard 5).

5.4 DISCUSSION

The increasing frequency and severity of droughts due to climate change, and the growing competition for the limited water resources, are some of the key factors limiting economic growth, job creation, and food security in arid and semi-arid countries (Falkenmark, 2013; Reinders et al., 2013). In South Africa, for example, there is an increasing realization that irrigated agriculture is critical for the future prosperity of the country given the increasingly unreliable rainfall patterns (National Development Plan., 2030). Yet the available water resources are already fully allocated in more than 80% of the catchments across the country (Gush et al., 2019). For this reason, it is essential that major water users such as the fruit industry identify options to reduce water use in order to free up water to support further irrigation expansion (Reinders et al., 2013; Gush and Taylor., 2014).

In orchards, the transpiration component of the trees is usually associated with tree productivity while the orchard floor evaporative fluxes have, for a long time, been related to non-beneficial water losses (Kool et al., 2014; Lopez-Olivari et al., 2016). Consequently, orchard floor management practices such as mulching and the use of localized irrigation systems such as drip irrigation are being widely used in orchards to reduce undesirable water losses (Hussain et al., 2018; Lötze and Kotze, 2014). In recent years however, two developments have influenced orchard floor management practices. The first relates to the need to reduce the use of agro-chemicals and pesticides in fruit production especially fruit that are destined for the export market. The second relates to the need to improve biodiversity in monoculture production systems such as orchards in order to enhance pests and disease management using eco-friendly practices (Jannoyer et al., 2011). Consequently, cover crops are increasingly part of the modern orchards, and they have many pros and cons. One disadvantage of the cover crops relates to their unknown water requirements and there is a suspicion that some species use large quantities of water. Among the benefits from cover crops include i) an ability to control pests and diseases by providing a habitat for beneficial insects, ii) improving the soil fertility e.g. through nitrogen fixation, iii) improving the soil structure, iv) supressing the proliferation of weeds thereby limiting the use of herbicides. It is therefore not surprising that in many orchards in South Africa, the cover crops are actually watered to maintain a healthy orchard ecosystem. The choice of appropriate cover crops is therefore an important consideration for fruit farmers in the arid climates. In South Africa for example, there has been a raging debate for decades whether or not indigenous cover crop species use less water than exotic ones. However, no quantitative studies have been done to provide clarity on this subject.

In this study, we for the first time, provide insights on the typical water use rates by cover crop measured under field conditions. A number of previous studies have indirectly estimated evaporative losses from the orchard floor as the difference between the whole orchard ET and transpiration measured using sap flow sensors or stable isotopes (Dzikiti et al., 2017; Er-raki et al., 2009; Gush and Taylor, 2014). The reliability of the orchard floor evaporative fluxes estimated in this way depends on the accuracy of both the ET and transpiration measurements. This study measured the transpiration using Granier probes in young orchards and the HRM in mature trees. The Granier probes are widely reported to significantly underestimate transpiration especially at high flow rates (Steppe et al., 2010; Dzikiti et al., 2011). In this study, we calibrated this method against weighing lysimeter data to minimize the errors. The HRM method, on the other hand, is designed to accurately measure low and reverse sap flows (Burgess et al., 2001). Its performance under high flow rates, characteristic of irrigated fruit tree crops such as apple trees, are not well known. However, the method has been calibrated against the weighing lysimeters on the high transpiring eucalyptus species and it gave reliable data as reported by Bleby et al. (2004). Given that we were unable to calibrate the HRM sensors on the apple trees, our tree transpiration data should therefore be interpreted within the constraints of this method.

Other studies that have quantified orchard floor evaporative fluxes have only measured the soil evaporation component and they assumed that the cover crop transpiration was negligible (Dzikiti et al., 2018a; Gush and Taylor, 2014; Testi et al., 2006). The present study used miniature stem heat balance sap flow gauges to directly measure the water use of the mostly grass cover crop. This method has been successfully used before on grasses by Senock and Ham, (1995) and by Ramirez et al. (2006), but this has been under controlled environments in greenhouses or with potted plants. A major source of uncertainty with this method under natural uncontrolled conditions arises from the thermal gradients which can distort the signals, especially after sunrise (Steppe and Lemeur, 2004). The current study demonstrates that these gauges give transpiration readings that are comparable with the leaf level transpiration measurements recorded using the infrared gas analyser if adequate precautions are taken to minimize the soil-plant thermal gradients in grasses.

5.5 CONCLUSION

This study has shown that cover crop contributes significantly to whole orchard water use, but this is strongly influenced by canopy cover of the trees. For example, the young orchard with a dense cover crop used almost three times as much water as that in a mature orchard with a well-maintained cover crop. Again, in non-bearing orchards with a dense cover crop cover, transpiration by the cover crop can account for close to 40% of the orchard ET. In mature orchards with large canopies, cover crop transpiration did not have a significant contribution mainly due to shading by tree canopies. Therefore, maximum water savings can be achieved by reducing the cover crop cover when the trees are still young. It appears as if water savings due to a sparse cover crop are less in mature orchards because the large canopies of the trees supress the cover crop transpiration rates.

CHAPTER 6: MODELLING EVAPOTRANSPIRATION USING A MULTIPLE SOURCE MODEL

Orchard floor management

Parts of this chapter are also published in:

***Z Ntshidi**, S Dzikiti, D Mazvimavi, Mobe NT., (2020). Contribution of cover crop to evapotranspiration partitioning in apple orchards under Mediterranean climatic conditions in South Africa. Agricultural Water Management.245, 103070.*

Abstract

Accurate estimates of actual evapotranspiration and its constituent components are important for accurate irrigation scheduling, irrigation system designs, and best possible on-farm water allocations especially in arid-semi-arid ecosystems. Precise measurements of ET remain challenging, expensive, arduous, and at times tricky to apply over heterogeneous surfaces such as crop fields. Hence, precise crop water-use models are required for orchard accurate water resources management. It is crucial to know how much of the applied water is used by the trees and how much is used by the orchard floor. This way irrigation specialists can adopt ways to minimize non-beneficial water uses (water use by the orchard floor) and prioritise beneficial water use (water used to grow the plant). In this study, we developed a simple model to estimate cover crop transpiration to better understand how the contribution of the cover crop transpiration to orchard ET varies with management and with canopy cover of the apple trees during the course of the growing season. The developed model was used to gain insights on the implications of various cover crop management practices on orchard ET partitioning through model sensitivity tests. Data were collected in five orchards spread across key apple producing regions in the Western Cape Province of South Africa over two growing seasons (2016/17, 2017/18). Cover crop transpiration was measured at selected intervals using micro stem heat balance sap flow gauges calibrated against infrared gas analyser readings. Then the model cover crop water use estimates were tested against cover crop water use measurements obtained from the sap flow technique. The results showed that the cover crop transpiration model accurately estimated the seasonal cover crop water use from apple orchards of different canopy covers. The results from the modelled Tc against the measured Tc yielded correlation coefficients of > 90% (R^2= 0.96).

6.1 INTRODUCTION

Cover crop comprises of plant life growing beneath the orchard or forest canopy without penetrating it to any great extent but above the orchard or forest floor. In orchards such vegetation is commonly planted between tree rows for purposes of 1) maintaining the soil structure (Fageria et al., 2005), 2) encouraging water infiltration (Busscher et al., 1996), 3) reducing soil erosion, among others. Cover crops can also enhance soil fertility through nitrogen fixation and increasing the organic matter content in the soil (Reicosky and Forcella, 1998; Chen et al., 2003). They also play a role in suppressing weeds, and hosting beneficial natural organisms that control pests and diseases in orchards (Sarrantonio and Gallandt, 2003; Guerra and Steenwerth, 2012). This in turn results in the reduced use of agrochemicals, mainly pesticides and herbicides that are harmful to both humans and the environment.

A major question surrounding the use of cover crops in orchards revolves around whether the benefits derived from them exceed the losses, particularly of scarce resources such as water and nutrients (Jannoyer et al., 2011). For instance, during the 2016-2018 drought that was reported in South Africa, many farmers impulsively removed cover crops supposedly to lower the orchard water use. The questions that remain as there is currently no quantitative information on the water use of cover crops are 1) how much water do cover crop species use in orchards under semi-arid sub-tropical conditions? 2) how does this water use differ with different apple tree canopy covers?

Evapotranspiration represents the most impactful loss of water from irrigated orchards in semi-arid regions and it is sensitive to vegetation cover variations (Wang and Wang, 2017). Accurate estimates of orchard ET and its components are important for accurate irrigation scheduling, irrigation system designs, and best possible on-farm water allocations especially in arid-semi-arid ecosystems. This information is crucial in countries like South Africa where frequent droughts are a norm while there’s also expectations of irrigation demand increase in future (Midgley and Lotze, 2011). This leaves the need to identify and adopt effective irrigation management strategies that increase the water productivity (Gush et al., 2019). Methods and tools needed to improve management of actual water use by crops in irrigated agriculture have significantly increased in recent years offering useful insights on plant water use patterns (Koech and Langat, 2018). Given the practical limitations of methods that currently exist, the development of simple but robust and operational models for estimating water use is crucial. To date, several models were developed to estimate water use of fruit trees. These models include the Soil Water Balance (SWB) model (Annandale et al., 2003), the big leaf Penman-Monteith model (Rana et al., 2005), dual source Shuttleworth and Wallace type models (Ortega-Farias et al., 2012) among others. Given the heterogeneity that characterizes orchard environments comprising of tree rows, bare soils, and cover crops, dual source models provide more accurate ET estimates as they partition ET into transpiration (T) and soil evaporation (Es) components (Kool et al., 2014). However, many of these models require parameters such as the aerodynamic and stomatal resistances, which are not easy to obtain, and they can be sources of uncertainty. Since it was not practical to measure *Tc* throughout the season, a simple model was developed to estimate the cover crop transpiration. The model uses a modified version of the Priestley and Taylor approach in which we treat the cover crop as a separate layer within the orchard.

The P-T model has been widely used for estimating ET and has been successfully applied over a wide range of biomes (Zhang et al., 2017; Shao et al., 2019; and Yang et al., 2019) but its application in orchards nor on cover crop has not been reported. The goal of this work was to parameterize and evaluate the utility and the performance of the modified P-T model that we developed in three 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.

6.2 MATERIALS AND METHODS

6.2.1 Modelling cover crop transpiration

This chapter builds up from the previous chapter (Chapter 5). Therefore, the orchards used, and methods used for cover crop measurements are the same as mentioned in Chapter 5. To convert the sap flow gauge readings to transpiration expressed over the entire orchard floor (T_c, in mm/h) first we normalised the sap flow (SF, in cm^3/h) of each instrumented plant with the leaf area (A, in cm^2). Then we multiplied the average of the normalized sap flow with the cover crop leaf area index (LAI_c) and the fraction of the orchard floor occupied by the cover crop (f_g).

$$T_c = \frac{\overline{SF}}{A} \times LAI_c \times f_g \times 10 \qquad (6.1)$$

Since it was not practical to measure T_c throughout the season, a simple model was developed to estimate the cover crop transpiration. The model uses a modified version of the Priestley and Taylor approach in which we treat the cover crop as a separate layer within the orchard. According to this approach

$$T_c = \propto_c (1 - \tau_c) E_{eq} \qquad (6.2)$$

where α_c is the Priestley and Taylor coefficient applied to the cover crop canopy, τ_c is the cover crop canopy transmission factor, and E_{eq} is the equilibrium evaporation term (Slatyer and McIlroy, 1961), such that:

$$\tau_c = e^{-kLAIc} \qquad (6.3)$$

where k is the extinction coefficient, and we used a value of 0.7. LAI_c is the cover crop leaf area index. The equilibrium evaporation was calculated as:

$$E_{eq} = \frac{\Delta}{\Delta + 2x0.93\gamma} R_{ng} \qquad (6.4)$$

where R_{ng} (MJ/m^2/d) is the net radiation on the orchard floor (at the top of the cover crop canopies), Δ (kPa/K) is the slope of the saturation vapour pressure vs air temperature curve, and γ (kPa/K) is the psychrometric constant. Given the non-uniform vegetation cover in the orchards, the net radiation at the orchard floor was calculated using a dual source model proposed for olive orchards by Ortega-Farias et al. (2016) in which:

$$R_n = f_r R_{nc} + (1 - f_r) R_{ns} \qquad (6.5)$$

where R_n (in MJ/m^2/d) is the net radiation at the orchard surface, R_{nc} and R_{ns} represent the net radiation at the tree canopy and soil surface, respectively (in MJ/m^2/d) and f_r is the fractional canopy cover at nadir. In this study $(1-f_r)R_{ns}$ is considered to be numerically equal to R_{ng} in equation 4. According to Ortega-Farias et al (2016), R_{ns} can be derived from:

$$R_{ns} = (1 - \alpha_s) R_s + L_d - L_{up} - (1 - \varepsilon_s) L_d \qquad (6.6)$$

where R_s is the solar radiation (MJ/m^2/d) measured at the weather station, L_d is the downwelling longwave radiation incident on the orchard floor, L_{up} is the longwave radiation emitted by the orchard floor (MJ/m^2/d), α_s and ε_s represents the albedo and emissivity of the surface, respectively. We assumed that the surface albedo of the cover crop was similar to that of a short grass reference crop at 0.23, and we used the surface emissivity of 0.95 used by Ortega-Farias et al (2016). According to Brutsaert (1979), L_d can be calculated as:

$$L_d = \varepsilon_a \sigma T_a^4 \qquad (6.7)$$

where T_a is the daily average air temperature in Kelvin, σ is the Stefan-Boltzmann constant (4.903×10^{-9} MJ K^{-4} m^{-2} d^{-1}) and ε_a is the emissivity of the air calculated according to Brutsaert (1979) as:

$$\varepsilon_{a=1.24\left(\frac{e_a}{T_a}\right)}\frac{1}{7} \qquad (6.8)$$

where e_a is the actual vapour pressure of the air (in hPa). The emitted longwave radiation was calculated as:

$$L_{up} = \varepsilon_s \sigma T_s^4 \qquad (6.9)$$

where T_s is the surface temperature in Kelvin which we assumed to be equal to T_a. According to Agam et al. (2010) the Priestley and Taylor coefficient ($\alpha = 1.26$) is variable and it is related to that at the vegetation canopy level (α_c) by:

$$\propto_c = \frac{\propto - \propto_{so}\tau_c}{1-\tau_c} \qquad (6.10)$$

where α_{so} is the Priestley and Taylor coefficient applied to the soil layer. For wet soil conditions, Agam et al (2010) suggested that $\alpha_{so} \approx 1.0$. This is a reasonable assumption to make in this study given that a large portion of the orchard floor was wetted by the micro-sprinklers. So, combining equations 2, 3, and 10, and assuming that $\alpha_{so} = 1$, then cover crop transpiration can be calculated as a function of LAI_c, LAI and the orchard floor microclimate as:

$$T_c = (1.26 - e^{-kLAIc})E_{eq} \qquad (6.11)$$

6.3 RESULTS

The cover crop water use data obtained during the campaigns indicated in Table 5.2 were used to validate the transpiration model and the results, pooled together from the various orchards, are shown in Fig. 6.1. The model predicted the cover crop transpiration to within 12% of the measured values. To gain insights on how the cover crop transpiration varied throughout the season, we applied the model to a mature (Orchard 4), medium bearing (Orchard 3), and young orchard (Orchard 5) using the LAI_c data in Fig. 5.3 and the climate data. Typical results illustrating the effect of the varying tree canopy cover, represented by the orchard leaf area index (Fig. 6.2a) are shown in Fig. 6.2b.

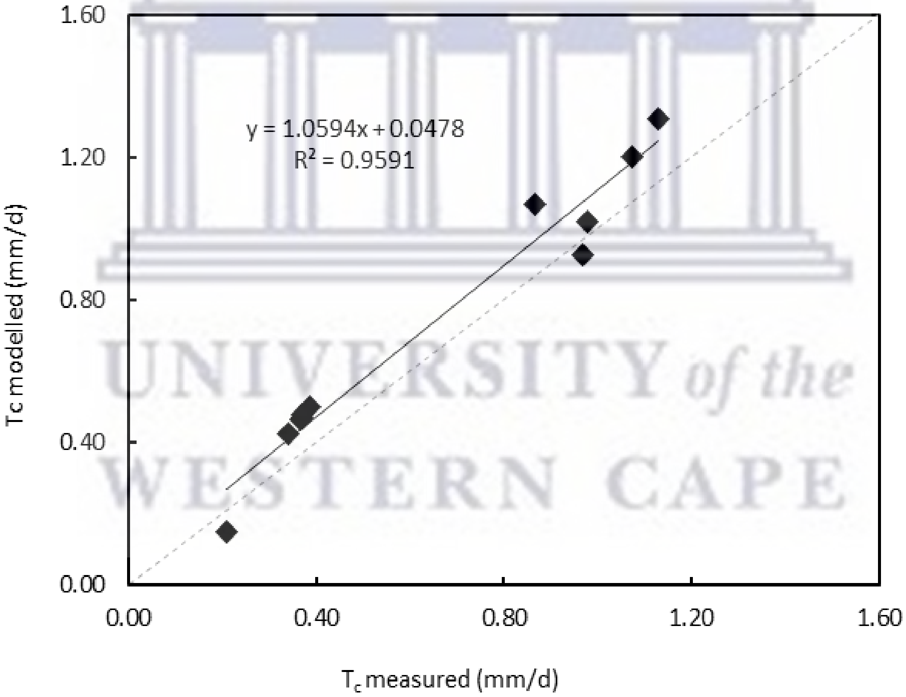


Fig. 6.1: Performance of the cover crop transpiration model with data pooled from five orchards with different cover crop characteristics.

Water use by the cover crop was similar at the beginning and end of the growing season when tree canopy cover was minimum. However, the rapid increase in tree canopy cover in mature orchards after spring flash resulted in a sharp decline in the cover crop transpiration due to increased shading. A similar trend occurred with the medium bearing orchard, but there was an increase in the transpiration levels due to the rising atmospheric evaporative demand and shading that was not as pronounced as in the mature orchard. As expected, the modelled cover crop transpiration was quite high in the young orchard with the peak daily water use just under 1.0 mm/d on warm summer days (Fig. 6.2b). The variability in the modelled fluxes in Fig.6.2b reflected the day-to-day variations in radiation reaching the orchard floor.

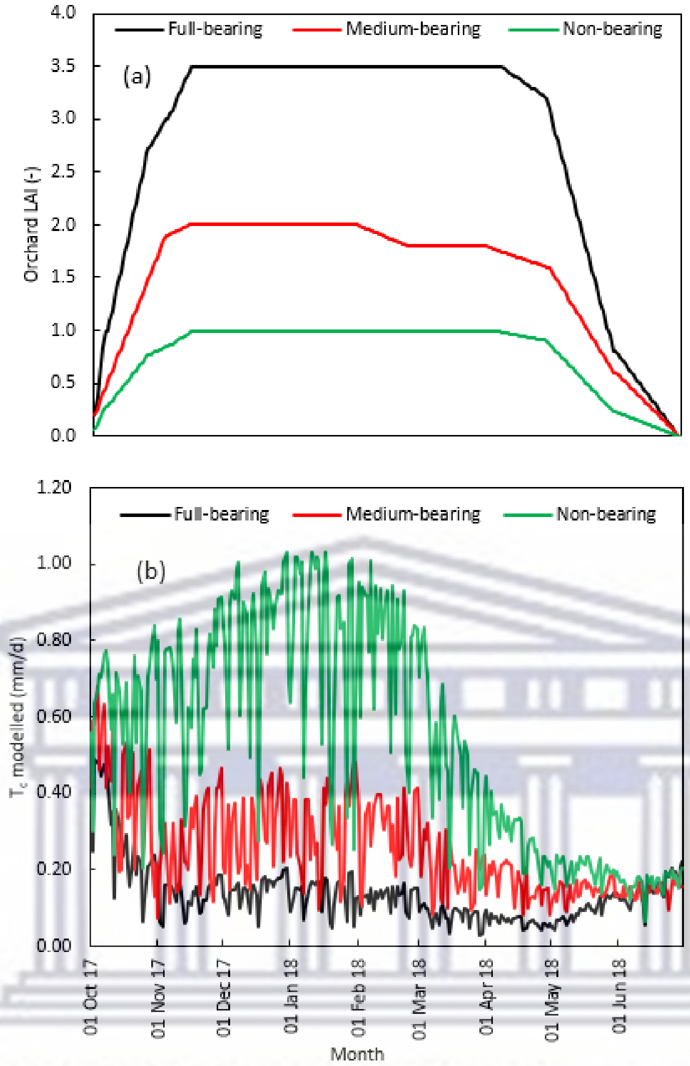


Fig. 6.2: Seasonal changes in (a) the leaf area index of three orchards of different age groups and (b) the modelled seasonal transpiration dynamics by the cover crop.

The typical seasonal totals of the measured tree transpiration and the modelled cover crop transpiration for the three orchard age groups are shown in Fig. 6.3. The seasonal total transpiration rates were about 640 mm for the mature orchard (Orchard 4), about 419 mm for the medium bearing (Orchard 3) and 198 mm for the young orchard (Orchard 5). The corresponding seasonal total for the cover crop transpiration were 50 mm for the mature, 96 mm for the medium bearing and 153 mm for the young orchard. Seasonal total ET was not measured due to equipment limitations.

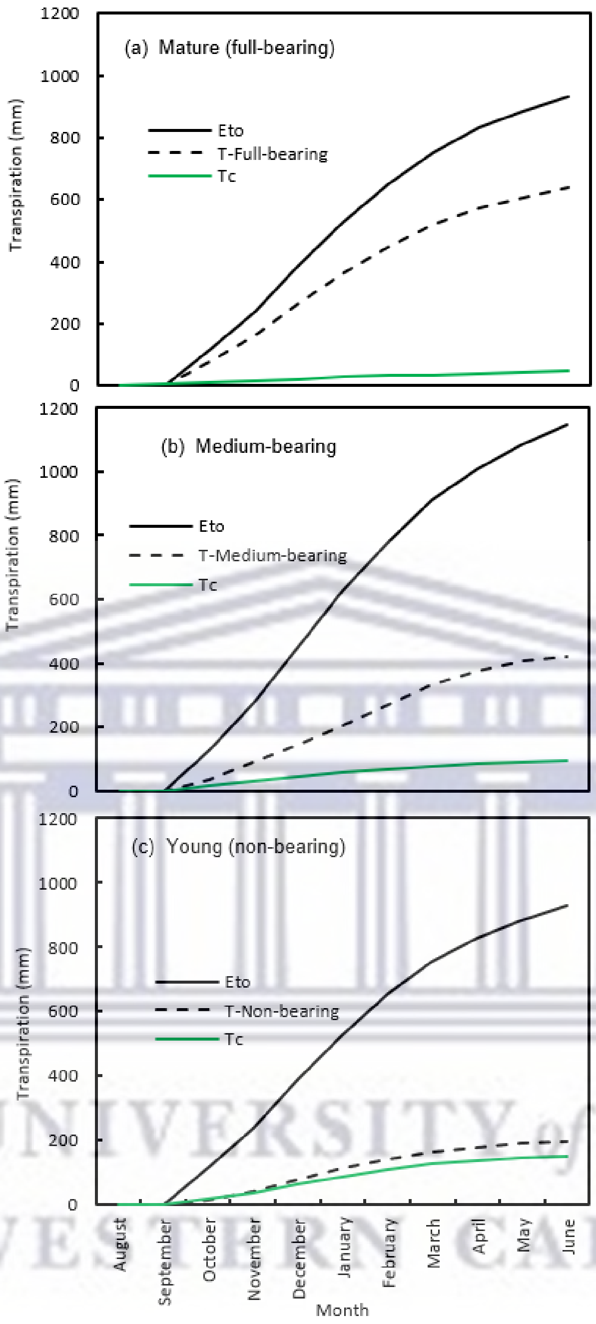


Fig. 6.3: Cumulative seasonal total ET$_o$, tree transpiration, and cover crop transpiration for: (a) a full-bearing orchard (Orchard 4), (b) a medium-bearing orchard (Orchard 3), and (c) a young non-bearing orchard (Orchard 5).

6.4 DISCUSSION

In this study, we quantified the water use of cover crop for the first time using the sap flow methods and calibrating with the infrared gas analyzer measurements. After that we successfully created a simple model that predicts the cover crop water use. Many researchers have modelled the water use using the Shuttle and Wallace model, but none of these researchers differentiated between the orchard floor evaporative fluxes. Most research assumes that the water use from the cover crop is negligible. However, this study has shown that this water is quite substantial especially in medium and young orchards where the orchard floor is more open. In addition, the transpiration from the stem heat balance sap flow gauges closely matched that predicted by a simple version of the Priestley and Taylor model although we did not distinguish between the different cover crop species as that would make the study very complex. Therefore, from this study, the Shuttle and Wallace model that predicts ET as the sum of transpiration from trees and evaporation from the soil has been modified by introducing the new sub model of cover crop and the modified S-W equation can be:

$$\lambda ET = \lambda T + \lambda E_s + \lambda T_c \qquad (6.12)$$

Where ET is the actual evapotranspiration, T is the transpiration from the actual trees (beneficial water use), Es is the evaporation from the soil (non-beneficial water use) and Tc is the transpiration from the cover crop (non-beneficial water use). The well-known S-W model can be represented graphically as follows with this new modification.

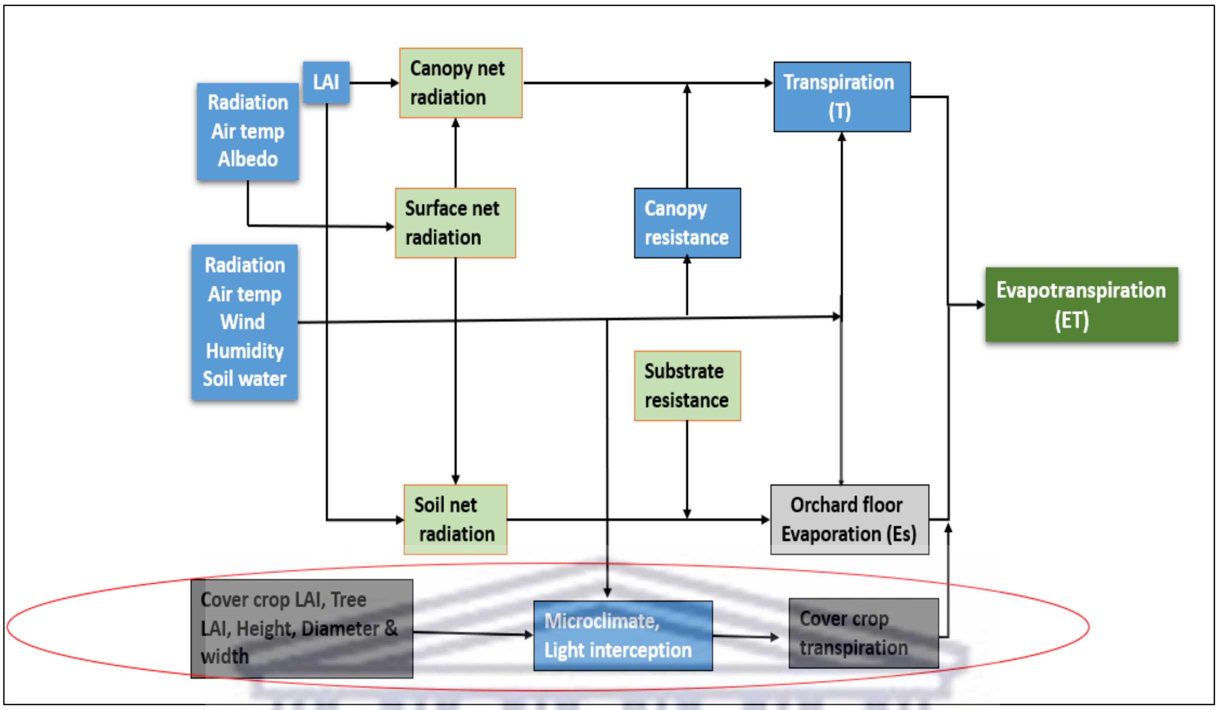


Fig. 6.4: Modified dual source Shuttle and Wallace (1985)

In addition, the transpiration from the stem heat balance sap flow gauges closely matched that predicted by a simple version of the Priestley and Taylor model although we did not distinguish between the different cover crop species as that would make the study very complex. Besides directly quantifying the contribution of the cover crop to the whole orchard ET, we also investigated how tree canopy cover influenced the cover crop transpiration dynamics and we studied the seasonal dynamics of the cover crop transpiration using the transpiration model. It is clear that tree canopy cover is a strong driver of the cover crop transpiration in apple orchards, and this is consistent with the observations by Herwitz et al. (2004) in a natural broadleaf forest. There are other factors that could have influenced the water use of the cover crops, such as the soil water content changes in the root zone, but we did not investigate these in this study. A sensitivity analysis of the model showed that increasing the leaf area index of the cover crop (LAIc) by about 30% increased the cover crop transpiration over the entire season by only 6% in mature compared to about 9% in young orchards. However, increasing the leaf area index of the orchard (LAI) by the same magnitude had a far greater impact on the cover crop transpiration. The cover crop transpiration decreased by about 40% and 22%, respectively when the orchard LAI was increased by 30% in mature and young orchards. There was a smaller transpiration reduction in young orchards because of the low initial canopy size. This suggested that the influence of shading by the trees (high LAI) on the cover crop transpiration was higher than that of an increase in the leaf area index of the cover crop. The Tc model was grafted in the model maker software as represented in Fig.6.5 and all sensitivity assessments done.

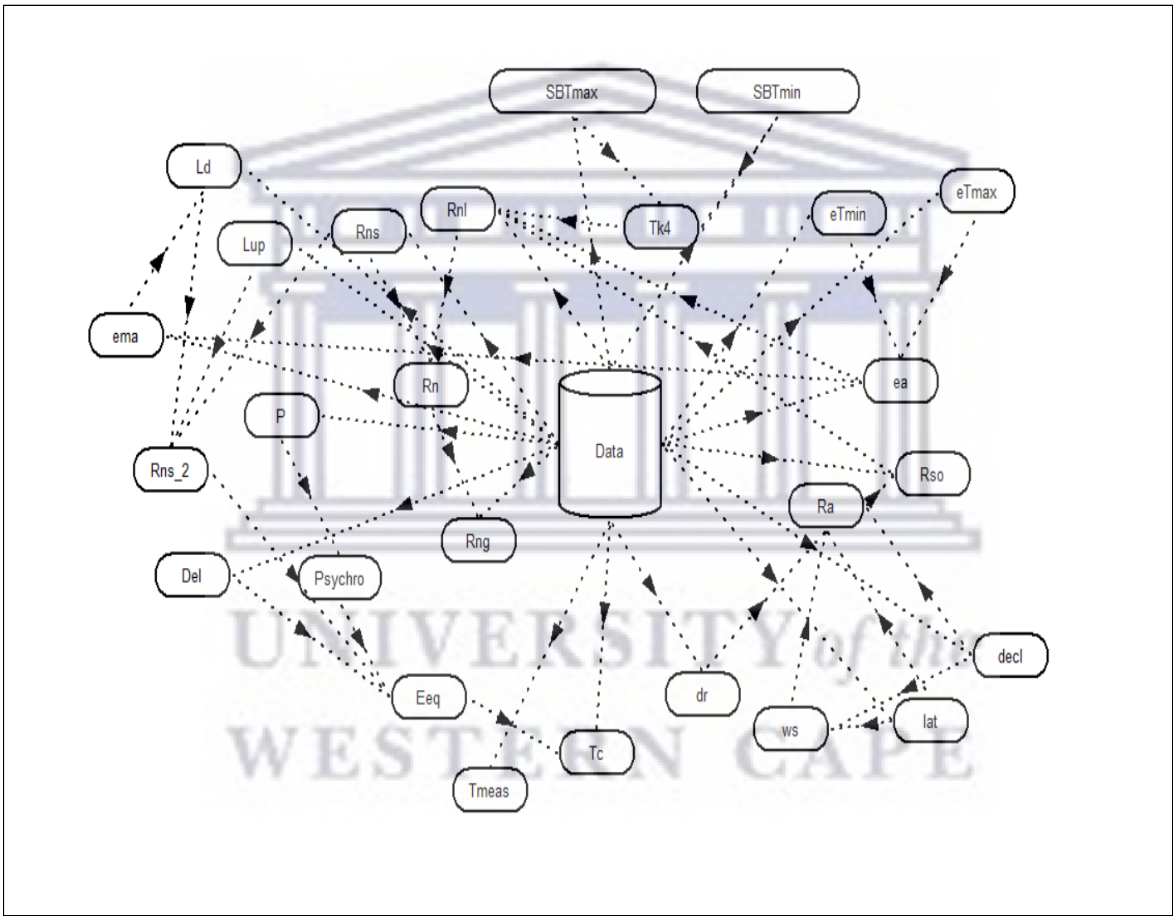


Fig. 6.5: Structure of the cover crop (T_c) model representation on the ModelMaker software

All descriptions for the model structure in Fig.6.5 can be found in appendix B. This model was tested on apple orchards of different canopy covers with satisfactory results as shown in Fig.6.1

6.5 CONCLUSION

In this study, we for the first time quantified the water use of cover crop using the sap flow methods and calibrating it with the infrared gas analyzer measurements. After that we successfully created a simple model that predicts the cover crop water use. Many researchers have modelled the water use using the Shuttle and Wallace model, but none of these researchers differentiated between the orchard floor evaporative fluxes. Most research assumed that the water use from the cover crop is negligible, but this study has shown that this water is quite substantial especially in medium and young orchards where the orchard floor is more open. This study has proposed an improvement to the dual source S-W ET model by adding a cover crop sub-model. The sub model was tested in orchards with varying canopy cover and the findings showed that the cover crop sub-model performance was satisfactory. We recommend validation of the model with data from a range of sites to build more confidence in it.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

This study investigated the water use of cover crops of different origin and for the first time in South Africa has quantified the water use of different cover crop species commonly grown in apple orchards. This research has closed this information gap by providing water use estimates measured with reliable state-of-the-art equipment. Exotic legumes used three times higher water use than the indigenous grasses under similar growing conditions. Yet the legumes were also most susceptible to water deficit because of their risk taking anisohydric responses to environmental stress. Exotic grasses that are commonly planted in orchards also had high water use rates and a weak response to drought stress, although they were marginally better than the legumes. Therefore, indigenous grasses are more suited as cover crops in the semi-arid tropical and sub-tropical regions because their physiology is more adapted to the harsh growing conditions. They do not need regular irrigation to survive.

Chapter 4 of this study investigated the effects of different irrigation systems on the water use of apple trees and how ET is partitioned and established the water relations then impacts on fruit quality from these two irrigation systems. Drip irrigated apple trees used less water as compared to micro-sprinkler irrigated trees. However, the drip irrigated apple trees were more stressed and subsequently produced smaller in size fruit with poorer quality as compared to the micro sprinkler irrigated apple trees. Using the drip irrigation system saves water, but compromises the quality of the fruit, and subsequently overall farm production. There was a significant contribution from the cover crop water use on the micro sprinkler irrigated trees setup, while there was more contribution from soil evaporation on the drip irrigated trees setup.

Chapter 5 investigated the partitioning of water use under different canopy covers and found that cover crops contribute significantly to whole orchard water use, but this is strongly influenced by canopy cover of the trees. A young orchard with a dense cover crop used almost three times as much water as that in a mature orchard with a well-maintained cover crop. Again, in young orchards with a dense cover crop, transpiration by the cover crop can account for close to 40% of the orchard ET. In mature orchards with large canopies, cover crop transpiration did not have a significant contribution mainly due to shading by tree canopies. Therefore, maximum water savings can be achieved by regularly mowing the cover crop when the trees are still young. It appears as if water savings due to a sparse cover crop are less in mature orchards because the large canopies of the trees suppress the cover crop transpiration rates.

In Chapter 6, we for the first time quantified the water use of cover crops in orchards using the sap flow methods and calibrated it with the infrared gas analyzer measurements. After that we successfully created a simple model that predicts the cover crop water use. This study has proposed an improvement to the dual source S-W ET model by adding a cover crop sub-model. The sub model was tested in orchards with varying canopy cover and the findings showed that the cover crop sub-model performance was satisfactory.

7.2 RECOMMENDATIONS

Due to lack of adequate knowledge on the water use of cover crops and their contribution to the whole orchard water use in South African apple orchards. This study has provided an improved understanding of how water use rates of different cover crops differ and their contribution to the orchard water balance using orchards with varying fractional cover and different irrigation systems. This was achieved by first studying cover crop water use under controlled conditions in a greenhouse study, then quantifying ET partitioning in orchards of different age groups and different irrigation systems over a period of 3-4 years in six apple orchards in two production regions. The data were subsequently used to parameterize and validate the cover crop sub-model that was created in this study.

We therefore suggest that indigenous grasses are more suited as cover crops in the semi-arid tropical and sub-tropical regions because their physiology is more adapted to the harsh growing conditions. They do not need regular irrigation to survive. However, it is also important to note that the water saving benefits of the indigenous cover crops demonstrated here should be considered together with other benefits in order to make informed choices when prioritizing species to plant.

Drip irrigated trees showed signs of stress, even though enough water was applied and even recorded by the deepest soil moisture sensor, while micro sprinkler irrigated trees did not show signs of stress. Since apple trees have shallow and lateral roots, farmers who use the drip irrigation system should consider adding more dripper lines on the surface, for the top layers of the soil to receive more water, rather than having two drippers that send water straight to the bottom of the soil profile. Given that water use rates were higher in micro sprinkler irrigated trees than drip irrigated trees that had small and more open canopies, options to improve the water use efficiency of micro sprinkler irrigated trees should be investigated, canopy management is critical to achieving water savings. These trees can also be covered by shade nets to reduce transpiration rates. The use of dwarfing rootstocks that can reduce canopy cover and thus lower water use rates can also be considered. Further studies on the impacts of drip irrigation on fruit quality as well as in summer regions are recommended to draw more informed conclusions. This part of the study was conducted in the same orchard, where micro sprinkler was introduced on the first year of the study. We therefore recommend conducting such a study in an environment where there are two orchards using different irrigation systems. This way the analysis will not be limited to a single row and there will be no uncertainties of whether the trees were still adapting to a newly introduced irrigation system.

Maximum water savings can be achieved by regularly mowing the cover crop when the trees are still young. It appears as if water savings due to a sparse cover crop presence are less in mature orchards because the large canopies of the trees suppress the cover crop transpiration rates. The use of short-range micro sprinkler irrigation or sub-surface drip irrigation is recommended, especially for orchards where the orchard floor is exposed. In such orchards farmers can also move more to the use of mulching to reduce evaporation from the soil and opt for indigenous cover crops that will still give them the benefits they need while using water in a more conservative manner. Finally, this study adopted and improved a dual ET model for the purposes of incorporating the contribution of cover crops to total ET. Although the overall performance of the model tested in trees with different canopy covers was satisfactory, further calibration and validation in a wide range of growing conditions to improve its accuracy is still recommended.

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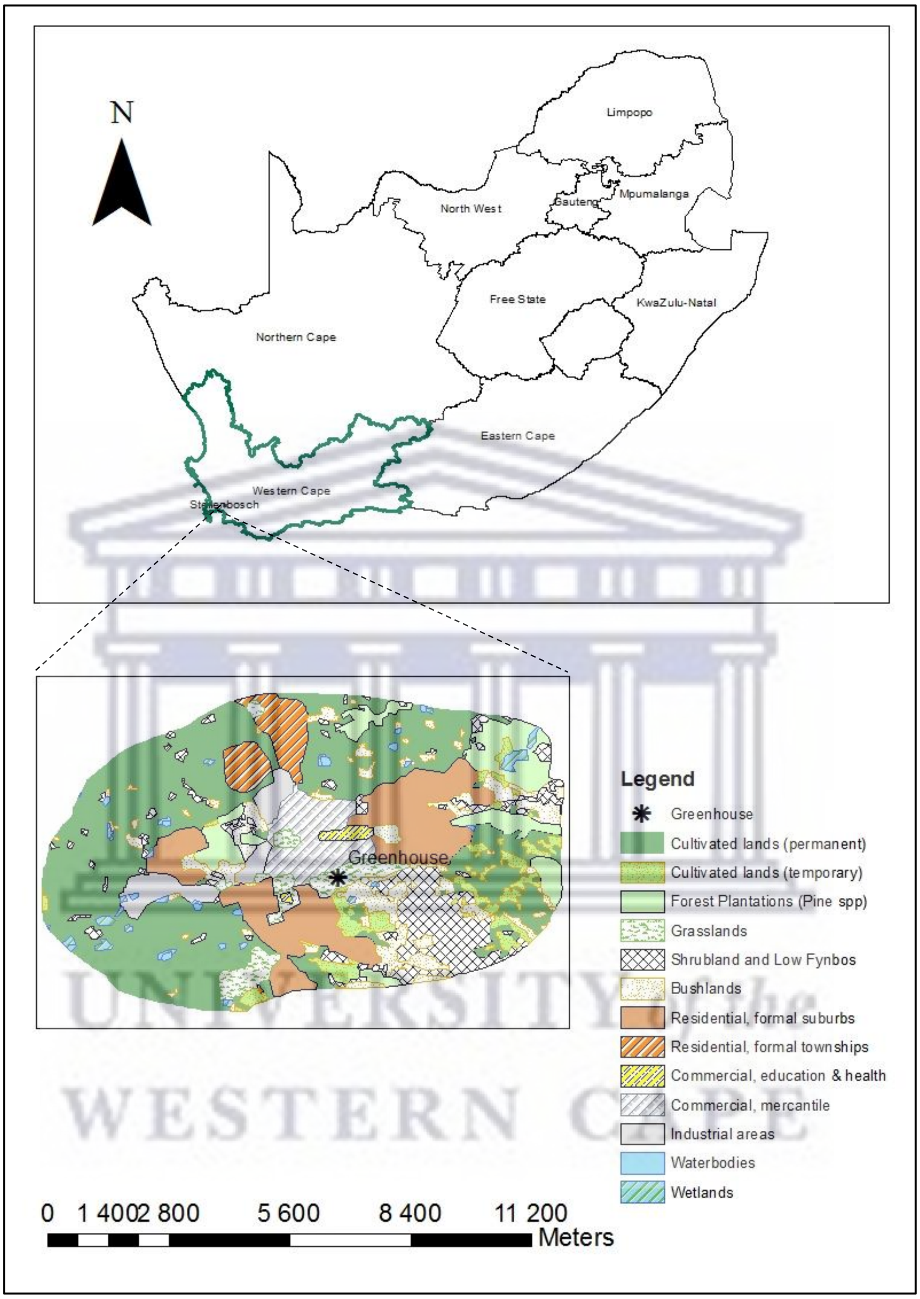
APPENDICES

Appendix A



__Appendix A:__ Map of South Africa, zooming into the town of Stellenbosch and showing the landcover surrounding the greenhouse.

APPENDIX B: T_C MODEL DESCRIPTION

t 12 0

Main

albedo 0.23 0

decl Unconditional

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

Del Unconditional

Slope of saturation vapour pressure vs air temperature curve (kPa/K)

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

dr Unconditional

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

ea Unconditional

average hourly actual vapour pressure (kPa)

ea = ((eTmin*(RHmax/100))+(eTmax*(RHmin/100)))/2

Eeq Unconditional

Equilibrium evaporation

Eeq = Del/(Del+2*0.93*psychro)*Rns_2

ema Unconditional

ema = 1.24*(ea*10/(Ta+273.16))^(1/7)

es 0.95 0

eTmax Unconditional

kPa

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

eTmin Unconditional

kPa

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

ke 0.6 0

t Control

Rs Controlled by: t

Linear interpolation

```
Ta  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

DOY  Controlled by: t

  Linear interpolation

LAI  Controlled by: t

  Linear interpolation

LAIc  Controlled by: t

  Linear interpolation

latitude  Controlled by: t

  Linear interpolation

z  Controlled by: t

  Linear interpolation

Tcmeas  Controlled by: t

  Linear interpolation

lat  Unconditional

lat = (pi/180)*-latitude

Ld  Unconditional

Ld = ema*es*4.903*10^-9*(Ta+273.16)^4

Lup  Unconditional

Lup = es*4.903*10^-9*(Ta+273.16)^4

P  Unconditional

Atmospheric Pressure (kPa)

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

pi        3.141592654   0
```

Psychro Unconditional

Psychrometric constant (kPa/K)

Psychro = 0.000665*P

Ra Unconditional

Ra = ((24*60)/pi)*0.082*dr*((ws)*sin(lat)*sin(decl)+cos(lat)*cos(decl)*sin(ws))

Rn Unconditional

Net radiation at the orchard surface

Rn = Rns-Rnl

Rng Unconditional

Net radiation on the orchard floor

Rng = Rn*exp(-0.6*LAI)

Rnl Unconditional

MJ/m2/d

Rnl = Tk4*(0.34-0.14*sqrt(ea))*(1.35*Rs/Rso-0.35)

Rns Unconditional

net radiation at the soil surface (MJ/m2/d)

Rns = (1-albedo)*Rs

Rns_2 Unconditional

Rns_2 = (Rns+Ld-Lup)*0.15

Rso Unconditional

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

SBTmax Unconditional

SBTmax = (4.903*10^-9)*((Tmax+273.16)^4)

SBTmin Unconditional

SBTmin = (4.903*10^-9)*((Tmin+273.16)^4)

Tc Unconditional

Under-storey transpiration

Tc = (1.26-exp(-ke*LAIc))*Eeq

Tk4 Unconditional

Tk4 = (SBTmax+SBTmin)/2

Tmeas Unconditional

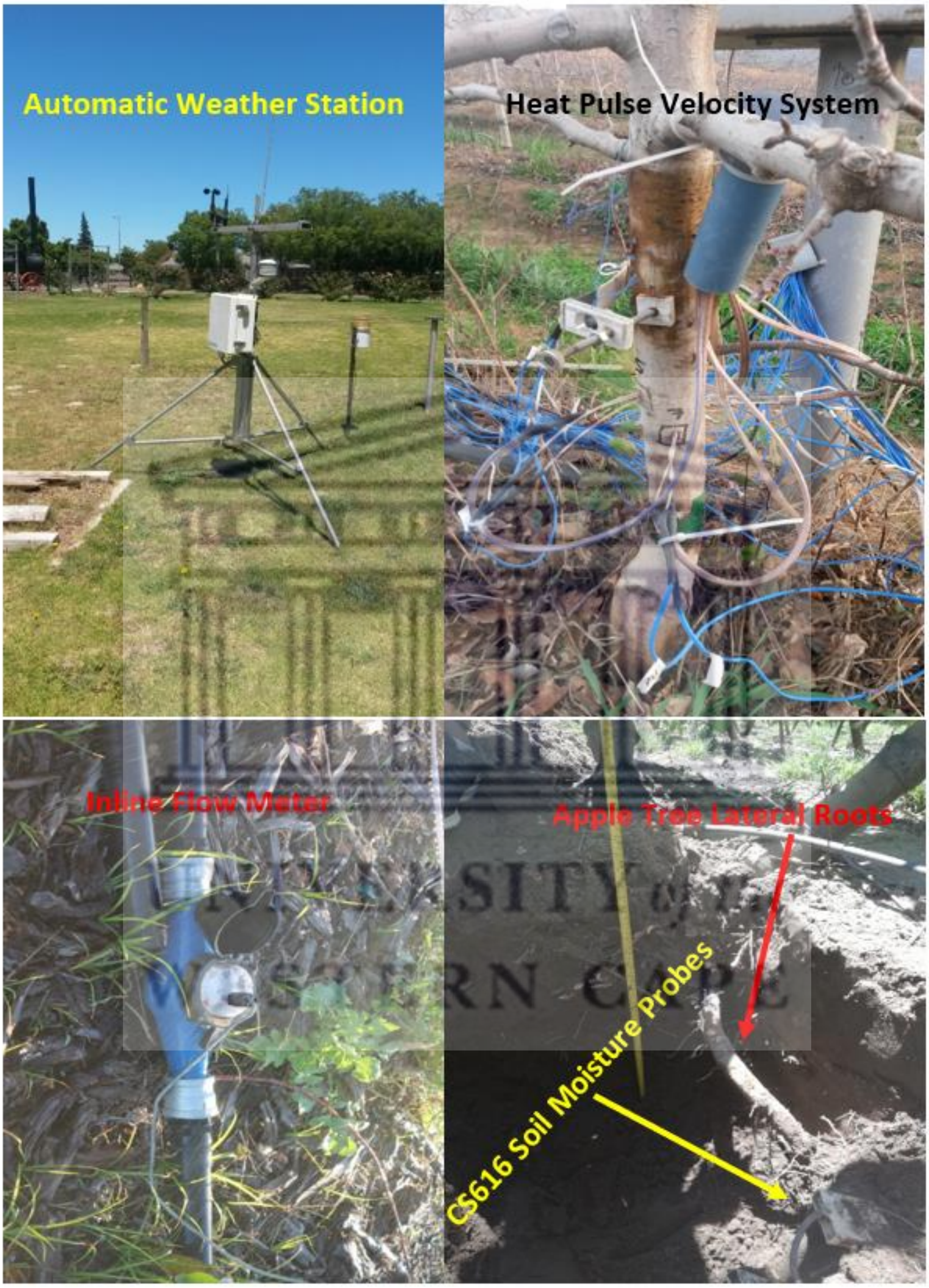
measured under-storey transpiration

Tmeas = Tcmeas

ws Unconditional

ws = arccos(-tan(lat)*tan(decl))

Appendix C: Monitoring Equipment



Appendix C: *Microclimate measured using a weather station, tree transpiration measured with an HPV system, applied irrigation measured with an inline flow meter and soil water content measured with CS616 soil moisture probes, apple tree lateral roots also displayed.*

Appendix D: More Measurements and Harvest

Appendix D: *Cover crop transpiration measured with an IRGA, plant water stress monitored with a pressure chamber, soil evaporation quantified using the lysimeters and harvest of the royal gala orchard under drip irrigation.*