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MEASUREMENT AND MODELLING OF WATER USE OF CITRUS ORCHARDS

By

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A thesis submitted in fulfilment of the requirements for the degree of PhD in Agronomy
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Declaration

I, Walter Mahohoma, declare that the dissertation, which I hereby submit for the degree PhD Agronomy at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at another university. Where secondary material is used, this has been carefully acknowledged and referenced in accordance with university requirements. I am aware of university policy and implications regarding plagiarism.

Walter Mahohoma

Date: 15 September 2016

Abstract

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Water requirements of evergreen citrus orchards in semi-arid regions of the world are mostly met through irrigation. Definitive knowledge of crop water use is the fundamental basis for sound water management under these production systems. The objectives of this study were two-fold: i) to measure long-term transpiration of well managed micro-irrigated citrus orchards and; ii) to test physically–based models that can be used to predict transpiration across different citrus growing regions. Whole tree transpiration measurements were conducted using the heat ratio method (HRM) sap flow technique in two well-irrigated citrus orchards [*Citrus sinensis* (L.) Osbeck] in the summer rainfall area of South Africa. The two orchards planted with ‘Delta’ Valencia and ‘Bahianinha’ Navel orange trees were located at Moosrivier Farm in Groblersdal. A data set from an orchard planted with ‘Rustenburg’ Navel orange trees that was located in the winter rainfall area was sourced for model validation. The orchard was located at Patrysberg Farm in the winter rainfall area. All the orchards were drip irrigated and managed according to the industry standards. Weather parameters were monitored using automatic weather stations that were situated close to the fields, for modelling purposes.

The HRM was initially calibrated against eddy covariance measurements in winter (31July to 3 August 2008) and autumn (21 to 25 May 2009) in the ‘Delta’ Valencia orchard, when soil evaporation was considered negligible. Calibration was done by adjusting the wounding width to ensure that average transpiration of sample trees matched crop evapotranspiration (ET_c) measured above the orchard using the eddy covariance method. The wounding width, termed the ‘virtual wound width’, was obtained by inputting ET_c into regression equations of daily transpiration against

wound width. Xylem anatomical assessments were conducted on excised stem samples prior to probe insertion and at the conclusion of sap flow measurements in in order to ascertain and explain the virtual wound width determined through calibration. The average virtual wound width that matched average transpiration of sample trees to ET_c in both winter and autumn was 3.2 mm. The similarity of the virtual wound width obtained during winter and autumn suggests that wounding did not increase with time and a single field calibration of the HRM using eddy covariance measurements is sufficient for measuring long term transpiration in citrus orchards.

The HRM was used to measure transpiration for periods of 364 days in the ‘Delta’ Valencia orchard, 301 days in the ‘Bahianinha’ Navel orchard and 365 days in the ‘Rustenburg’ Navel orchard. Average transpiration in the ‘Delta’ Valencia orchard was 1.15 mm day^{-1} and 2.17 mm day^{-1} in winter and summer, respectively. On average, ‘Bahianinha’ Navel orange trees transpired 0.77 mm day^{-1} and 1.69 mm day^{-1} in winter and summer, respectively. In the ‘Rustenburg’ Navel orchard average transpiration was 2.26 mm day^{-1} for summer and 2.08 mm day^{-1} for winter. Total transpiration measured in the ‘Delta’ Valencia, ‘Bahianinha’ and ‘Rustenburg’ Navel orchards was 650, 433 and 682 mm, respectively. Transpiration coefficients (K_t) determined in the three orchards ranged between 0.28 and 0.71. The K_t values were almost constant throughout the seasons in the summer rainfall area and significantly higher in the winter months than in the summer months in the winter rainfall area. Derived monthly and seasonal K_t determined for the three orchards were much lower than the standardised values published in the FAO56. Differences among the transpiration coefficients determined in the orchards in this study means that they are orchard specific and can therefore not be directly applied or transferred to different growing regions of the world.

There is a need to develop an easy method for estimating site-specific crop coefficients, in order to improve water management in citrus orchards. The determination of basal crop coefficients based on physical characteristics of the vegetation and an adjustment for relative crop stomatal control over transpiration formulated by Allen and Pereira (2009) was tested. Use of the parameters for generic citrus trees suggested by the authors did not provide good estimates of transpiration in the three study orchards. A good agreement between measured and estimated K_t values was obtained by back-calculating leaf resistances using measured transpiration values, as recommended by Allen and Pereira (2009). The values of leaf resistances obtained through this procedure were higher than the values suggested by Allen and Pereira (2009), but comparable to those reported in literature and measured in the ‘Rustenburg’ navel orchard. A relationship between mean monthly leaf resistance and ET_o in the ‘Rustenburg’ Navel orchard provided a means of estimating mean leaf resistance which estimated K_t values with a reasonable degree of accuracy in the three orchards. However, this relationship only provided good seasonal estimates of transpiration, which means that it can only be useful for irrigation planning.

A more mechanistic model capable of capturing the dynamics of the canopy conductance in citrus varieties is required to predict transpiration of citrus trees on day-to-day basis for purposes such as irrigation scheduling. The use of the Penman-Monteith equation coupled with a Jarvis-type canopy conductance to predict long-term transpiration was evaluated in the three orchards. Bulk canopy conductance was calculated from the measured transpiration using a top-down approach by inverting the Penman-Monteith equation. Response functions for solar radiation, temperature and vapour pressure deficit were parameterised for a Jarvis model based on the measured data. The Jarvis model was first parameterized in the ‘Delta’ Valencia orchard. On validation the approach predicted transpiration in the same orchard reasonably well. However, transpiration was overestimated in the ‘Bahianinha’ orchard and underestimated in the ‘Rustenburg’ Navel orchard when the Jarvis parameters obtained in the ‘Delta’ Valencia orchard were applied to the two orchards. When the Jarvis model was parameterized in the ‘Bahianinha’ and ‘Rustenburg’ Navel transpiration was predicted fairly well. A single set of response functions for canopy conductance obtained in each orchard was found to be able to accurately predict transpiration in the respective orchard for a fairly long period. This approach may be applicable to sub-tropical conditions where wetting of the canopy by rainfall and occurrence of cloudy/overcast conditions are both infrequent.

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List of abbreviations and symbols

Abbreviations

CHPM	compensation heat pulse method
CSC	circumference size classes
DWAF	Department of Water Agriculture and Forestry
$\mathrm{ET_c}$	orchard evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
HRM	heat ratio method
IPCC	Inter-Governmental Panel on Climate Change
IRGA	open path infrared gas analyser
LAI	leaf area index
MAE	mean absolute error
OPEC	open path eddy covariance
$\mathrm{S_c}$	sample tree circumference
TC	thermocouple

Symbols

Symbol	**Description**
A_b	canopy basal area
A_T	total area allocated to each tree in the orchard
c_w	specific heat capacity of the wood matrix
c_s	specific heat capacity of the sap
d	characteristic leaf dimension
$\mathrm{ET_c}$	crop evapotranspiration
$\mathrm{ET_o}$	reference evapotranspiration
f_{ceff}	effective fraction of ground covered or shaded by vegetation near solar noon
F_r	adjustment factor relative to stomatal control
G	Ground heat flux
g_c	canopy conductance
$g_{c\ max}$	maximum canopy conductance
h	mean maximum plant height during the midseason period or full cover period

k	thermal diffusivity of green (fresh) wood
$\mathrm{K_{cb}}$	basal crop coefficient
$K_{cb\ full}$	basal crop coefficients for fully grown orchard
$K_{\mathrm{c\ min}}$	minimum crop coefficient for bare soil
K_d	crop density coefficient
$\mathrm{K_e}$	soil water evaporation coefficient
K	canopy extinction coefficient of light attenuation
M_w	wet mass of the sapwood sample
M_d	dry mass of the sapwood sample
M_L	parameter that simulates the physical limits imposed on water flux through the plant root, stem and leaf systems
N	number of sample trees on which transpiration was conducted
p_{ti}	portion of trees represented by the i^{th} tree sampled in the orchard
Q	sap flux
R_w	inter-row spacing
R_{eff}	effective precipitation
RH_{min}	minimum relative humidity
r_k	radii forming the annuli rings of the sap wood measured from the centre of the trunk
r_l	mean leaf resistance
$\mathrm{R_n}$	net irradiance
R_n	total net radiation flux density
S_R	solar radiation
RO	run-off
r_s	estimated mean canopy bulk resistance for the citrus trees
T	orchard transpiration
$\mathrm{T_a}$	mean daily air temperature at 2 m height
T_L	lower temperature limit to transpiration
T_U	upper temperature limit to transpiration
T_{post}	temperature measured after the heat pulse
T_{pre}	average temperature before the heat pulse
$\mathrm{u_2}$	wind speed at 2 m height

v_1	increase in temperature of upper thermocouple after the heat pulse is released
v_2	increase in temperature of the lower thermocouple after the heat pulse is released
V_c	corrected heat pulse velocity
V_h	heat pulse velocity
VPD	vapour pressure deficit
V_s	sap velocity
V_w	volume of wood sample
W	average or effective tree canopy width
w	wounding width
Δ	slope of the vapour pressure curve
δM	function of soil water content deficit
ρ_b	basic density of wood
ρ_s	density of water
γ	psychrometric constant

Introduction and structure of thesis

The genus Citrus (family *Rutaceae*) is a range of fruits which includes oranges, mandarins, tangerines, tangelos, clementines, satsumas, lemons, limes, and grapefruits (Syvertsen and Lloyd, 1994; Carr, 2012). Citrus are perennial evergreen trees believed to have originated from the humid tropics of the south-eastern parts of China and in southern India (Kriedemann and Barrs, 1981; Sippel, 2006). The species have, however, become widely adapted to the semi-arid regions of the world (Carr, 2012). They are cultivated primarily for fresh fruit and juice, although there are other by-products, such as food additives, pectin, marmalades, cattle feeds (from the peel), cosmetics, essential oils, chemicals, and medicines.

Citrus is a one of the most important fruit crops grown across the world, as well as in South Africa. South Africa has an average production of 2.16 million tons per year, which accounts for 4.2 % of world production and as a result the country is ranked thirteenth in the world in terms of citrus production (FAO, 2012). In South Africa, Valencia (including mid-seasons) and Navel orange orchards occupy the bulk of the 64 510 ha planted with citrus at the present moment, accounting for 40 and 24.3 % of the total area planted to citrus, respectively (Citrus Growers Association of Southern Africa, 2015a) (Figure 1). Figure 2 shows total orange production and the quantity of fruit that was used for local consumption, processed and exported in South Africa in recent years (Citrus Growers Association of Southern Africa, 2015b). While the quantity of fruit used for local consumption and processing has remained fairly constant over the years, there has been a gradual increase in the fruit sold on the export market. This is probably due to the ever increasing price of fresh fruit on the export markets (Figure 3) where South Africa is ranked third.

Citrus is grown in all provinces of South Africa with rare to frost-free conditions (this excludes Gauteng and Free State) (Bijzet, 2006). The major producing provinces are the Eastern Cape, Mpumalanga, Limpopo and Western Cape (Figure 1). A large portion of these areas receive seasonal rainfall, less than 500 mm per annum, making them semi-arid and therefore irrigation is required in order to meet crop water requirements and enable the successful production of citrus in these areas.

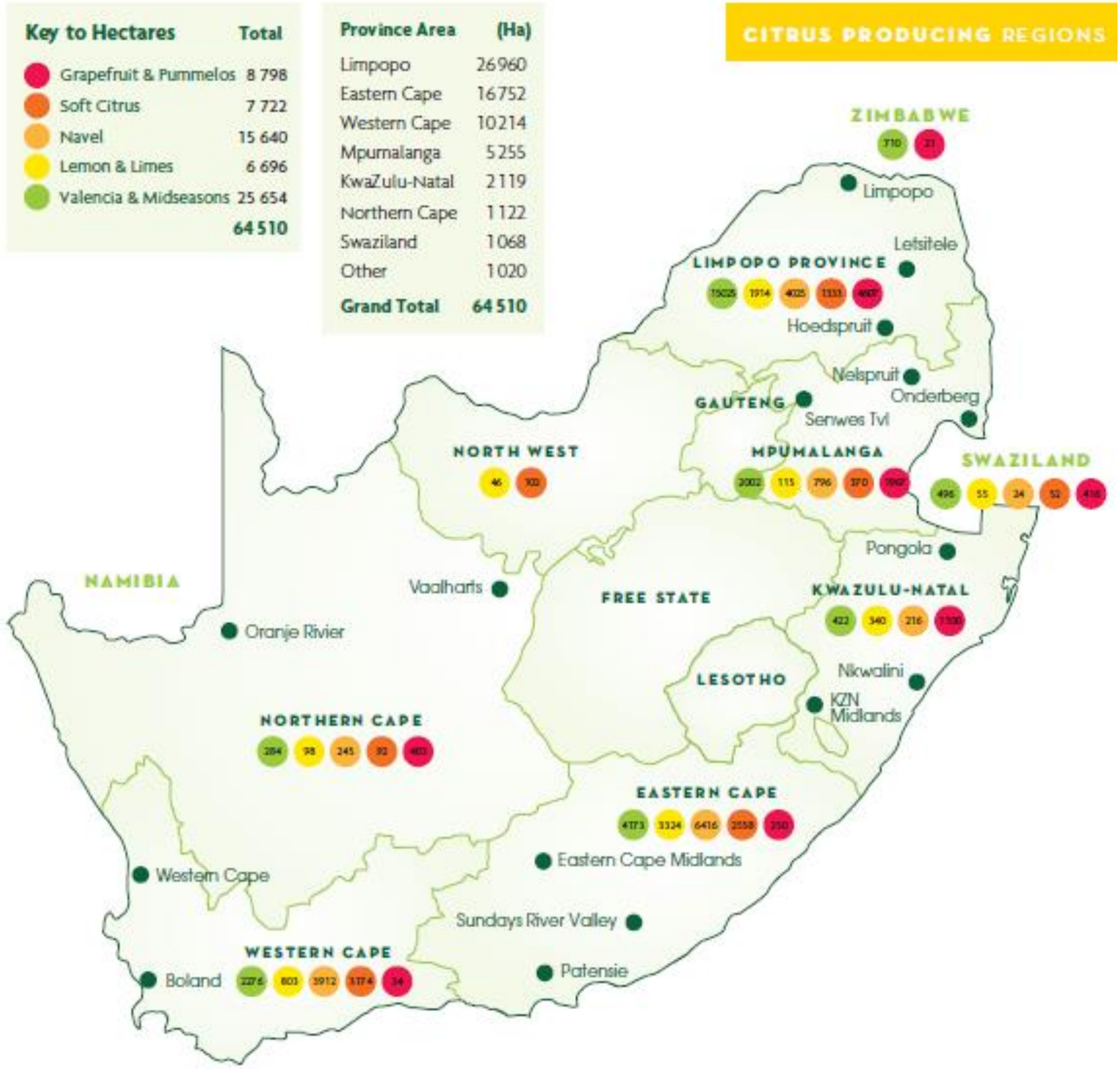

Figure 1. Citrus production according to province and type in South Africa in the 2014/15 growing season (Citrus Growers Association of Southern Africa, 2015a).

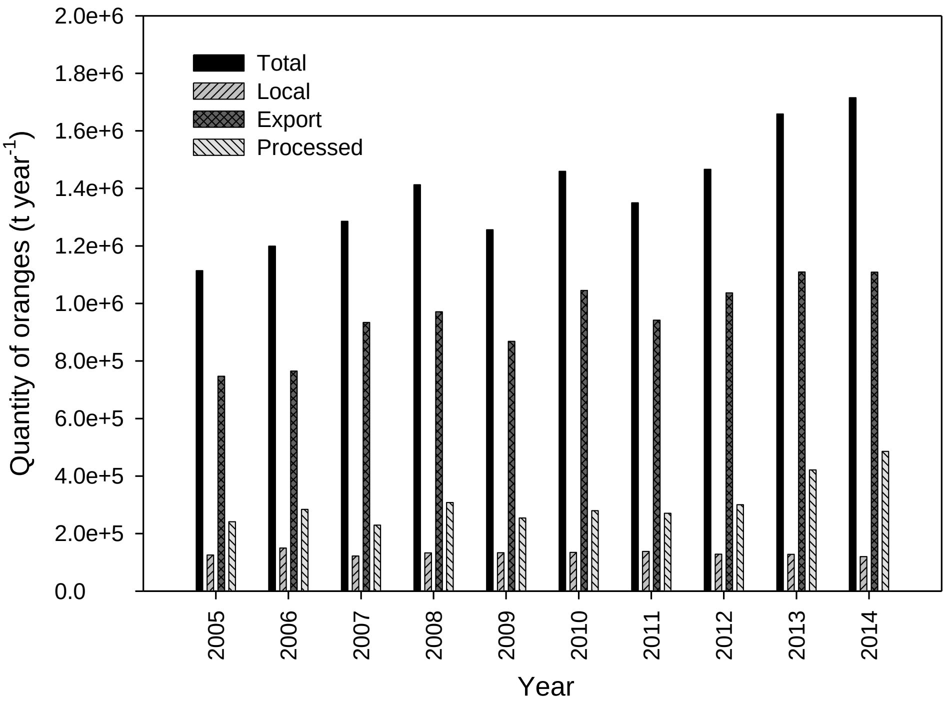

Figure 2. Quantity of oranges produced for local consumption, exports and processing in South Africa (Source: Citrus Growers Association of Southern Africa, 2015b).

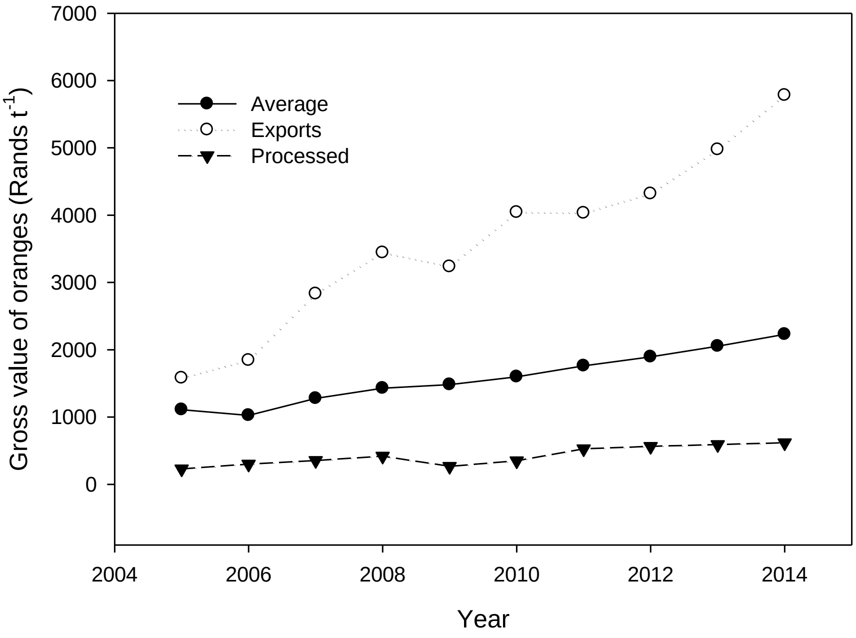

Figure 3. Gross values of oranges on the different markets in South Africa (Source: Citrus Growers Association of Southern Africa, 2015b).

Currently, it is estimated that irrigated agriculture uses approximately 70 % of the available fresh water resources on a global scale (FAO-AQUASTAT, 2003) and in South Africa it is estimated at 60 % (DWAF, 2013). It has been predicted that as the world population expands and economies grow, competition for water will increase, while water resources become more polluted. These changes are expected to be exacerbated as a result of climate change, which is believed to have already increased the frequency and severity of droughts in southern Africa in recent years (IPCC, 2007). Consequently, the demand for water will exceed supply, and less water will be available for agriculture. These population and climate dynamics will have catastrophic effects on 90 % of the fruit production industry in South Africa which, according to Annandale *et al.* (2005), is entirely dependent on irrigation water. Water-saving agricultural practices and sound water management strategies are therefore urgently required to ensure the long-term sustainability of the industry.

The advent of precision irrigation systems, such as drip, provides an opportunity to match crop water requirements and irrigation amounts, but needs to be coupled with appropriate water management techniques (Jones, 2004). Insufficient knowledge of fruit tree water use under these relatively new systems has been identified as a major factor hindering the development of sound water management tools in South Africa (Pavel *et al*., 2003; Volschenk *et al*., 2003). Available literature on citrus water use measurements is in the form of Green and Moreshet (1979) and Du Plessis (1985), which emphasizes that very little has been done in terms of research on citrus water use in South Africa in recent years. There is need to update such information to cater for changes in production practices.

Accurate and reliable methods of measuring water use in fruit tree orchards are needed to gather information to fill this knowledge gap. Crop evapotranspiration (ET_c) can be measured using a number of systems which include lysimeters, micro-meteorological methods, soil water balance, sap flow, scintillometry and satellite-based remote sensing (Allen *et al*., 2011). Quantification of the transpiration component that forms the larger portion of orchard water use (Reinders *et al*., 2010) and is directly related to productivity (Villalobos *et al*., 2013), is critical in micro-irrigated fruit tree orchards. Reviews by Swanson (1994), Smith and Allen (1996), Wullschleger *et al*. (1998) and Allen *et al*. (2011) have reported sap flow measurements as accurate and reliable methods for estimating long-term transpiration of woody species such as citrus trees, provided the method is calibrated and that due care is taken during installation of the equipment.

Measurements of crop water use are considered to be expensive and time consuming, requiring specialised expertise, which is not always available. Physically-based models can be used for the extrapolation of measured crop water use to different environments for the improvement of irrigation water management (Boote *et al*., 1996). The term irrigation water management used here encompasses the activities of irrigation system planning, irrigation scheduling and issuing of water rights/permits. According to Allen *et al*. (2011), ET_c is typically modelled on a physical basis using weather data and algorithms that describe the surface energy and aerodynamic characteristics of the crop. Simultaneous measurements of ET_c and weather data are required to improve the current models; as well as adapt the models to account for new production practices e.g. use micro-irrigation.

The crop coefficient approach first published by Doorenbos and Pruitt (1977), and later refined by Allen *et al*. (1998), has been used extensively and is currently considered as the standard model of ET_c. Although site specific crop coefficients are probably best, the crop coefficients for a generic citrus tree orchard are often used for water management, due to a lack of reliable information on tree water use. The basal crop coefficient (K_{cb}), which is directly linked to transpiration, is very important in micro-irrigated orchards, as it represents the major component of orchard water use and is directly linked to productivity (Villalobos *et al*., 2013). Villalobos *et al*. (2013) highlighted that the K_{cb} factors published by Allen *et al*. (1998) contain some residual diffusive evaporation component supplied by soil water below the dry surface and by soil water from beneath dense vegetation; such that the term transpiration coefficients (K_t) should be used when basal crop coefficients are determined using transpiration determined by sap flow methods.

The crop coefficient approach is often used in irrigation water management because it is relatively simple to implement. Research has shown much variation in crop coefficients reported for citrus orchards across the different growing regions of the world (García Petillo and Castel, 2007; Snyder and O'Connell, 2007). This means that crop coefficients may be site specific and may not be readily transferable from one orchard to another (Testi *et al*., 2006). Allen and Pereirra (2009) consolidated the FAO56 procedure for estimating crop coefficients and developed a method for developing site specific crop coefficients based on the fractional cover and height of the vegetation and the degree of stomatal control over transpiration relative to most agricultural crops. The use of this approach still needs to be tested against K_t determined using sap flow measurements in citrus orchards.

Citrus trees have been associated with high resistances that play a major role in the regulation of water movement within the plant (van Bavel *et al*. 1967; Kriedemann and Bars, 1981; Meyer and Green, 1981; Sinclair and Allen, 1982). Sap flow-based transpiration measurements have proved useful in the parameterisation of canopy conductance models for different tree species including citrus (e.g. Rana *et al*., 2005; Oguntunde *et al*., 2007; Villalobos *et al*., 2009; Villalobos *et al*., 2013). A canopy conductance model, that has been evaluated for short periods, as in the case for the studies for citrus cited above, is the multiplicative approach that was conceived by Jarvis (1976). Besides aiding scientists in understanding the bulk behaviour of stomatal conductance with respect to changing environmental conditions (Wullschleger, 1998), it has also been incorporated into the Penman-Monteith equation to estimate transpiration. The use of such a canopy conductance modelling approach can play a vital role in mechanistically modelling transpiration of citrus trees, where hydraulic conductance plays an important role in regulating transpiration.

This study was part of a project solicited, initiated, managed and funded by South Africa's Water Research Commission (Project K5/1770) entitled "Water use of fruit tree orchards" with core objectives of measuring and modelling of water use of selected fruit tree orchards.

Aim of the study

The aim of this study was to measure transpiration of well managed micro-irrigated citrus orchards and test physically–based models that can be used to estimate transpiration across different citrus growing regions.

Thesis objectives

The objectives of the thesis were to:

1. Calibrate the heat ratio method (HRM) sap flow technique using micro-meteorological measurements for long-term transpiration measurement in a citrus orchard
2. Quantify long-term transpiration and transpiration crop coefficients in citrus orchards using the calibrated sap flow technique
3. Evaluate the appropriateness of the canopy cover-based transpiration crop coefficient approach as a method for estimating transpiration in citrus orchards
4. Use sap flow-based transpiration measurements to parameterise a Jarvis-type conductance model for inclusion in the Penman-Monteith model for predicting long-term transpiration of citrus orchards

Hypotheses

The main hypotheses that were formulated and tested in this study were as follows:

- Citrus sapwood matrix is not thermally homogeneous such that conversion of measured heat pulse velocity to transpiration requires an empirical calibration factor which will be constant for long-term measurements
- A dynamic estimate of leaf (or canopy) resistance is needed to predict the daily and seasonal changes of transpiration in citrus orchards

Thesis outline

A review of the current knowledge on the measurement of evapotranspiration in citrus is initially presented in Chapter 1. The main body of the thesis consists of four chapters. The first two chapters (2 and 3) cover the specifics of measurement of water use in three citrus orchards. Chapter 2 covers the calibration of the heat ratio method (HRM) using micrometeorological measurements for estimating sap flow for transpiration measurements in a ‘Delta’ Valencia orchard. In Chapter 3 details of measuring long term transpiration using the calibrated HRM in three citrus orchards are presented. Transpiration coefficients were determined for the three orchards based on measured transpiration data and reference evapotranspiration determined using the FAO56 Penman-Monteith equation. Physically-based models that can be used for predicting transpiration of citrus orchards were tested in Chapters 4 and 5. In Chapter 4, crop coefficients determined from measurements of canopy cover and tree height, following the method of Allen and Pereira (2009), were evaluated against those calculated based on measured transpiration and reference evapotranspiration data. In Chapter 5, a mechanistic approach of modelling long-term citrus transpiration using the Penman-Monteith equation coupled with a Jarvis-type canopy conductance model was tested. Chapter 6 gives the general conclusions reached in this work and some recommendations for future studies in relation to measurement and modelling transpiration in citrus orchards.

Chapter 1: Literature Review

1.1 Measurement of citrus water use

1.1.1 Introduction

Knowledge of crop evapotranspiration (ET_c) is the fundamental basis for efficient irrigation water management strategies. The term irrigation water management encompasses activities such as irrigation systems planning, irrigation scheduling and issuing of water rights/permits. Besides irrigation water management knowledge of crop evapotranspiration is also used across various disciplines as explained by Allen *et al*. (2011) "crop ET_c information is more and more frequently used as a foundation for court determinations of injury among water users, for parameterization of important hydrologic and water resources planning and operation models, for operating weather and climate change forecasting models, and for water management and allocation in water-scarce regions, including the partitioning of water resources among states and nations".

A great deal of research has been published on the water relations of *Citrus spp.* Several reviews that synthesize this information have been published, which include photosynthesis (Ribeiro and Machado, 2007), physiological aspects of the control of the water status (Jones, 1985), irrigation (Shalhevet and Levy, 1990), physiological responses to the environment (Syvertsen and Lloyd, 1994) and general water use (Kriedemann and Barrs, 1981; Carr, 2012). Published data for ET_c of Citrus species across the different growing regions of the world is presented in Table 1.1. According to these studies, citrus water use ranges from 0.8-8.5 mm day^{-1}. Variation of crop water use in citrus orchards can be attributed to a number of factors that include varieties grown, rootstock, tree spacing, canopy height, ground cover, tillage, microclimate, irrigation method and frequency; and method of measuring crop water use (Snyder and O'Connell, 2006; Naor *et al*., 2008).

Table 1.1. Average annual and seasonal crop water use (mm day^{-1}) of citrus tree orchards, in different growing areas of the world.

Reference	**Location**	**Tec.**	**CM**	**Winter**	**Spring**	**Summer**	**Autumn**	**Annual**	**Age**	**spha**
Koo and Sites (1955)[*]	Florida, USA	SWB	ET_c	1.7	2.7	4.0	2.8	2.8		
Kalma and Stanhill (1969)[*] (Shamouti oranges)	Israel	SWB	ET_c	1.1		4.4		2.3		
Green and Moreshet (1979) (Valencia oranges)	South Africa	Lys	ET_c	2.7	2.2	4.6	5.2	3.68	15	
Hoffman *et al*. (1982) (Oranges)	Arizona, USA	SWB	ET_c	1.1	4.0	7.3	3.7	4.0		
Smajstrla *et al*. (1982)	Florida, USA	SWB	ET_c	1.9		3.9				
Wiegand and Swanson (1982) (Valencia oranges)	Texas, USA	SWB	ET_c	1.8	2.6	4.8	3.7	3.2		
Rogers *et al*. (1983)	Florida, USA	SWB	ET_c			5		3.3	8	
Du Plessis (1985) (Valencia oranges)	South Africa	Lys	ET_c	2.3		6.0-8.5				
Castel *et al*. (1987)[*] (Oranges)	Valencia, Spain	SWB	ET_c	0.9-1.0	1.5-2.0	3.0-3.2	1.4-1.8	1.7-2.0		
Sepaskhah and Kashefipour (1995)[*] (Lemons)	Iran	SWB	ET_c	1.4	4.4	8.5	4.2	4.6		
Castel (1997) (Clementines)	Spain	Lys	ET_c	0.5		1.5		1	7-11	432
Fares and Alva (1999) (Hamlin oranges)	Florida,USA	SWB	ET_c	<1.0		>4.0				

[*] Water use figures obtained from other sources and not the original reference

Tec – technology used to measure water use: Lys – lysimeter; SWB – soil water balance; SF – sap flow; SR – surface renewal; EC – eddy covariance; µLys – microlysimeter

CM – component of crop evapotranspiration that was measured: ET_c –crop evapotranspiration; T – transpiration; E_s – soil evaporation

spha – stems per hectare (i.e. number of trees per hectare);

Table 1.1 continued

Reference	**Location**	**Tec.**	**CM**	**Winter**	**Spring**	**Summer**	**Autumn**	**Year**	**Age**	**spha**
Castel (2000) (Clementines)	Valencia, Spain	Lys	ET_c	0.7-1.0		2.0-2.8		1.9		
Yang *et al*. (2003) (Murcott oranges)	Japan, Greenhouse	Lys	ET_c	0.6		5		4.4	8	4444
Rana *et al*. (2005) (Clementines)	Italy	SF	T		3	8		4	10	400
Consoli *et al*. (2006) (Navel oranges)	California, USA	SR	ET_c			0.7mm h^{-1}		July-August	4	337
						0.8mm h^{-1}			15	299
						0.9mm h^{-1}			34-36	284
Alarcon *et al*. (2006) (Lemons)	Spain	SF	T			1.8L day^{-1}		1.4 L day^{-1}	2	
García Petillo and Castel (2007) (Valencia oranges)	San Jose, Uruguay	SWB	ET_c	1.3	2.8	3.0	1.1	2.1		
Snyder and O'Connell (2007) (Navel oranges)	Linsay, California	SR	ET_c	2.36	3.86	5.55	4.7	4.14	33-37	283
Villalobos *et al* (2009) (Clementina mandarin)		EC µLys	T E_s	1.3 0.82		1.8 0.82			17	333
Marin and Angelocci (2011) (Lemons)	Sao Paulo, Brazil	SF	T	0.8		2			7	179
			ET_c	0.8		2.7				
Villallobos *et al*. (2013) (Navel oranges)	Southern Spain	SF	T	1.3		2.3			11	476
				0.7		1.5			10	416

Table 1.1 also shows that the soil water balance has been used quite extensively to measure ET_c (and/or its components) of citrus. Other methods that have been used for determining citrus ET_c and/or its components include the micro-meteorological methods (eddy covariance), lysimeters, and sap flow. Carr (2012) and García Petillo and Castel (2007) highlighted that it is not easy to quantify the water requirements of an orchard crop such as citrus or to compare the results of measurements taken under different conditions and with different methods. Generally ET_c measurements are considered to be expensive, time consuming and requiring specialised expertise (Allen *et al*., 2011). The situation is made worse in fruit tree orchards due to the variability of tree sizes and the perennial nature of the crop, which means long time periods are required to gather such information (Hoffman *et al.*, 1982; Castel *et al*., 1987).

Such dynamics may have had an effect on research of ET_c of fruit trees in South Africa, where such information is considered lacking (Pavel *et al*., 2003; Volschenk *et al*., 2003). Research work from South Africa cited in Table 1.1 and in other reviews (e.g. Carr, 2012; García Petillo and Castel, 2007) pertaining to citrus water use was performed over three decades ago. There is need to update such information to cater for changes in production practices such as rootstock choice (from the more vigorous ‘Rough Lemon’ to the rootstocks of intermediate vigour which include ‘Carrizo’, ‘Troyer’ and ‘Swingle’); and adoption of micro-irrigation systems.

The use of micro-irrigation systems helps to maximise transpiration (i.e. beneficial water use) and minimise evaporation (i.e. non-beneficial water use) in farming systems (Reinders *et al*., 2010). It is important that ET_c measurements in micro-irrigated orchards focus on the transpiration component as it represents the major component of ET_c and is directly linked to productivity (Villalobos *et al*., 2013). Thermometric sap flow techniques have shown great promise as methods for measuring transpiration of woody tree species such as citrus (Smith and Allen, 1996; Wullschleger *et al*., 1998). Sap flow methods have recently been used to quantify transpiration of citrus orchards on a long-term basis by Marin and Angelocci (2011) and Villallobos *et al*. (2013). Such methodologies can be utilised to expedite the gathering of information on transpiration of citrus orchards in South Africa.

The next section reviews thermometric sap flow methods of measuring transpiration in woody species. Emphasis is placed on the operational aspects that need to be considered when quantifying long-term transpiration in orchards.

1.1.2 Sap flow measurements of crop water use

A number of methods have been used to directly estimate transpiration of trees in general, including fruit trees (Wullschleger *et al*., 1998). These include weighing lysimeters, large tree potometers, ventilated chambers, radioisotopes, stable isotopes and a range of heat balance/heat dissipation methods. The most accurate and accepted method is the weighing lysimeter and as such it has been used in a number of studies in orchards (Moreshet and Green, 1984; du Plessis, 1985; Castel, 1996; Girona *et al*., 2002; Ayars *et al*., 2003; Girona *et al*., 2003; Yang *et al*., 2003; Williams and Ayars, 2005). However, they are expensive to install in existing orchards, as well as to maintain.

Amongst the several methods that have been used to measure tree transpiration, the use of thermometric sap flow measurements has shown considerable promise (Smith and Allen, 1996; Wullschleger *et al*., 1998; Allen *et al*., 2011). Sap flow measurements at stem level can be used to estimate tree transpiration if performed over sufficiently long periods to negate changes in stem storage and neglecting the 2-5 % of the water used for photosynthesis (Salisbury and Ross, 1978; Waring and Roberts, 1978). Some of the advantages of these methods include their ability to estimate transpiration, which has a direct relationship with productivity; easy interface to data loggers for direct automated transpiration measurements; their applicability is not inhibited by complex terrain and heterogeneity within fruit tree orchards; and they exhibit relatively good accuracy when compared to conventional methods of measuring orchard water use, e.g. the eddy covariance method (Rana *et al*., 2005).

Thermometric techniques that have been used for transpiration measurements in woody species can be broadly categorized into heat pulse, heat balance and heat dissipation methods (Smith and Allen, 1996). Heat pulse techniques, particularly the compensation heat pulse method (CHPM), have been widely used, mainly because they are relatively easy to use and have low power requirements (Green *et al*., 2003; Edwards *et al*., 1997; Smith and Allen, 1996). However, there are limitations to the CHPM, of which the major shortcoming is the inability to measure low and reverse sap flow rates, which usually occur under water stress conditions or at night (Becker, 1998). Burgess *et al*. (2001) developed the heat ratio method (HRM) as an improvement to the CHPM, in order to cater for low and reverse sap flow rates in woody species. The HRM has been used to study transpiration dynamics in *Jatropha curcas L.* (Gush, 2008), olive (Williams *et al*., 2004; Er-Raki *et al.*, 2010), *Eucalyptus marginata* (Bleby *et al*., 2004) and *Prosopis* (Dzikiti *et al*., 2013).

1.1.2.1 Theory of heat pulse sap flow technique

The idea of using heat as a tracer of sap flow in woody tree species has been perfected by several scientists over the years (Swanson, 1994). Marshall (1958) further developed the theoretical framework used for heat pulse techniques, based on a set of analytical solutions to the following heat flow equation:

$$\rho_w c_w \frac{dT}{dt} = \frac{d}{dx}\lambda_x \frac{dT}{dx} + \frac{d}{dy}\lambda_y - au\rho_s c_s \frac{dT}{dx} + Q \qquad \textit{Equation 1.1}$$

where *dT* is the temperature departure from ambient (K) over an axial distance *dx* , *dt* is an increment in time (s), λ is the thermal conductivity (W m^{-1} K^{-1}) in the axial (*x*) and tangential (*y*) directions, *a* is the fraction of xylem cross sectional area occupied by sap streams moving with a velocity *u* in the *x*-direction, and *Q* is the amount of internal heat flux per unit length that is released from the heater (W m^{-3}). Equation 1.1 ideally represents the two dimensional pattern of temperature surrounding a line heater of zero dimension that is inserted into a section of sapwood of uniform physical and thermal properties.

The velocity of the heat pulse carried by the moving sap stream is used to estimate the rate of sap flow. Following the application of a heat pulse, the temperature rise in the sapwood (T_s) at a distance from the heater is given by Marshall (1958) as:

$$T_s = \frac{Q}{4\pi\kappa t} exp\left[\frac{(x-V_h)+y^2}{4\kappa t}\right] \qquad \textit{Equation 1. 2}$$

where κ is the thermal diffusivity (m^{2} s^{-1}) of the sapwood, t is time since the heat pulse was applied, (x,y) is the point in the xylem at which temperature measurements are made at time t and V_h is the heat pulse velocity.

Measurements of V_h are effected by inserting a line heater and a set of temperature sensors into the sapwood of the species to be measured. In order to ensure that the heater and temperature sensors are correctly aligned a guide jig is normally used when drilling the holes. At least four probes consisting of the heater probe and temperature sensors are required to capture the radial variations of sap flow rates in the sapwood (Hatton *et al*., 1990). The method is suitable only for use on woody stems of at least 30 mm in diameter that can accommodate the probes (Smith and Allen, 1996). Its use is also limited in large stems where the entire sapwood cannot be accessed.

1.1.2.2 Compensation heat pulse method

Of the heat pulse techniques the CHPM has been the most widely used (Goodwin *et al*., 2006; Edwards *et al*., 1996). In the CHPM a heater probe is inserted radially into the sapwood portion of the stem together with two temperature sensors located up- and down-stream of the heater probe (commonly –5 and 10 mm, respectively). To monitor the sap velocity, wood and sap are heated in pulses and heat is carried through convection by the moving sap stream. When both temperature sensors have warmed to the same temperature, the heat pulse would have moved to the midpoint between the probes. The heat pulse velocity (V_h) is calculated from the time taken for the heat pulse to cover this distance as follows:

$$V_h = \frac{x_1 + x_2}{2t_0} \times 3600 \qquad \textit{Equation 1.3}$$

where t_o is time (s) for the downstream and upstream temperature probes to reach thermal equilibrium after the heat pulse has been released; and x_1 and x_2 denote distance in mm between the heater and the downstream and upstream temperature probes respectively. A negative value is assigned to x_2 because it is located on the opposite side of the heater to x_1.

The principle used for measuring V_h in the CHPM has been found to overestimate low, zero and reverse sap flow rates (Becker, 1998). This is because when sap flow rates are low, the heat pulse may dissipate by conduction before it reaches the measurement point, such that the sensors record equal temperatures (Burgess *et al*., 2001). Lower thresholds for measurement of V_h depend on the sensitivity of temperature sensors to capture the temperature changes, as well as the rate of thermal diffusivity in xylem. Various lower limits that are undistinguishable from zero have been reported e.g. 94 - 157 mm h^{-1} by Barrett *et al*. (1995); 36 - 72 mm h^{-1} by Becker (1998); 40 mm h^{-1} by Burgess *et al*. (1998) and 30 mm h^{-1} by Swanson and Whitfield (1981). Measured peak V_h in most woody species is seldom greater than 350 - 450 mm h^{-1}, with mean rates less than half this value (Burgess *et al*., 2001). Consequently, an inability of the CHPM to measure V_h below 30 - 40 mm h^{-1} will affect the lower 10 - 30% of measurements. Measurements of transpiration during winter, at night (Benyon, 1999) or on cloudy days are likely to be most affected. Such erroneous measurements would have an impact on the long-term transpiration of citrus which is known to have low conductance to water uptake.

1.1.2.3 Heat ratio method

Burgess *et al*. (2001) developed the HRM as an improvement to the CHPM to cater for low and reverse sap flow rates in woody species. In the HRM, the ratio of the increase in temperature is measured at points equidistant from a central heater soon after a heat pulse is released. Heat pulse velocity (V_h) is calculated as:

$$V_h = 3600\frac{k}{x} ln\left(\frac{v_1}{v_2}\right) \qquad \text{Equation 1.4}$$

where k is thermal diffusivity of green (fresh) wood (assigned a nominal value of 2.5 x 10^{-3} cm^2 s^{-1}), x is distance (cm) between the heater and either temperature probe, and v_1 and v_2 are increases in temperature (from initial temperatures) at equidistant points downstream and upstream (x cm) from the heater (Figure 1.1). During operation temperature increases are measured and v_1/v_2 ratios are recorded between 60 and 100 s after the release of the heat pulse. V_h are calculated based on the average of the ratios during a measurement occasion of approximately 40 s. Burgess *et al*. (1998; 2000) noted that there was a lesser occurrence of unexplained variations of V_h data measured using the HRM as compared to CHPM equivalents due to this improvement in sampling of measurements.

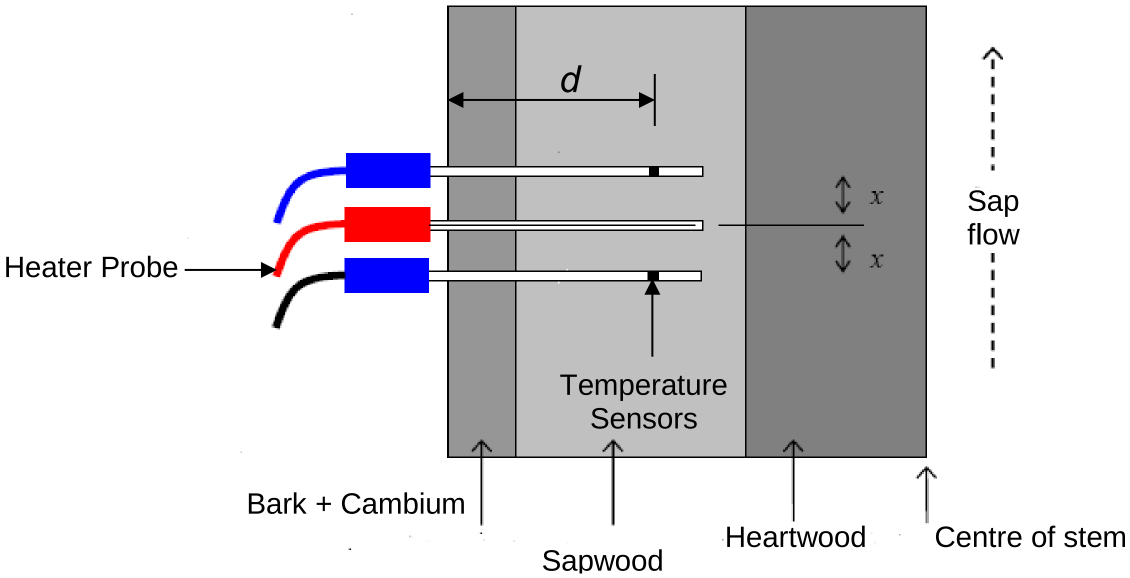

Figure 1.1 Schematic diagram of a probe set used for sap flow measurements using the HRM showing the heater probe, upper (down-stream) and lower (up-stream) temperature sensors. The depth of probe insertion *d*; and the distance between the heater probe and both temperature sensors *x* are also shown.

1.1.2.4 Correction for wounding

Heat pulse techniques are invasive in nature because the probes are inserted in the sapwood and they therefore require correction of measured V_h to account for the damage caused by drilling and constant heating, as well as the influence on heat transfer of the materials used to construct the temperature sensor (Green and Clothier, 1988; Fernández *et al*., 2006; Steppe *et al*., 2010). For the CHPM the correction can be made using empirical models derived by Swanson and Whitfield (1981) and Green and Clothier (1988) for a variety of temperature sensors spacings and materials used to construct the heater probes and temperature sensors. The models are of the following form:

$$V_c = a + bV_h + cV_h^2 \qquad \textit{Equation 1.5}$$

where V_c is corrected heat pulse velocity, and *a, b* and *c* are coefficients calculated by the models for various wound widths. The models used to estimate these coefficients as derived by Swanson and Whitfield (1981) and/or Green and Clothier (1988) cannot be solved at zero sap flow and; that only compounds the problem of poor resolution at low sap velocities using this method (Closs, 1958; Marshall, 1958; Barrett *et al*., 1995).

Burgess *et al*. (2001) developed models for wound correction of the following form:

$$V_c = bV_h + cV_h^2 + dV_h^3 \qquad \textit{Equation 1.6}$$

where *b, c* and *d* are coefficients calculated by the models for various wound widths. The models developed by Burgess *et al*. (2001) for wounding correction to be used in conjunction with the HRM are theoretically capable of estimating zero sap flow.

1.1.2.5 Calibration of the heat pulse techniques

Calibration of the heat pulse techniques is necessary for species with wood that are not thermally homogeneous (Smith and Allen, 1996). Thermally homogeneous sapwood should have both average xylem vessel lumen diameter and average distance between the xylem vessels of less than 0.4 mm (Swanson, 1983). Sap flow methods have been calibrated against other established methods to determine adjustment coefficients (Green and Clothier, 1988; Steppe *et al*., 2010). These established methods include weighing lysimeters (Caspari *et al.*, 1993; Nortes *et al*., 2008), whole tree gas exchange systems (Dragoni *et al*., 2005; Pernice *et al.*, 2009), cut tree experiments (Green and Clothier, 1988; Hatton *et al*., 1995; Fernández *et al*., 2001), stem perfusion experiments (Green and Clothier, 1988; Fernández *et al*. 2006; Steppe *et al*., 2010) and micrometeorological measurements (Kostner *et al*., 1992; Williams *et al*., 2004; Conceição and Ferreira, 2008; Poblete-Echeverría *et al*., 2012).

Of all the parameters required to convert V_h to transpiration the wound width (i.e. the damage caused by drilling and constant pulse heating) is difficult to estimate using experimental procedures. A number of calibrations have shown that once all other parameters have been experimentally determined, an apparent wound width can be used to convert V_h measurements to transpiration in sapwood that is not thermally homogeneous (Green and Clothier 1988; Zreik *et al*., 2003; Fernández *et al*., 2006). Fernandez *et al*. (2006) termed this apparent wound width that could be used to convert V_h's to transpiration so that it matched transpiration measure with an independent method a "virtual wound width".

There seem to be contradicting views on the development of the wound width when heat pulse techniques are used for long-term transpiration measurements. Early research findings reported that wounding effects increase with time and recommended that V_h probes should be moved regularly, either to a different part of the same stem or to a new stem (Swanson and Whitfield, 1981; Marshall *et al*., 1981; Smith and Allen, 1996; Zreik *et al*., 2003). To the contrary other authors showed that only limited changes occurred in xylem properties during a long period of V_h measurements in olive trees (Fernández *et al*., 2001; Giorio and Giorio, 2003; Pernice *et al*., 2009). Dragoni *et al*. (2005) also suggested that a single calibration was sufficient for long-term transpiration measurements in an apple orchard.

1.1.2.6 Scaling from sample trees to orchard level

In orchard situations sap flow measurements are normally conducted on a few representative trees from which whole stand transpiration is then extrapolated. The scaling of transpiration from sample trees to stand level can be based on leaf area (Jara *et al*., 1998), variability of plant stem diameter (Daamen *et al*., 1999; Bethenod *et al*., 2000) or plant density (Dugas and Mayeux Jr, 1991; Dragoni *et al*., 2005). Irrigated fruit tree orchards constitute clonal trees that are genetically identical and are normally trained similarly. The trees are mostly the same size, receive almost equal amounts of radiant energy and receive equal amounts of water from a uniform irrigation system. Little variation in transpiration of individual trees is expected (Smith and Allen, 1996) such that stand transpiration can be estimated from the sample trees using planting density (e.g. Dragoni *et al*., 2005). Use of allometric relationships between sap flow of sample trees growth parameters (i.e. stem diameter, stem basal area, sapwood area or leaf area) (e.g. Allen and Grime, 1995; Soegaard and Boegh, 1995; Vertessy *et al*., 1995) may not hold true since the canopies are manipulated. However, in studies of Cohen *et al*. (2008) and Conceição and Ferreira (2008) transpiration of sample trees was successfully scaled to whole stand transpiration as a weighted mean based on stem diameter of the sample trees in the orchards.

1.1.3 Micrometeorological estimates of evapotranspiration

The EC is one micrometeorological method that is normally deployed into the equilibrium boundary layer of a cropped area to estimate ET$_c$ (Allen *et al.*, 2011). Micrometeorological methods require large flat fields for the establishment of fetch and minimum equipment height equipment to produce representative data (Paw *et al*., 1995). Generally, instrumentation used for micrometeorological methods is relatively fragile and expensive, such that constant technical attention is required; and hence they are usually deployed into the field for short periods of time.

1.1.3.1 Eddy covariance method

Eddy covariance systems have been widely used to estimate ET$_c$ in orchards e.g. olive (Testi *et al*., 2004; Villalobos *et al*., 2000; Pernice *et al*., 2009), apple (Jones *et al*., 1988), pecan (Samani *et al*., 2011), mango (Teixeira and Bastiaanssen, 2012) and citrus (Rana *et al*., 2005; Villalobos *et al*., 2009; Consoli *et al*., 2006) orchards. The theory behind these measurements is based on the principle that turbulence in the atmospheric boundary layer dominates mixing and the diffusion of sensible and latent heat to and from the underlying surface (Swinbank, 1951). This requires high speed measurement of sonic temperature, wind velocity, and water vapour pressure or specific humidity, usually at frequencies of 5–20 Hz, using quick response sensors. ET$_c$ is measured based on the high frequency of the turbulent ‘eddy flux’ motions in the surface boundary using the following statistical relationship of Swinbank (1951):

$$ET_c = \rho_a \overline{w'q'} = \frac{0.622}{p}\overline{w'e'} \qquad \textit{Equation 1. 7}$$

where ρ_a is density of moist air, p is atmospheric pressure, q' is the instantaneous deviation of specific humidity from mean specific humidity, e' is the instantaneous deviation of vapour pressure from mean vapour pressure, and w' is the instantaneous deviation of vertical wind velocity from mean vertical wind velocity. The over-bar signifies a time average over a specified interval of time and the prime indicates a departure from the mean. Sensors must measure vertical wind speed, sonic temperature and humidity with sufficient frequency response to record the most rapid fluctuations important to the diffusion process. Wind speed and humidity sensors should be installed close to each other but separated sufficiently to avoid interference because if the separation is too large, an underestimate of the flux may result (Lee and Black, 1994). Many corrections are applied to arrive at the actual flux measurements.

The wide use of the EC method has been attributed to a number of reasons which include: relatively easy to setup, reduced cost of sensors and the ability to co-measure energy balance components (as well as carbon dioxide fluxes depending on equipment configuration) (Allen *et al*., 2011). ET_c measurements based on the EC method can be done using a direct measurement or calculated as a residual in the shortened energy balance.

1.1.3.1.1 Direct measurement

Instrumentation for direct measurement of water fluxes using the EC method involves the use of sonic anemometers and rapid-response open-path infra-red gas analysers (Tanner, 1988; Tanner *et al*. 1993; Wilson *et al*., 2002; Baldocchi, 2003; Shaw and Snyder, 2003; Meyers and Baldocchi, 2005). Using these instruments fluxes of latent (λET_c) and sensible heat (H) are measured with a high level of precision and with a high degree of spatial and temporal resolution averaging 15-30 minute periods. Typically, a frequency of the order of 5–10 Hz is used, but the response-time requirement depends on wind speed, atmospheric stability and the height of the instrumentation above the surface.

1.1.3.1.2 Energy balance method

ET_c can be calculated as a residual of the energy balance once the measurement of other components of the energy balance has been determined. The shortened energy balance equation can be written as follows:

$$\lambda ET_c = R_n - G - H \qquad \textit{Equation 1.8}$$

where λET_c is the latent heat flux, R_n is the net radiation, G is the heat flux transfer into the soil, H is the sensible heat flux density. All terms have units of W m^{-2}. R_n is measured using net radiometers and *G* is measured using soil heat flux plates. The sensible heat flux is measured using the EC method based on the following statistical relationship of Swinbank (1951):

$$H = \rho_a C_p \overline{w'T'} \qquad \textit{Equation 1.9}$$

where *T'* is the instantaneous deviation of air temperature from mean temperature and C_p is specific heat of moist air. The use of the shortened energy balance has an advantage of eliminating the requirement for the quick response hygrometer, which can be expensive and can create high frequency fallout caused by physical separation of the hygrometer from the sonic anemometer. The disadvantage of estimating ET_c as a residual of the shortened energy balance is the need to measure R_n and G accurately, which can be problematic under conditions with sparse or heterogeneous vegetation such as fruit tree orchards (Burba and Anderson, 2008). It is also assumed that other terms of the full energy balance such as canopy stored heat flux, advection flux e.t.c are negligible.

There are several corrections that must be applied to measurements because practical instrumentation cannot fully meet the requirements of the underlying micrometeorological theory (Foken *et al*., 2012). Typically, measurements are made in a finite sampling volume rather than at a single point, and the maximum frequency response of the sensors is less than the highest frequencies of the turbulent eddies responsible for the heat and mass transport. Both of these cause a loss of the high-frequency component of the covariances used to calculate fluxes. Errors also arise in calculating fluxes of trace gas quantities using open-path analyzers because of spurious density fluctuations arising from the fluxes of heat and water vapour. The several corrections required on the sampled high frequency data for the EC method to ensure that quality data are done using software such as EdiRe (Mauder *et al*., 2008).

When the shortened energy balance is used it also must be checked for energy balance closure error (Allen *et al*., 2011).This error occurs when the sum of measured $\lambda ET_c + H$ does not equal measured $R_n - G$ and can be in the range of 10 to 30 % for field experiments (Aubinet *et al*. 2000; Wilson *et al*. 2002). Foken *et al*. (2008) listed the following as the possible causes for lack of closure (i) different reference levels and different sampling scales of the measuring methods for net radiation, turbulent fluxes, and soil heat flux (ii) heterogeneous landscape in the vicinity of a flux-measurement site that is capable of generating eddies at larger time scales, that can be detected by the EC method (iii) advection and fluxes associated with longer wavelengths, and (iv) measurement errors. Energy balance closure is usually achieved by scaling λET_c and H in the same proportion (Twine *et al*., 2000) or using multiple linear regression equations (Allen *et al*., 2008).

1.2 Modelling citrus water use

1.2.1 Introduction

Variability in measured ET_c of citrus orchards means that these measurements cannot be directly applied to all areas in which the crop is cultivated and under all management practices. In addition measurements of ET_c are expensive, time consuming and requires specialised expertise which is not always available. Models play a pivotal role in extrapolating these measurements to regions in which they were not conducted. ET_c is modelled on a physical basis using weather data and algorithms that describe the crop's surface and aerodynamic resistances (Allen *et al*., 1998). According to Allen *et al*. (1998) the Penman-Monteith equation has been used quite extensively. The form of the equation is as follows:

$$\lambda ET_c = \frac{\Delta(R_n - G) + \rho C_p \frac{VPD}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \qquad \textit{Equation 1.10}$$

where λET_c is the evapotranspiration rate per unit leaf area (W m^{-2}), R_n is the net radiation flux density absorbed by the leaf (W m^{-2}), ρ and C_p, are the density (kg m^{-3}) and specific heat capacity (J kg^{-1} K^{-1}) of air at constant pressure, λ is the latent heat of vaporisation of water (J g^{-1}), γ is the psychrometric constant (kPa ^{o}C), Δ is the slope of the water vapour pressure curve (kPa ^{o}C) at ambient air temperature T_a (^{o}C), VPD is the saturation vapour pressure deficit of the air (kPa), r_a is the aerodynamic resistance (s m^{-l}), and r_s is the bulk surface resistance (s m^{-1}).

The r_s and r_a terms used to simplify the exchange process in a vegetation layer in Equation 1.10, are crop specific and cannot be determined easily (Figure 1.2). The r_s

term is used to describe the resistance of water flow through the soil-plant-atmosphere continuum. The r_s term combines resistances through the plant system and r_a describes the resistance from the surface of the vegetation upward and involves friction from air flowing over vegetation surfaces (Figure 1.2). In order to obviate the need to estimate the resistances parameters for each crop at different stages of growth, the crop coefficient approach was introduced.

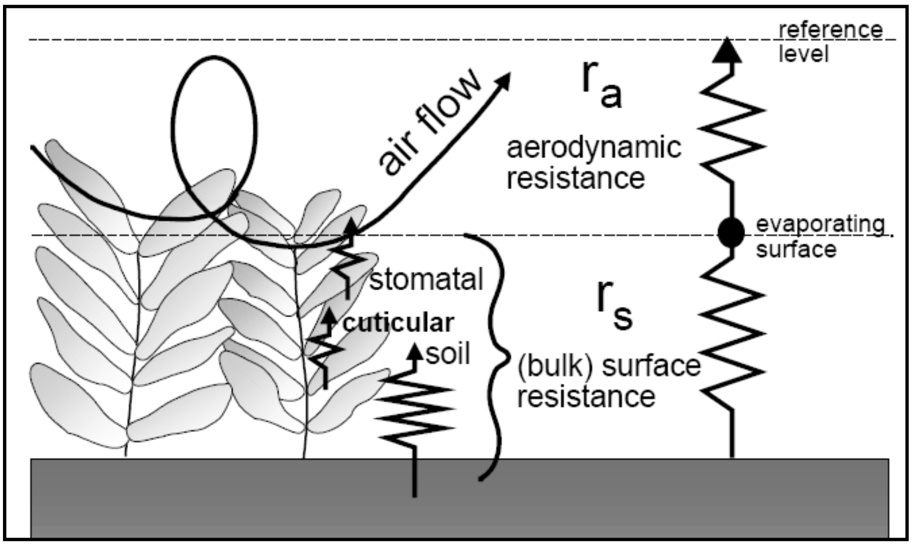

Figure 1.2. Simplified representation of the (bulk) surface and aerodynamic resistances for water flow through the soil-plant-atmosphere continuum (Allen *et al*., 1998).

1.2.2 Crop coefficient approach

The crop coefficient approach that was first published by Doorenbos and Pruitt (1977) and later refined by Allen *et al*. (1998) has been used quite extensively in modelling ET_c, such that it is considered a standard for estimating ET_c. ET_c under standard conditions is calculated as a product of experimentally determined crop coefficients (K_c) and reference evapotranspiration (ET_o). Standard conditions imply that the crops are disease free, well fertilised, growing in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions. The method has been accepted in the field of irrigation water management because it is relatively simple to use. The technical advantage of the crop coefficient approach is that it makes it possible to consider the independent contributions of evaporation and transpiration (Allen *et al*., 1998). This is done by splitting the K_c factor into two separate coefficients namely soil evaporation coefficient (K_e) and a basal crop coefficient (K_{cb}).

1.2.2.2 Single crop coefficient

In the single crop coefficient approach, the individual contributions of transpiration and evaporation are combined to determine ET_c as follows:

$$ET_c = K_c \times ET_o \qquad \textit{Equation 1.11}$$

The K_c coefficient averages evaporation and transpiration and should be used to compute ET_c for weekly or longer time periods for irrigation water management, where the averaged effects of soil wetting are acceptable and relevant e.g. in furrow and sprinkler systems (Allen *et al*., 2007).

1.2.2.3 Dual crop coefficient

The dual crop coefficient allows for the separation of evaporation and transpiration such that Equation 1.12 can be written as:

$$ET_c = (K_{cb} + K_e) \times ET_o \qquad \textit{Equation 1.12}$$

Allen *et al*. (1998) defined the K_{cb} as the ratio of ET_c to ET_o when the soil surface layer is dry, but where the average soil water content of the root zone is adequate to sustain full plant transpiration. This is best suited for irrigation water management in micro-irrigation systems where high frequency irrigation is practised and large variations in day to day soil wetness are experienced.

1.2.2.4 Reference evapotranspiration

Reference evapotranspiration may be expressed based on two reference crops, clipped, cool-season grass or tall alfalfa, whose common symbols are ET_o and ET_r, respectively. One, a 0.12-m tall cool-season clipped grass, follows the definition by FAO-56 (Allen *et al*., 1998, 2006) and uses the PM equation with specific parameterizations that now differ from the original 1998 FAO-56 definition (Figure 1.3) only in the value for bulk surface resistance prescribed for hourly or shorter time-step calculations, where r_s was reduced (Allen *et al*., 2006) from the daily value of 70 s m^{-1} to a new value of 50 s m^{-1} for hourly or shorter periods during daytime. For ET$_r$ the standardized reference surface is the 'tall' reference, defined to be very similar to a 0.5 m tall crop of dense, full-cover alfalfa (lucerne) having surface resistance of 30 s m^{-1} for hourly or shorter calculation time-steps during daytime and 45 s m^{-1} for daily calculation time-steps (Pereira *et al*., 2015). Crop coefficients (K_c) may be expressed in relation to clipped, cool-season grass as more often used (Allen *et al*., 1998; 2007) or to alfalfa; for which the symbol K_{cr} is adopted (ASCE-EWRI, 2005; Allen *et al*., 2007).

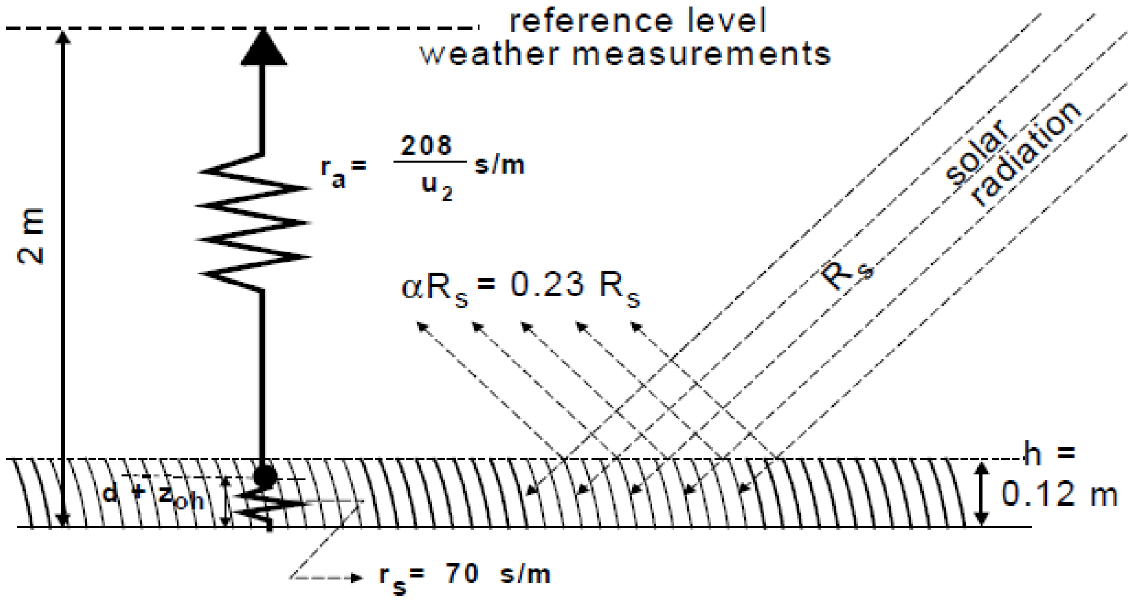

Figure 1. 3. Characteristics of the hypothetical short grass reference crop used for calculation of ET$_o$ in the FAO Penman-Monteith equation (Allen *et al*., 1998).

The Penman-Monteith equation standardised for the determination of ET$_o$ takes the following form (Allen *et al*., 2006; Allen *et al*., 2007; Pereira *et al*., 2015):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T_a + 273} u_2 VPD}{\Delta + \gamma(1 + C_d 0.34 u_2)} \qquad \textit{Equation 1.13}$$

where ET_o is reference evapotranspiration (mm day^{-1}), R_n is net irradiance at the crop surface (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), T_a is mean daily air temperature at 2 m height (°C), u_2 is wind speed at 2 m height (m s^{-1}), *VPD* is saturation vapour pressure deficit (kPa), Δ is slope of the vapour pressure curve (kPa °C^{-1}), γ is the psychrometric constant (kPa °C^{-1}), C_n is a numerator constant that changes with reference type and calculation time step and C_d is a denominator constant that changes with reference type and calculation time-step. The values for C_n and C_d are presented in Table 1.2. The values for C_n consider the time-step and aerodynamic roughness of the surface (i.e., reference type). The constant in the denominator, C_d, considers the time-step, bulk surface resistance, and aerodynamic roughness of the surface.

Table 1.2. Values for C_n and C_d in equation 1.13 for use when determining evapotranspiration for short (ET_o) and tall (ET_r) reference crop (Allen *et al*., 2007)

Calculation time-step	ET_o		ET_r		Units for ET_o, ET_r	Units for R_n, G
	C_n	C_d	C_n	C_d		
Daily	900	0.34	1600	0.38	mm d^{-1}	MJ m^{-2} d^{-1}
Hourly (daytime)	37	0.24	66	0.25	mm h^{-1}	MJ m^{-2} h^{-1}
Hourly (nighttime)	37	0.96	66	1.7	mm h^{-1}	MJ m^{-2} h^{-1}

1.2.2.5 Citrus crop coefficients

The standard crop coefficients for citrus published by Allen *et al.* (1998), which are largely based on the work of Doorenbos and Pruitt (1977), used for estimating ET_c are presented in Table 1.3. In developing the crop coefficients (K_c and K_{cb}), the growing season is divided into four distinct growth stages (i.e. initial, crop development, mid-season and late season stages) that are related to changes in water use due to crop development. For a generic citrus crop Allen *et al*. (1998) stipulated the lengths of the initial, development, mid-season and late season growth stages as 60, 90, 120 and 95 days, respectively. However, only the crop coefficients during the initial, mid-season and late season presented in the table are required to construct the crop coefficient curve.

Table 1.3. Citrus crop coefficient (K_c and K_{cb}) values for standard climate of RH_{min} = 45 % and u_2 = 2 m s^{-1} as published for use with FAO Penman-Monteith ET_o (Allen *et al*. 1998).

Orchard and ground conditions	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$	$K_{cb\ ini}$	$K_{cb\ mid}$	$K_{cb\ end}$
No ground cover						
70 % canopy	0.7	0.65	0.7	0.65	0.6	0.65
50 % canopy	0.65	0.6	0.65	0.6	0.55	0.6
20 % canopy	0.5	0.45	0.55	0.45	0.4	0.5
Active ground cover						
70 % canopy	0.75	0.7	0.75	0.75	0.7	0.75
50 % canopy	0.8	0.8	0.8	0.75	0.75	0.75
20 % canopy	0.85	0.85	0.85	0.8	0.8	0.85

NB: subscripts ini, mid and end are incorporated to mean initial, mid-season and end stages of crop growth.

Citrus crop coefficients presented in Table 1.3 either decrease during the mid-season or are constant throughout the season. This is in contradiction to the general crop coefficient curve for annual crops where the highest values occur during the mid-season. The occurrence of the highest crop coefficients during this period in most crops is probably due to the fact that leaf area of these crops is highest at this point, which translates into maximum water use at this time. The decrease of citrus crop coefficient values during the mid-season may be interpreted to mean that as the atmospheric demand increases, transpiration does not increase at the same rate (Green and Moreshet, 1984; García Petillo and Castel, 2007; Villalobos *et al.*, 2009). This behaviour has been linked to strong regulation mechanisms within the citrus tree hydraulic path (Kriedemann and Barrs, 1981).

The adoption and subsequent use of the FAO-56 crop coefficients in citrus is regardless of the fact that a wide range of crop coefficients has been reported for the crop in different growing regions (Table 1.4). Three significant deductions can be made from the data presented in Table 1.4. Firstly, the crop coefficients of Allen *et al*. (1998) are all less than one, as opposed to some studies in Table 1.4. Secondly, the values reported by some of the authors are much lower than those reported by Allen *et al*. (1998). Thirdly, some of the crop coefficients referred to in Table 1.4 are lower in summer (period normally coinciding with the mid-season, which is associated with active tree growth and fruit production) than in winter which agrees with the crop coefficients of Allen *et al*. (1998). According to Goldhamer *et al*. (2012) this is generally attributed to the citrus stomata being sensitive to evaporative demand (the air vapour pressure deficit, VPD), closing under dry, hot, windy conditions and opening under the opposite conditions. Thus, the K_c in the mild Mediterranean and coastal climates should be higher than those of more arid, inland valleys. In addition, in Mediterranean environments, high K_c values in winter reflect high soil evaporation rates from frequent rainfall during that part of the season.

The factors that affect the water use of citrus trees that were mentioned above will have an inherent effect on the crop coefficients. These factors include differences in variety, rootstock, tree spacing, canopy height, ground cover, tillage, leaf area index, method of estimating reference evapotranspiration, microclimate, irrigation method and frequency and method of measuring crop evapotranspiration (Snyder and O'Connell 2007; Naor *et al*. 2008). Another source of variation that is particular to K_{cb} values, that are based on transpiration determined using sap flow methods (i.e. Rana *et al*. 2005; Villalobos *et al*., 2009; Marin and Angelocci, 2011; Villalobos *et al*., 2013), is that the K_{cb} values of Allen *et al*. (1998) represent the transpiration component of ET_c and a small evaporation component from soil that is visibly dry at the surface. Although the evaporation component is small, it is not detected by sap flow methods. To distinguish the two forms, Villalobos *et al*. (2013) suggested that sap flow-based crop coefficients should be termed transpiration coefficients (K_t).

Table 1.4. Seasonal crop coefficients determined in citrus orchards across the growing regions of the world.

Reference	**Region**	**ET_o**				**K_c**			
		Summer[a]	**Autumn**	**Winter**	**Spring**	**Summer**	**Autumn**	**Winter**	**Spring**
Villalobos *et al*. (2013)	Spain					0.34	0.5	0.27	0.3
Marin and Angelocci (2011)	Brazil	4.4		2.7		0.7		0.26	
Villalobos *et al*. (2009)	Spain		4.99		5.88		0.44		0.43
Fares *et al.* (2008)	USA	4.40		2.24		0.86		0.69	
Snyder and O'Connell (2007)	USA	6.27	3.03	1.10	4.13	1.00	1.07	1.15	1.13
Alves *et al*. (2007)	Brazil	4.33	3.49	2.90	4.33	1.05	0.93	0.53	0.69
García Petillo and Castel (2007)	Uruguay	4.99	1.77	1.45	4.06	0.64	0.77	0.84	0.83
Romero *et al*. (2006)	Spain					0.7	0.7	0.9	0.7
Rana *et al*. (2005)	Italy					1.04	0.77	0.81	1.16
Yang *et al*. (2003)	Japan	4.40		0.60		0.90		0.60	
Castel (1997)	Spain	4.69	2.75	1.66	3.68	0.32	0.49	0.36	0.24
Castel *et al*. (1987)	Spain	4.93	2.57	1.53	3.43	0.70	0.77	0.65	0.61
Rogers *et al*. (1983)	USA	4.1	3.13	2.37	4.37	1.04	1.01	0.93	0.81
Hoffman *et al*. (1982)	USA	7.7	4.1	2.27	5.27	0.85	0.83	0.77	0.80
Green and Moreshet (1979)	South Africa	6.86	3.15	2.62	4.59	0.80	1.28	0.79	0.62
van Bavel *et al*. (1967)	USA	7.91	3.77	2.25	6.30	0.62	0.72	0.48	0.48

[a] Seasons were determined according to the equinoxes and solstices, with each season comprising 3 months. Measured data available for the period in the specific seasons was used for each cited work.

Most of the works reported on crop coefficients in citrus in Table 1.4 (i.e. Castel, 1997; Rana *et al*., 2007; Marin and Angelocci, 2011; Villalobos et al., 2009; Consoli and Papa, 2013; Villalobos et al., 2013; Marin *et al*., 2016), and other fruit tree orchards (Ayars *et al*., 2003; Girona *et al*. 2003; Testi *et al*. 2004; Girona *et al*., 2005; Johnson *et al*., 2005; Paco *et al*., 2006), have used ET_o. This is despite of the fact that these tall tree crops with a large roughness that can probably be best described by ET_r rather than ET_o. The use of the ET_o as the principal reference method has been attributed to its early adoption in FAO24 and the simplicity in cultivating this reference (clipped, cool season grass) across a wide range of locations and climates (Pereira *et al*., 2015). Generally, ET_r is about 1.1 to 1.4 times that of ET_o due to the increased roughness and leaf area of alfalfa.

In an attempt to improve on the accuracy of crop coefficients when transferred amongst different orchards Allen and Pereira (2009) consolidated and formalised the FAO-56 procedure for estimating the crop coefficients as a function of fraction of ground cover and crop height.

1.2.3 Estimation of transpiration crop coefficients from fractional ground cover and crop height

Allen *et al*. (1998) suggested a procedure for estimating the crop coefficients as a function of fraction of ground cover and crop height using a plant density coefficient. The advantage of this method is that it is relatively simple and is based on physical measurements that can easily be carried out in the field. Allen and Pereira (2009) further consolidated the concept to enable the estimation of site-specific crop coefficients based on the fraction of ground covered or shaded by the vegetation, the height of the vegetation and the degree of stomatal regulation under wet soil conditions.

Allen and Pereira (2009) conceived the idea of an upper, energy-constrained limit on K_c that can be adjusted for vegetation without full ground cover, such as orchards. They defined this upper limit, termed $K_{c\ max}$, as the maximum value for K_c following rain or irrigation. The value for $K_{c\ max}$ is governed by the amount of energy available for evaporation of water, which is largely encapsulated in ET_o. The $K_{c\ max}$ varies with general climate, ranging from about 1.05 to 1.30 (Allen *et al*., 1998; Allen *et al*., 2005) as follows:

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

Equation 1.14

where RH_{min} is average daily minimum relative humidity during the growth state or period and h is the mean plant height (m) during the period of calculation (initial, development, midseason, or late-season).

Transpiration increases with plant density or leaf area, so does the K_c value (Allen and Pereira, 2009) until the optimum is reached at a value of maximum canopy cover, which is usually defined as a leaf area index (LAI) equal to 3. In situations where full canopy cover is not achieved the K_{cb}, which correlates with the amount of vegetation because it represents mostly transpiration, can be expressed in terms of a density coefficient, K_d, where:

$$K_{cb} = K_{c\,min} + K_d\left(K_{cb\,full} - K_{c\,min}\right)$$ *Equation 1.15*

where K_{cb} is the approximation for the basal crop coefficient for conditions represented by the density coefficient, K_d, $K_{cb\ \mathrm{full}}$ is the estimated basal K_c during peak plant growth for conditions having nearly full ground cover (or LAI = 3), and $K_{c\ \mathrm{min}}$ is the minimum basal K_c for bare soil ($K_{cb\ \mathrm{min}}$ is approximately equal to 0.15 under typical agricultural conditions).

1.2.3.1 Basal crop coefficient during peak plant growth ($K_{cb\ full}$)

$K_{\mathrm{cb\ full}}$ for large stand size (greater than about 500 m^2) can be approximated as a function of mean plant height and adjusted for climate following Allen *et al*. (1998) as:

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

Equation 1.16

where F_{r} [0-1] is a relative adjustment factor for stomatal control, h is mean monthly plant height (m), Parameter F_{r} applies a downward adjustment ($F_r \leq 1.0$) if the vegetation exhibits more stomatal control on transpiration than is typical of most annual agricultural crops, a situation that is typical of citrus (Kriedemann and Barrs, 1981). Allen and Pereira (2009) suggested the following calculation for F_{r} for full cover vegetation, based on the FAO Penman-Monteith equation and assuming full cover conditions:

$$F_r \approx \frac{\Delta+\gamma(1+0.34u_2)}{\Delta+\gamma\left(1+0.34u_2\frac{r_l}{100}\right)}$$ *Equation 1.17*

where r_l is mean leaf resistance for the vegetation in question (s m^{-1}); Δ is the slope of the saturation vapour pressure versus air temperature curve (kPa °C^{-1}) and γ is the psychrometric constant (kPa °C^{-1}). For most annual agricultural crops the value of r_l is 100 s m^{-1}, which sets F_r to 1. Allen and Pereira (2009) suggest a value of 420 s m^{-1} for the initial and midseason periods and 150 s m^{-1} at the end of the season for citrus.

1.2.3.2 Estimation of plant density coefficient (K_d)

According to Allen and Pereira (2009), K_d describes the increase in K_c with increase in amount of vegetation. The shape of the K_d curve is curvilinear with LAI or fraction of ground cover because of effects of micro-advection of convective and radiative energy from exposed soil and height of vegetation. The density coefficient K_d can be estimated as a function of measured or estimated LAI or as a function of fraction of ground covered by vegetation.

1.2.3.2.1 Estimation of K_d from LAI

Where LAI can be measured or approximated, K_d can be approximated under normal conditions using an exponential function by suggested by Allen *et al*. (1998) as follows:

$$K_d = 1 - e^{0.7LAI}$$ *Equation 1.18*

where LAI is defined as the area of leaves per area of ground surface averaged over a large area with units of m^2 m^{-2}. Only one side of green healthy leaves that are active in vapour transfer is counted.

1.2.3.2.2 Estimation of K_d from ground covered by vegetation

K_d can also be estimated from measurement of ground covered by the vegetation using the following formula suggested by Allen *et al*. (1998):

$$K_d = \min\left(1, M_L f_{\text{c eff}}, f_{\text{c eff}}^{\left(\frac{1}{1+h}\right)}\right)$$ *Equation 1.19*

where $f_{c\ \mathrm{eff}}$ is the effective fraction of ground covered or shaded by vegetation [0.01-1] near solar noon, M_L is a multiplier on $f_{c\ \mathrm{eff}}$ and is an attempt to simulate hydraulic resistances within the plant and is expected to range between 1.5-2.0, with a value of 1.5 recommended for citrus (Allen and Pereira, 2009).

Of the two methods for determining K_d, Equation 1.19 is of practical importance due to the ease involved in determining $f_{c\ \mathrm{eff}}$ and h. For canopies such as trees $f_{c\ \mathrm{eff}}$ can be estimated according to Allen *et al*. (1998) as follows:

$$f_{\mathrm{c\ eff}} = \frac{f_c}{\sin\beta} \leq 1 \qquad \textit{Equation 1.20}$$

where β is the mean angle of the sun above the horizon during the period of maximum ET_c and f_c is the fraction of surface covered by vegetation as observed from directly overhead. β at solar noon can be calculated as:

$$\beta = \arcsin[\sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)] \qquad \textit{Equation 1.21}$$

where φ is latitude and δ is solar declination in radians.

For ready application of the methodology, Allen and Pereira (2009) recommended a set of generic parameters to be used in conjunction with Equations 1.16, 1.17 and 1.19 for different crops including citrus. Generic parameters for citrus orchards are presented in Table 1.5. Typical crop coefficients developed from effective ground cover that have been published for mature citrus orchards are presented in Table 1.6. The r_l values in Table 1.5 were estimated by inverting Equation 1.17 after solving for F_r by inverting Equation 1.16 using known $K_{cb\ full}$ values. This procedure aimed at producing values for K_c and K_{cb} that agree with literature values, including those from FAO-56. It is emphasised that values for r_l determined by this inversion are only for reuse in Equation 1.17. Allen and Pereira (2009) advised that r_l computed in this way must be evaluated with caution, and recommend the need to conduct research to improve the estimation of this parameter.

Nearly all r_l values obtained for orchards and vine crops following this approach exceeded the average value of 100 s m^{-1} normally associated with annual agricultural vegetation. This was interpreted by Allen and Pereira (2009) as an indication of strong degree of stomatal control exhibited by different fruit tree species under typical growing conditions. In a comparative study Meyer and Green (1981) observed that leaf resistances of citrus trees were much lower than that observed in soybean and wheat grown under similar environmental conditions. Average leaf resistances higher than what was suggested by Allen and Pereira (2009) have also been reported in citrus species e.g. 500 to 2000 s m^{-1} in Shamouti orange trees (Cohen and Cohen, 1983), 200 to 8280 s m^{-1} in Navel orange trees (Dzikiti *et al*., 2007) and 295 and 830 s m^{-1} in oranges (Pérez-Pérez *et al*., 2008).

Table 1.5. Generic parameters for a citrus crop for estimating crop coefficients.

Orchard ground conditions			Parameters at initial and midseason periods			Parameters at end of season		
	M_L	h (m)	f_c	r_l	F_r	f_c	r_l	F_r
No ground cover	1.5	2	0.25	420	0.71	0.20	150	0.94
Ground cover	1.5	2.5	0.45	420	0.71	0.40	275	0.82

Table 1.6. Citrus values of K_{cini}, $K_{c\ mid}$, $K_{c\ end}$, K_{cbini}, $K_{cb\ mid}$ and $K_{cb\ end}$ for standard climate of RH_{min} = 45 % and u_2 = 2 m s^{-1} as expanded from FAO-56 (Allen *et al*. 1998) for a range of values for effective ground covered by the tree canopy ($f_{c\ eff}$) during the midseason and using the procedure of Allen and Pereira (2009) with recommended parameter values.

Tree density and ground conditions	K_{cini}	$K_{c\ mid}$	$K_{c\ end}$	K_{cbini}	$K_{cb\ mid}$	$K_{cb\ end}$
No ground cover						
High ($f_{c\ eff}$ = 0.70)	0.95	0.90	90	0.85	0.85	0.85
Medium ($f_{c\ eff}$ = 0.50)	0.80	0.75	0.75	0.70	0.70	0.70
Low ($f_{c\ eff}$ = 0.25)	0.55	0.45	0.45	0.40	0.40	0.40
Active ground cover						
High ($f_{c\ eff}$ = 0.70)	1.00	0.95	0.95	0.90	0.90	0.90
Medium ($f_{c\ eff}$ = 0.50)	0.95	0.95	0.95	0.85	0.90	0.90
Low ($f_{c\ eff}$ = 0.25)	0.90	0.90	0.90	0.80	0.85	0.85

Citrus trees exhibit high resistances to water movement (van Bavel *et al*., 1967; Cohen and Cohen 1983; Syvertsen and Graham 1985; Rodríguez-Gamir *et al*. 2010) in the soil-plant-atmosphere continuum that can be detected at leaf level. The resistance is an essential parameter for understanding the mechanisms of plant transpiration in citrus orchards. Ideally it would be good to conduct extensive measurements of leaf resistances using porometry. However, such measurements are affected by a number of shortcomings which include: (i) sampling of leaf resistances in the field are not only labour intensive but are further complicated by the fact that r_l varies with leaf age and climatic conditions (van Bavel *et al*., 1967); (ii) automation of such measurements cannot be made because the sensor creates an artificial environment, which may lead to changes in the physiological properties of the leaf; and (iii) manual measurements performed with hand held porometers do not allow simultaneous sampling of the leaves exposed to varying levels of solar radiation by one user (Jarvis, 1976).

When measurements of water use are available, the bulk resistance of a vegetated surface can be obtained using the top–down approach by inversion of Equation 1.10 (Baldocchi *et al*., 1991). Transpiration measured using sap flow methods have been used quite extensively to determine bulk resistances in this manner (Wullschleger *et al*., 1998). Researchers have, however, reported these in terms of the bulk conductance rather than resistances. This is because flux is directly proportional to the conductance, such that errors in conductance, rather than the resistances are normally distributed (Campbell and Norman, 2008). The general approach has been to use such data sets to parameterise models that can predict canopy conductance as a function of canopy size and environmental variables (e.g. Zhang *et al*., 1997; Oguntunde *et al*., 2007; Villalobos *et al*., 2009; Granier and Loustau 1994; Green and McNaughton 1997) for predicting transpiration using Equation 1.10.

1.2.4 Modelling canopy conductance

Stomatal conductance of illuminated leaves has been shown to be dependent upon current levels and history of the immediate environmental variables, which includes radiant flux density, ambient carbon dioxide concentration, leaf air vapour pressure difference and leaf water status (Jarvis, 1976). A number of models have been formulated to describe the behaviour of stomatal conductance in relation to these environmental variables (Damour *et al*., 2010). Conductance models can be largely divided into multiplicative (Jarvis-type) and multiple linear regression models.

1.2.4.1 Jarvis-type model

Jarvis (1976) proposed the first multiplicative model involving radiant flux density (S_R), ambient carbon dioxide concentration (C_a), leaf-air water vapour pressure difference (*VPD*), air temperature (T_a) and leaf water status (Ψ_l), which is of the following form:

$$g_s = g_{s\,max} f(S_R) f(C_a) f(VPD) f(T_a) f(\Psi_l) \qquad \textit{Equation 1.22}$$

where g_s is the stomatal conductance predicted by the Jarvis model (m s^{-1}), $g_{s\,max}$ is the maximum stomatal conductance (m s^{-1}). This complex set of factors modulating stomatal all at once makes it almost impossible to quantify the effects of each environmental effect in the field. Controlled laboratory studies have been used to understand the stomatal responses to each of these factors in citrus and other crops.

Citrus stomata were shown to increase with photosynthetically active radiation until saturation at around 500 µmol m^{-2} s^{-1} (Kriedemann, 1971). Stomata of most plants response to the increase in atmospheric carbon dioxide concentration by reducing the stomatal aperture. Although transpiration is reduced photosynthetic assimilation increases such that water use efficiency is increased. Such responses will have implications for gas exchange of all terrestrial plants under future elevated concentrations of carbon dioxide. According to Levy and Kaufmann (1976) citrus stomata over react to a step-change increase in VPD by opening and closing rhythmically even when environmental conditions remain constant. Significant responses of citrus stomata to temperature were observed in the range 20 to 35 ^{o}C with the maximum occurring at 30 ^{o}C (Khairi and Hall, 1976). It was also shown that values of leaf water potential at which appreciable citrus stomatal closure occur (-2 500 to -3 000 kPa) are much lower than typical values averaging -2 300 kPa observed in irrigated trees (Syvertsen and Lloyd, 1994). As such leaf water potential does not have a direct impact on stomatal behaviour of well-irrigated citrus orchards. Based on these facts Syvertsen and Lloyd (1994) concluded that a Jarvis model with functions of S_R, T_a and *VPD* should be sufficient to describe the stomatal conductance of well-irrigated citrus trees.

By assuming the ‘big-leaf’ theory the Jarvis-type models have been extended to predict canopy conductance (g_c). The model, however, has been parameterised using the minimum number of weather variables that captures the variations of canopy conductance, with satisfactory accuracy in several fruit tree species (e.g. Stewart, 1988; White *et al*. 1999; MacFarlane *et al*., 2004; Misson *et al*., 2004; Noe and Giersch, 2004; Villalobos *et al*., 2000; Cohen and Cohen, 1983; Oguntunde *et al*., 2007). Results of the application of the Jarvis-type model in citrus orchards are not consistent. Cohen and Cohen (1983) reported that a Jarvis-type model containing S_R, VPD and T_a poorly ($R^2 = 0.11$) described stomatal resistance of citrus trees. Oguntunde *et al*. (2007) on the other hand showed that a similar model could describe the variations of canopy conductance fairly well ($R^2 > 0.7$). Elimination of the temperature function did not affect the performance of the model in the case of Oguntunde *et al*. (2007).

It is imperative that the aerodynamic conductance (g_a) term should be determined in order for g_c to be calculated or predicted using Equation 1.10. However, it has been argued that in the case of well-ventilated canopies, such as orchards, the effect of g_a on transpiration is far less critical than that imposed by g_c (Tan *et al*., 1978; McNaughton and Jarvis, 1983). The methods that have been used to determine g_a are reviewed in the next section.

1.2.4.3 Aerodynamic conductance

The transfer of water vapour at the surface of the crop canopy is sustained by molecular diffusion through a thin skin of air, known as the boundary layer, in contact with the surface (Monteith and Unsworth, 1990). The resistance to water vapour movement in this layer is known as boundary layer or aerodynamic resistance and; is difficult to quantify under field conditions, such that they are usually estimated using empirical models (Pereira *et al*., 2006). One model that has been used frequently for trees with leaves subjected to mutual interference is that proposed by Landsberg and Powell (1973). The original model is:

$$r_a = 58p^{0.56}\left(\frac{d}{u}\right)^{0.5} \qquad \textit{Equation 1.23}$$

where *p* is a measure of foliage density to wind, estimated by the ratio between the tree leaf area and the area of its silhouette projected on to a vertical plane, *d* is a characteristic leaf dimension (m), sometimes taken as the square root of the mean leaf area, and *u* is the average wind speed (m s^{-1}) at the mid-canopy height.

Rana *et al*. (2005), working in a Clementine orchard, also developed a model for estimating boundary layer resistance, which was later used by Oguntunde *et al*. (2007) in a citrus orchard. This method relies on indirect estimations of zero plane displacement height, roughness length governing the transfer of heat and vapour, roughness length governing momentum transfer, von Karman's constant and wind speed measurements. The requirement for wind speed measurements at a certain height above the canopy is the major drawback to this method. The equation has the following form:

$$r_a = \frac{ln\left(\frac{z-d}{z_o}\right)ln\left(\frac{z-d}{h_c-d}\right)}{k^2 u_z} \qquad \textit{Equation 1.24}$$

where k is the von Karman's constant equal to 0.4, u_z is the wind speed (m s^{-1}) at the *z* wind measurement height (m), d is the zero plane displacement estimated as d = 0.67h_c, z_o is the roughness length taken as 0.1h_c and h_c is the mean orchard height. Equation 1.23 is usually used by most researchers because of of its simplicity.

1.3 Scope of the study

Long-term studies of citrus ET_c are needed to update such information in the South African industry. This study focussed on the long-term measurement of tree transpiration in three citrus orchards using the HRM sap flow technique developed by Burgess *et al*. (2001). Calibration of the sap flow technique was performed using the eddy covariance method during the dry season (i.e. winter and autumn) when evaporation from the orchard floor was considered negligible. Calibration of the HRM was done by establishing a 'virtual wound width' used to convert heat pulse velocities to transpiration. Crop coefficients have been used quite extensively in estimating crop water use including citrus orchards. However, the variations among the recently published crop coefficients have cast doubt on their transferability among different growing regions. Allen and Pereira (2009) formalised the FAO-56 methodology for estimating site-specific crop coefficients using canopy height, a crop density factor and leaf resistance. Citrus trees exhibit high resistances to water movement and quantifying their resistance is an important step towards developing mechanistic models of transpiration in these species. Transpiration measurement at stem level presents the opportunity to determine canopy conductance, that are difficult to quantify under field conditions (Blad *et al*., 1982; Allen *et al*., 1998), using a top-down approach. The possibility of using a Jarvis-type canopy conductance model in conjunction with the Penman-Monteith equation to predict seasonal citrus transpiration was investigated in three orchards.

Chapter 2: Calibration of the heat ratio method (HRM) sap flow technique for long-term transpiration measurement in citrus orchards

2.1 Introduction

Accurate and reliable methods of measuring water use of fruit tree orchards are needed to gather information that is necessary to improve available irrigation water management tools. Amongst the many methods that have been used to measure tree transpiration, thermometric sap flow techniques have shown considerable promise (Smith and Allen, 1996; Wullschleger *et al.*, 1998). Some of the advantages that have led to the popularisation of these methods include that they are easily interfaced to data loggers for direct automated transpiration measurement; their applicability is not inhibited by complex terrain and soil heterogeneity within fruit tree orchards; they allow an estimation of transpiration which has a direct relationship with productivity; and their relatively high accuracy of measuring orchard water use as compared to other conventional methods e.g. eddy covariance (Rana *et al*., 2005) and soil water balance approaches (Nicolas *et al.*, 2005).

Thermometric techniques that have been employed for sap flow measurements in woody species can be broadly categorized into heat pulse, heat balance and heat dissipation methods (Smith and Allen, 1996). Heat pulse velocity (V_h) techniques, the compensation heat pulse method (CHPM) in particular, have been most widely used, mainly because they are relatively easy to use and require less power in the field (Edwards *et al.*, 1997; Conejero *et al*., 2007). However, CHPM is associated with limitations, of which the major one is the inability to measure low sap flow rates, which usually occur at night and under water stress conditions (Becker, 1998). Burgess *et al*. (2001) developed the heat ratio method (HRM) as an improvement to the CHPM in order to cater for low and reverse rates of sap flow in woody species. The use of this relatively new method of measuring transpiration has not been independently tested in citrus orchards.

Heat pulse techniques are invasive in nature because the probes are inserted into the sapwood and require correction for the damage, commonly referred to as wounding, caused by drilling and constant heating (Swanson, 1994). Conversion of measured V_h's to sap volumetric flow is performed using numerical models as a function of a number of wood parameters, which include sapwood water content, sapwood density and wound width. The most sensitive and difficult parameter to determine using experimental procedures is the actual wound width (Smith and Allen, 1996; Fernández *et al*. 2006; Poblete-Echeverria *et al.*, 2012). Some studies have used predetermined corrections based on the theoretical calibrations of Swanson and Whitfield (1981) (e.g., Nicolas *et al*., 2005, Villalobos *et al*., 2013) with visually determined wounding widths (Green and Clothier, 1988; Dragoni *et al*., 2005) or empirical calibration factors (Green and Clothier, 1988; Steppe *et al*., 2010) to correct for wounding.

It has been demonstrated that for sapwood that is not thermally homogeneous a “virtual wound width” is usually required to convert heat pulse velocities to volumetric sap flow with appreciable accuracy (Green and Clothier, 1988; Zreik *et al*., 2003; Fernández *et al*., 2006). Thermal homogeneity has been based on the work of Swanson (1983) who categorised it on the basis of the sapwood xylem vessels (particularly the diameter and density). However, there seem to contradicting reports on the response of wood tissue surrounding the inserted probes during long-term transpiration measurements. Smith and Allen (1996) suggested that wounding effects increase with time and the V_h probes should be moved regularly, either to a different part of the same stem or to a new stem. On the contrary, some studies seem to suggest that only limited changes occur in xylem properties during long periods of V_h measurements in some tree species e.g., olives (Fernández *et al*., 2001; Giorio and Giorio, 2003; Pernice *et al*., 2009) and apples (Dragoni *et al*., 2005).

Sap flow measurements for determining individual tree transpiration have been calibrated against independent methods of measuring tree transpiration, which include weighing lysimeters (Caspari *et al.*, 1993; Nortes *et al*., 2008), whole tree gas exchange systems (Dragoni *et al*., 2005; Pernice *et al.*, 2009), cut tree experiments (Green and Clothier, 1988; Hatton *et al*., 1995; Fernández *et al*., 2001), stem perfusion experiments (Green and Clothier, 1988; Fernández *et al*., 2006) and micrometeorological measurements (Jones *et al*., 1988; Poblete-Echeverría *et al*., 2012). The eddy covariance method has been used in a number of experiments to calibrate sap flow measurements in orchard situations (e.g., Conceição and Ferreira, 2008; Poblete-Echeverría *et al*., 2012).

Crop evapotranspiration (ET_c) measurements using micrometeorological measurements conducted in orchards, during dry periods with minimal ground cover when soil evaporation is negligible have shown that water loss from the orchard is predominantly due to tree transpiration (Rogers *et al*., 1983; Pernice *et al*., 2009; Marin and Angeloci, 2011). ET_c measurements conducted during such periods can be used to calibrate sap flow methods in the field. ET_c measurements using micrometeorological measurements are usually done for short periods of time, largely because they require constant technical attention by well-trained personnel and instrumentation is fragile and expensive (Allen *et al*., 2011). There is therefore a need to establish the minimum number of ET_c measurements required for calibration of the HRM when it is used for long-term transpiration measurements.

The aim of this work was to calibrate the HRM, for measuring transpiration, against ET_c, measured using the eddy covariance method, in citrus tree orchards during dry periods when evaporation is assumed negligible. It was hypothesized that citrus sapwood matrix is not thermally homogeneous such that conversion of measured heat pulse velocity to transpiration requires an empirical calibration factor which will be constant for long-term measurements.

2.2 Materials and methods

2.2.1 Experimental Site and Climate

Measurements were conducted in a commercial orchard in the 2008/9 season at Moosrivier Farm (Schoeman Boerdery Group) about 15 km north of the town of Groblersdal. The farm is located in the summer rainfall area of Mpumalanga Province of South Africa (25^o 02’ 32.69” S and 29^o 22’ 09.76” E) with an altitude of approximately 900 m.a.s.l. The area receives an average annual rainfall of 535 mm (Lynch and Schulze, 2006) and has an average minimum air temperature of 12.2°C and maximum air temperature of 24.6°C (Schulze and Maharaj, 2007). The orchard was planted in 1997 with ‘Delta’ Valencia orange trees (*Citrus sinensis* L. Osbeck) grafted on ‘Swingle’ rootstock, at a spacing of 5.5 m x 2.75 m in a north–south orientation (0° N). Measured leaf area index (LAI) of the orchard was 2.85 m^2 m^{-2}. Every alternate tree was "sandwich" pruned, meaning this tree was pruned narrower every year to allow for the trees on either side to grow into the pruned space. "Sandwich" pruned trees are removed once the trees on either side have reached an adequate size as determined by the grower. Average tree height was 4.1 m. The orchard was drip irrigated with one line per tree row and pressure compensating emitters with a discharge of 2 L h^{-1} spaced 1 m apart. The soil type was sandy loam with an average of 7-12 % clay in the first 1 m depth. The orchard block was circular in shape with an average diameter of 595 m which allowed a fetch of 300 m from the prevailing northerly winds for micrometeorological measurements conducted at the centre of the circular field (Figure 2.1).

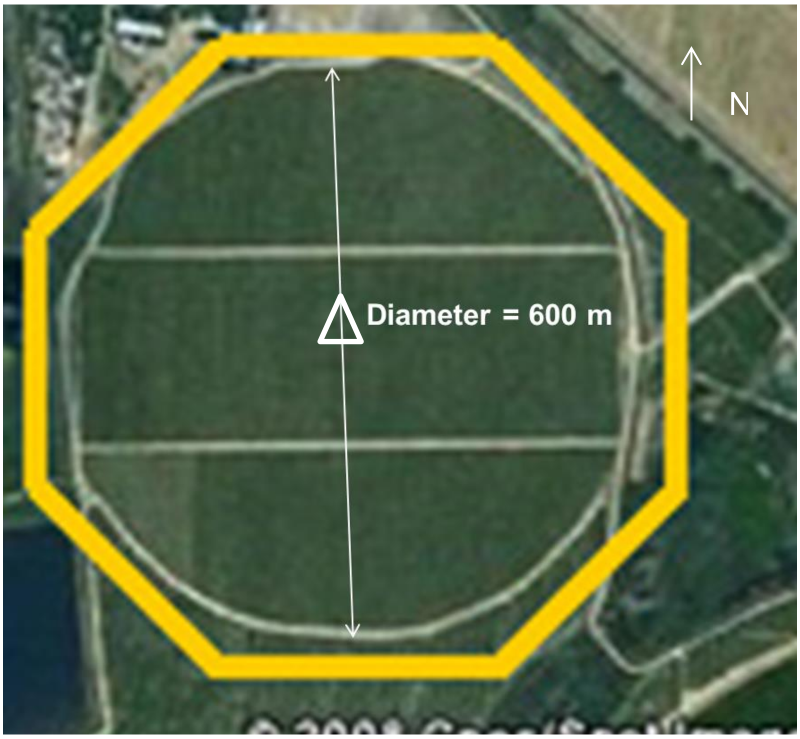

Figure 2.1. Map showing the 'Valencia' orange orchard highlighted by the yellow boarder line. The position of the tower during micrometeorological measurements is indicated by the Δ on the map.

2.2.2 Sap flow measurements

2.2.2.1 Measurement of heat pulse velocities

Sap flow measurements were conducted at stem level using the heat ratio method as described by Burgess *et al.* (2001) on three sample trees in the orchard. Selection of the three sample trees that were instrumented was based on a tree stem circumference survey at the start of the study. Stem circumferences of 40 trees were measured at a height of 40 cm above the ground and ranged from 32.7 to 47.7 cm. The results of the survey were then fitted to a normal distribution to establish suitable circumference ranges to be used and select representative trees to be instrumented. Table 2.1 shows the ranges of the stem circumference that were established and the dimensions of the trees that were selected for instrumentation.

Table 2.1. Established circumference size classes (CSC) established, the number of trees in the class (*n*), the sample tree representing each class, sample tree circumference (S_c) and the fraction represented by each sample tree in the 'Delta' Valencia orchard as a percentage (p_t).

CSC (mm)	*n*	S_c (mm)	Probe Depths (mm)	p_t
≤400	12	327	7, 14, 22, 30	17
401-449	34	382	7, 20, 30, 40	49
≥45	24	477	7, 20, 30, 40	34

Four probes were inserted in the sapwood of each tree at various depths from the bark to capture the radial variation of sap flux density with sapwood depth. The depths to which the different probes were inserted in each sample tree are shown in Table 2.1. One measuring probe set consisted of a heater probe and two thermocouples placed upstream and downstream at a distance of 50 mm (Figure 2.2). The 60-mm long line-heaters were made from 1.8-mm outside-diameter stainless steel tubing, enclosing a constantan filament. Type T (copper/constantan) thermocouples were embedded in 2 mm outside diameter polytetrafluoroethene (PTFE) tubing. Drilling was performed using a drill guide strapped to the tree to ensure that holes were parallel.

Core samples, with a diameter of 5 mm, were taken using an incremental borer from trees that closely resembled the chosen trees. Simple measurements showed that the bark thickness was 5 mm and sapwood depth of the trees was 40 mm. Sapwood depth was based on wood discolouration. The core samples were preserved in formalin, acetic acid and alcohol and taken to the laboratory for anatomical studies of the xylem structure.

Figure 2.2. Sap flow probes installed in two trees in the 'Delta' Valencia orchard. Insert shows situation of the probes around a stem of one of the sample trees.

The V_h for each probe set was calculated following Marshall (1958) as:

$$V_h = \frac{k}{x} ln\left(\frac{v_1}{v_2}\right) \times 3600 \qquad \textit{Equation 2. 1}$$

where k is the thermal diffusivity of green (fresh) wood (assigned a nominal value of 2.5 x 10^{-3} cm^2 s^{-1}), x is distance in cm between the heater and either thermocouples (= 0.5 cm), v_1 and v_2 are changes in temperature after the heat pulse is released (from initial temperatures) as measured by the upstream and downstream thermocouples and 3600 converts seconds to hours. Heat pulse velocities were measured and logged on an hourly basis using a CR10X data logger and an AM16/32B multiplexer (Campbell Scientific Inc., Logan, Utah, USA).

2.2.2.2 Wounding correction

The heat pulse velocities were corrected for wounding (i.e. xylem tissue mechanical damage) caused by installation of probes and heating using coefficients *b, c*, and *d* obtained from a numerical model developed by Burgess *et al.* (2001) using the following equation:

$$V_c = bV_h + cV_h^2 + dV_h^3$$ *Equation 2.2*

where V_c is the corrected heat pulse velocity. The functions describing the correction coefficients in relation to wound width (w) are as follows:

$$b = 6.6155w^2 + 3.332w + 0.9236$$ *Equation 2.3*

$$c = -0.149w^2 + 0.0381w - 0.0036$$ *Equation 2.4*

$$d = 0.0335w^2 - 0.0095w + 0.0008$$ *Equation 2.5*

The wound width was initially assumed to be equal to the size of the largest drill bit which was 0.2 cm for the thermocouples (Green and Clothier, 1988; Dragoni *et al*., 2005). Visual inspection during the measurement period on a piece of wood chiselled from one of the trees (Figure 2.3) and after Tree 1 was cut down at the end of the measurement season (Figure 2.4) revealed a wounding width of 0.2 cm.

2.2.2.3 Determining sap velocity

Sap velocity (V_S) was calculated from the corrected heat pulse velocity using the equation suggested by Marshall (1958) that was later modified by Barrett *et al*. (1995):

$$V_s = \frac{V_s \rho_b (c_w + m_c c_s)}{\rho_s c_s}$$ *Equation 2.6*

where ρ_b is the basic density of wood, c_w and c_s are specific heat capacity of the wood matrix (1200 J kg^{-1}°C^{-1} at 20 °C (Becker and Edwards, 1999) and sap (water, 4182 J kg^{-1} °C^{-1}) at 20 °C (Lide, 1992), respectively, m_c is water content of the sapwood and ρ_s is the density of water (1000 kg m^{-3}).

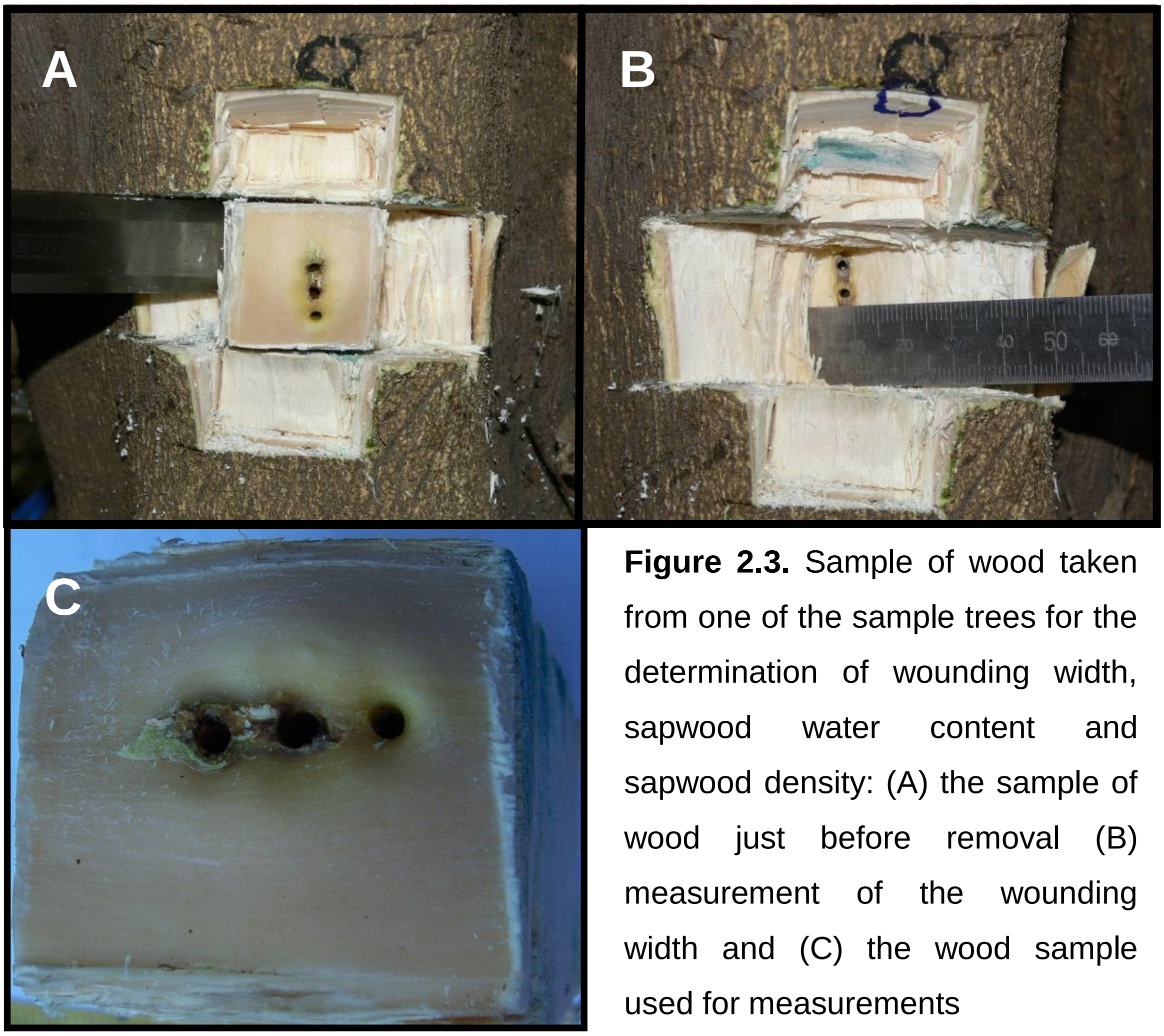

Figure 2.3. Sample of wood taken from one of the sample trees for the determination of wounding width, sapwood water content and sapwood density: (A) the sample of wood just before removal (B) measurement of the wounding width and (C) the wood sample used for measurements

Figure 2.4. Measurement of the wounding width on a wood sample cut transversely from the trunk of one of the sample trees at the end of the measuring season in August 2009 (photo courtesy of Mark Gush).

The sapwood moisture content and basic density were determined on freshly excised wood samples. The sapwood samples were chiselled from the tree and immediately placed in a plastic bag to preserve moisture content. The green mass of the sample was measured; the volume (cm^3) was determined by water-displacement in a beaker and then oven-dried at a constant temperature of 70 °C until there was no significant change in mass. Sapwood moisture content was calculated as:

$$m_c = \frac{M_w - M_d}{M_w}$$ *Equation 2. 7*

where M_w and M_d are wet and dry mass (kg) of the sapwood sample.

The basic density ρ_b was calculated as:

$$\rho_b = \frac{M_d}{V_w}$$ *Equation 2. 8*

where V_w is the volume of the wood sample which is equal to the volume of water displaced in the beaker.

2.2.2.4 Converting sap velocity to sap flux density

Volumetric flow for individual probes was calculated as the product of sap velocity (V_s) and cross-sectional area of conducting sapwood represented by the specific. Integration of sap flux measurements by individual probes to obtain whole stem flux (Q) was performed following the method of weighted average of heat pulse velocity with depth as presented by Hatton *et al*. (1990) using Equation 2.9.

$$Q = \pi[r_1^2 * v_1 + (r_2^2 - r_1^2) * v_2 + (r_3^2 - r_2^2) * v_3 + (r_4^2 - r_3^2) * v_4]$$ *Equation 2.9*

where v_k is the heat pulse velocity measured by sensor k placed between radii r_{k-1} and r_k. Integrated sap flux (assumed to be equal to whole tree transpiration) over the whole sapwood area, calculated on an hourly basis, was normalised to millimetres of water by dividing by the area allocated to each tree in the orchard (15.125 m^2). The annular cross-section of the sapwood of the tree was divided into four concentric annuli as shown in Figure 2.5.

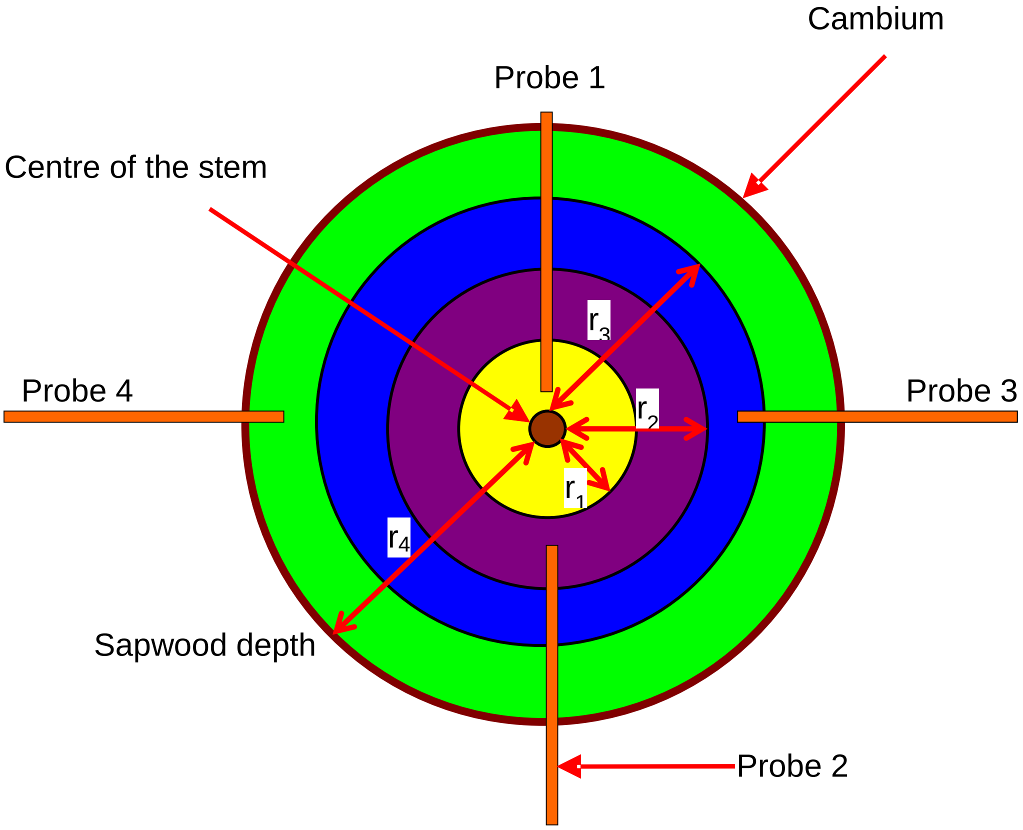

Figure 2.5. Idealised cross-sectional areas of four annuli rings represented by probe sets inserted at different depths in the conducting sapwood of a tree stem shaded in different colours.

2.2.2.5 Xylem anatomical assessments

Xylem anatomical assessments were conducted on excised stem wood samples prior to probe insertion and at the conclusion of sap flow measurements in wood tissue surrounding the drilled holes in order to determine the extent of wounding caused by implantation of probes in the sapwood of the ‘Delta’ Valencia trees and to assess the thermal homogeneity of the wood. Transverse sections above and below the drilled holes, radial sections on both sides of the drilled hole and tangential sections across the drilled hole were made using a sliding microtome. To aid with contrast during wood tissue observation sections were stained with safranin and fast green and observed with a Wild Leitz GMBH light microscope (Abbott Laboratories, Illinois, USA). Safranin normally dyes lignin red and fast green appears a brilliant green in cytoplasm and cellulosic cell walls (Glime and Wagner, 2013). These stains are considered generally good for staining plant tissues and hence are normally used for wood. Photomicrographs of the xylem structure and vessel distribution were taken with a PowerShot A630 digital camera (Canon Inc., USA) mounted on the microscope. Average xylem vessel lumen diameter and distance between groups of vessels were measured with an optical scale on the microscope. To get an overall picture of the sapwood, individual photos of cross sections, taken in radial sequence, were then 'stitched' together using HP Photosmart Essential software (Hewlett-Packard Development Company, L.P.).

2.2.3 Measurement of orchard evapotranspiration

ET_c measurements to calibrate the sap flow method were conducted in the orchard during two window periods, from 31 July to 3 August 2008 (winter) and from 21 to 25 of May 2009 (autumn). ET_c during the two window periods was measured using the eddy covariance method by the Hydroscience Research Group of the Council for Scientific and Industrial Research (CSIR) based in Stellenbosch. The measurement of ET_c during winter 2008 was conducted soon after installation of the V_h system and the measurement in autumn coincided with the end of the orange fruit growing season in the orchard. V_h measurements were done throughout the season in fruit growing season in the orchard.

2.2.3.1 The eddy covariance system

Fluxes of latent (λET_c) and sensible heat (H) were measured with an extended open path eddy covariance (OPEC) system, comprising a Campbell CSAT3 three-dimensional sonic anemometer and in autumn an LI-7500 open path infrared gas analyser (LiCor Inc., Lincoln, Nebraska, USA) was used, which were mounted on a lattice mast 6.2 m above the soil surface at the centre of the field. The fetch requirements of approximately 300 m were met from all directions. The configuration of instruments is shown in Figure 2.6. Measurements were sampled at a frequency of 10 Hz and logged on a CR5000 data logger (Campbell Scientific Inc., Logan, Utah, USA). Air temperature and humidity were measured using a Vaisala HMP45C temperature and humidity probe (Vaisala Oyj, Vantaa, Finland). Net irradiance (R_n) was measured using two net radiometers at 6.4 m above the soil surface (Model

240-110 NR-Lite, Kipp and Zonen, Delft, The Netherlands), with one placed above the trees and the other between the tree rows. Soil heat flux (G) was determined from four soil heat flux plates (model HFT-S, REBS, Seattle, Washington, USA) placed within the tree rows and in-between the tree rows at a depth of 80 mm. A system of four Campbell TCAV-L soil temperature averaging probes at depths of 20 and 60 mm were used to calculate the heat stored above the plates. Volumetric soil water content in the first 60 mm was measured using a Campbell CS616 time domain reflectometer. These sensors were connected to a CR23X datalogger and measurements were performed at 10 Hz frequency, with averages obtained every 30 minutes. In order to ensure that the ETc measured were representative of the orchard a quality analysis of the high frequency data for the EC was done using EdiRe software (Campbell Scientific Inc., Logan, Utah, USA). The rotations did not change the fluxes that much for the Groblersdal site.

Energy balance closure during the winter period was assessed using the energy balance ratio (EBR) on a daily basis and was calculated as follows:

$$EBR = \frac{H+\lambda ET_c}{R_n - G} \qquad \textit{Equation 2.10}$$

where H, λET_c, R_n and G are expressed in MJ m^{-2} day^{-1}. Throughout the May 2009 measurement period, when the IRGA was used to estimate LE, less than 10 % error in energy balance measurements was found (i.e. EBR>0.9 or EBR<1.1). In August 2008 the shortened energy balance was used to estimate λET_c from measurements of H, R_n and G.

2.2.4 Calibration of the HRM sap flow technique

Transpiration measured with the sap flow method and up-scaled to orchard level was compared to ET_c measured using the eddy covariance method during the two window periods i.e. from 1 to 4 August 2008 (winter) and from 21 to 25 of May 2009 (autumn). These periods were chosen because the orchard was expected to have negligible rates of evaporation of intercepted water from the canopy or ground surface (due to limited ground cover and the absence of rainfall) as observed in orchards by Rogers *et al*. (1983), Pernice *et al*. (2009) and Marin and Angelocci (2011). The contribution of irrigation water to evaporation was also considered negligible, since the orchard was drip-irrigated and water was applied directly under the tree, wetting small areas of soil, which were shaded by the trees. As a result ET_c was expected to equal orchard transpiration.

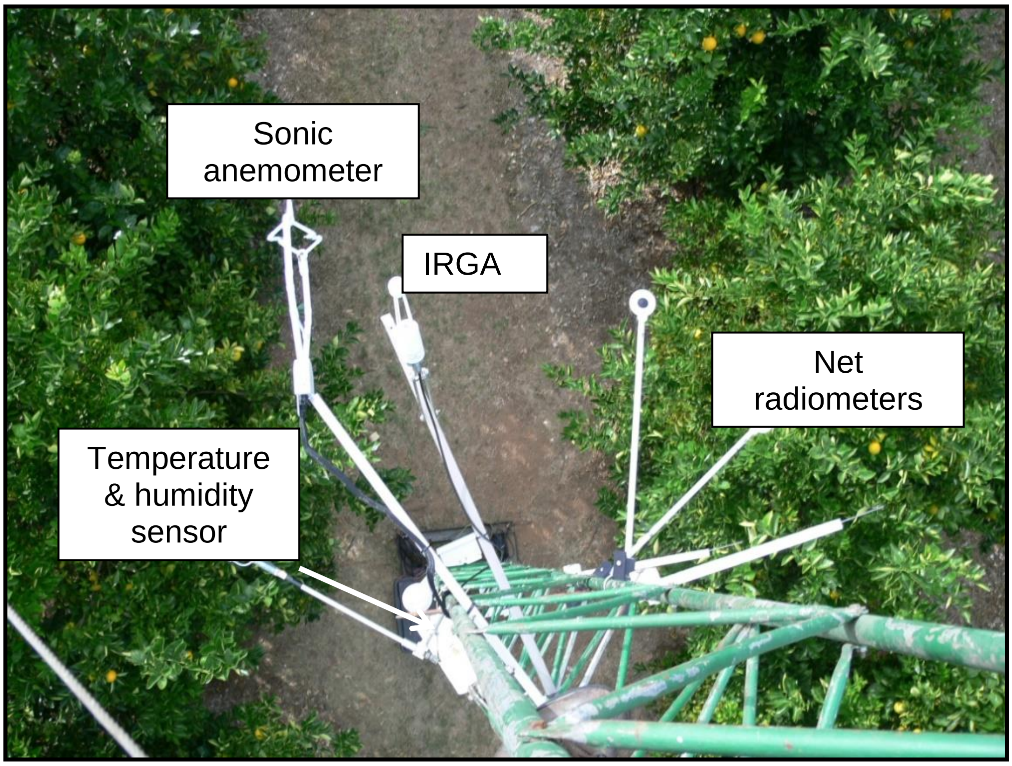

Figure 2.6. Micro-meteorological instruments including mounted on a lattice mast at the centre of the 'Delta' Valencia orchard (photo courtesy of Mark Gush).

A sensitivity analysis was performed to assess the effect of wound width, sapwood water content and sapwood density on final transpiration values during the autumn measurement period. The percentage change in transpiration was determined as a result of a percentage change in each parameter, which varied between 5 and 30%, whilst keeping the other parameters at their original values. Based on the results of the sensitivity analysis and the fact that sapwood water content and density were estimated using experimental procedures the calibration procedure was targeted on wound width, as in the case of Zreik *et al*. (2003) and Fernández *et al*. (2006).

A wound width termed a “virtual wound width” that could be used in the conversion of heat pulse velocities to tree transpiration, so that average daily sap flow measurements of the sample trees matched daily ET_c measurements, was determined using linear regression equations. Using this method, HRM-based transpiration was initially calculated using different wound widths (2, 3, 4 and 5 mm). Linear regression equations were then formulated between HRM-based transpiration and the wound width. A “virtual wound width” that matched HRM-transpiration to ET_c was calculated by inputting the measured ET_c into the regression equations. Daily values were chosen to avoid issues associated with capacitance within the citrus trees, which could result in time lags between sap flow and ET_c measurements.

2.3 Results

2.3.1 Calibration of the HRM sap flow technique

It is evident that when using the observed wound width of 0.2 cm, up-scaled sap flow underestimated the ET_c measured over the orchard using the eddy covariance method. This underestimation of transpiration during the two measurement periods ranged from 50 to 192 %. A sensitivity analysis of wound width, sapwood water content and sapwood density revealed that final transpiration values were in fact most sensitive to changes in wound width, where a 30 % change in wound width resulted in an error of 50 % in transpiration (Figure 2.7). Although final transpiration values were also shown to be fairly sensitive to changes in sapwood density and sapwood water content, a survey across citrus species revealed these two parameters to be fairly conservative in well-irrigated citrus trees (Table 2.2). The use of these conservative values for citrus is therefore likely to result in an error of less than 13%, which is deemed acceptable.

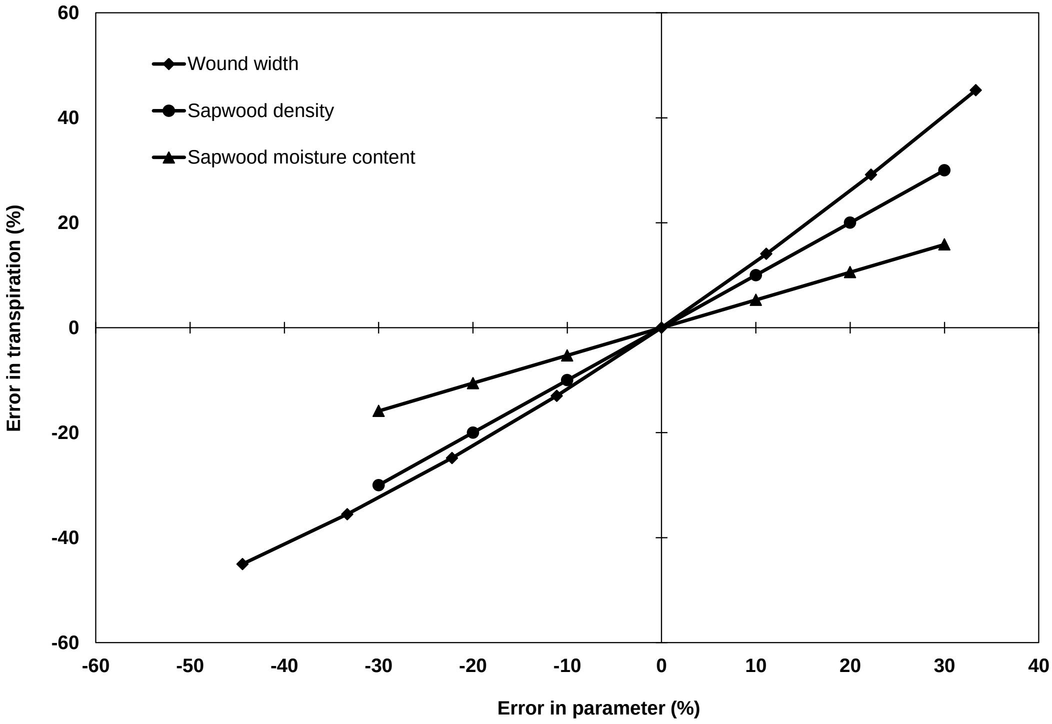

Figure 2.7. Error analysis illustrating resultant percentage error in transpiration from the HRM due to errors in selected parameters in the up-scaling equations from V_h's to transpiration, whilst maintaining all other parameters at their original value.

Table 2.2. Sapwood water content and sapwood density for various citrus species. A total of 19 samples were taken, with six from lemon, nine from sweet orange, two from soft citrus and two from grapefruit.

Parameter	Value	SD	%CV
Sapwood water content (kg kg^{-1})	0.61	0.8	13.11
Sapwood density (kg m^{-3})	0.74	0.04	5.41

The slopes, intercepts and R^2 values of the regression equations of HRM-transpiration against wound width on different days are presented in Table 2.3. The virtual wound widths that were determined by inputting measured ET_c into the regression equations are also shown in Table 2.3. The average virtual wound width that resulted in good agreement between daily sap flow-based transpiration and daily ET_c measurements during the winter and autumn periods were 3.3 and 3.1 mm, respectively. Figure 2.8 shows a very good agreement between daily transpiration (obtained using a virtual wound width of 3.3 mm for the winter period and 3.1 mm for the autumn period) and ET_c.

Table 2.3. Slopes and intercepts of the regression equations used to determine wounding width by inputting ET_c on different days. The R^2 values and the virtual wound widths determined from the regression equations are also shown.

Date	Slope	Intercept	R^2 value	Wound width (mm)
Winter 2008				
31 July	7.25	-0.41	0.99	3.4
1 August	6.79	-0.39	0.99	3.7
2 August	6.62	-0.23	0.99	3.1
3 August	8.08	-0.49	0.99	3.1
Average				**3.3**
Autumn 2009				
21 May	3.83	-0.14	0.99	3.1
22 May	4.17	-0.17	0.99	2.8
23 May	3.62	-0,06	0.99	3.0
24 May	3.81	-0.06	0.99	3.3
25 May	5.67	-0.05	0.99	3.2
Average				**3.1**

There was a small difference of 2 mm between the average virtual wound widths obtained in the winter and autumn measurement periods. The average of the two virtual wound widths, i.e. 3.2 mm, was then used to convert heat pulse velocities to tree transpiration for the two short-term seasonal crop ET_c measurement campaigns. A comparison of hourly transpiration obtained using the average virtual wound width with measured ET_c resulted in a good agreement between measured ET_c and transpiration from the calibrated HRM for most of the days considered (Figure 2.9). Regression analysis between transpiration and ET_c when forced through the origin resulted in slopes of 1.21 and 1.07 in winter and autumn.

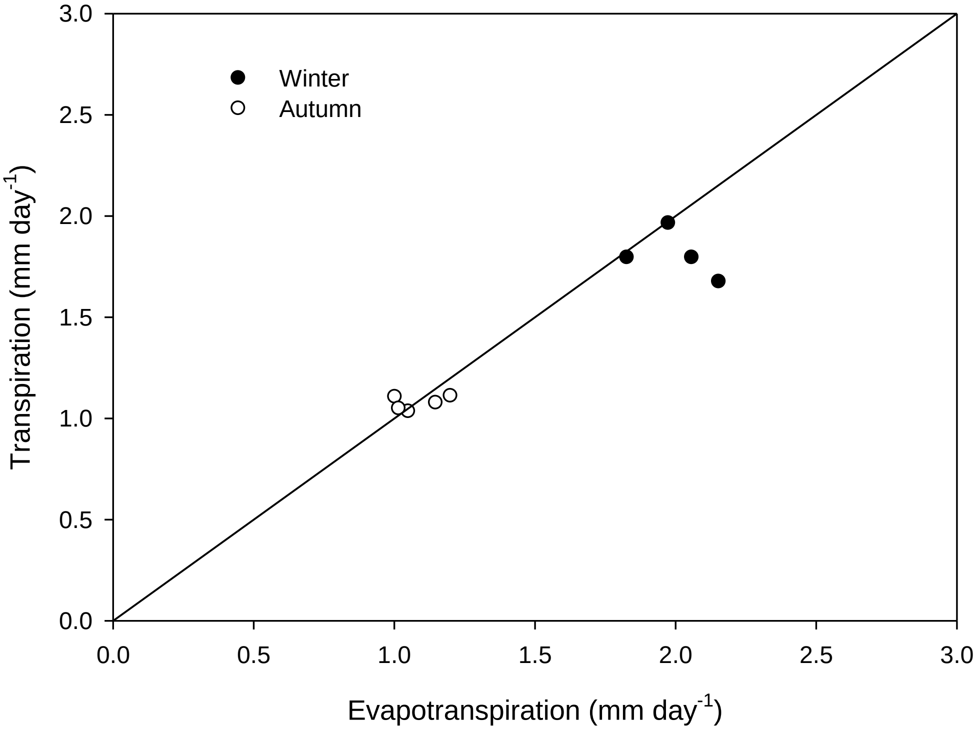

Figure 2.8. Comparison between daily transpiration obtained using a virtual wound width of 3.3 mm for the winter period and 3.1 mm for the autumn period.

2.3.3 Xylem anatomy

A ‘stitched’ transverse section of the citrus sapwood before the insertion of the probes illustrates that citrus trees have diffuse–porous xylem anatomy i.e. early- and latewood pores show little variation in size or density (Figure 2.10A). The xylem elements occur in two to four radial groups or clusters, which form the xylem vessels. Measured average lumen diameter of the xylem vessels was (0.15 ± 0.02) mm and the average distance between clusters was (0.8 ± 0.22) mm. Figure 2.10B is a photograph of the position of a heater probe in the sap wood of one of the instrumented trees showing the extent of the damage caused by drilling and constant heating. The average wound width that was observed for all the probes by the naked eye was 0.2 cm. Tangential sections around the same hole showed blocked xylem elements appearing as dark stripes as illustrated in Figure 2.10C. The discolouration of ray cells and vessels blocked with gum (g) and phenols (p), that extend for at least 6 mm from the drilled holes (Figure 2.10D), which could also be seen a transverse section of the sapwood approximately 1 mm above the downstream thermocouple

(Figure 2.10E), suggests that the effective wounding caused by drilling and heating extends beyond the visible wound width of 2 mm.

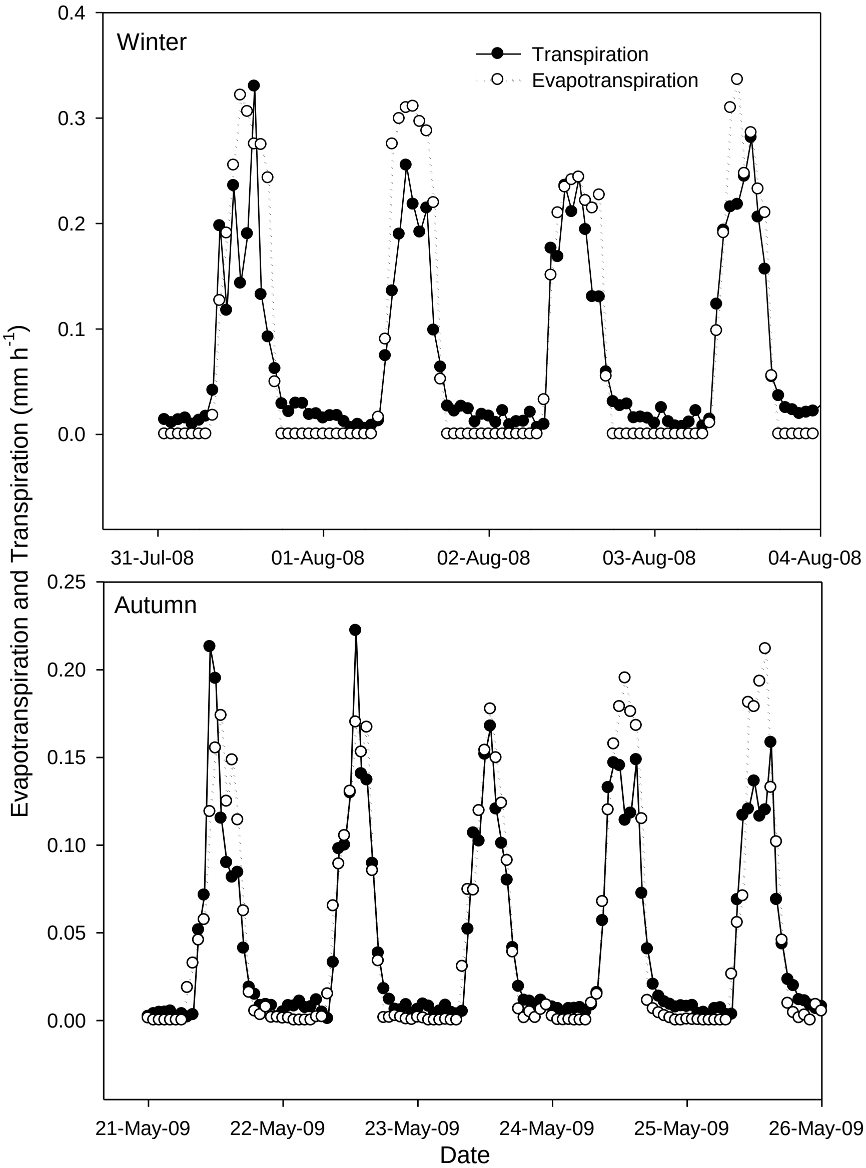

Figure 2.9. Up-scaled HRM-based transpiration using a “virtual wound width” of 3.2 mm as compared to micrometeorological measurements of evapotranspiration.

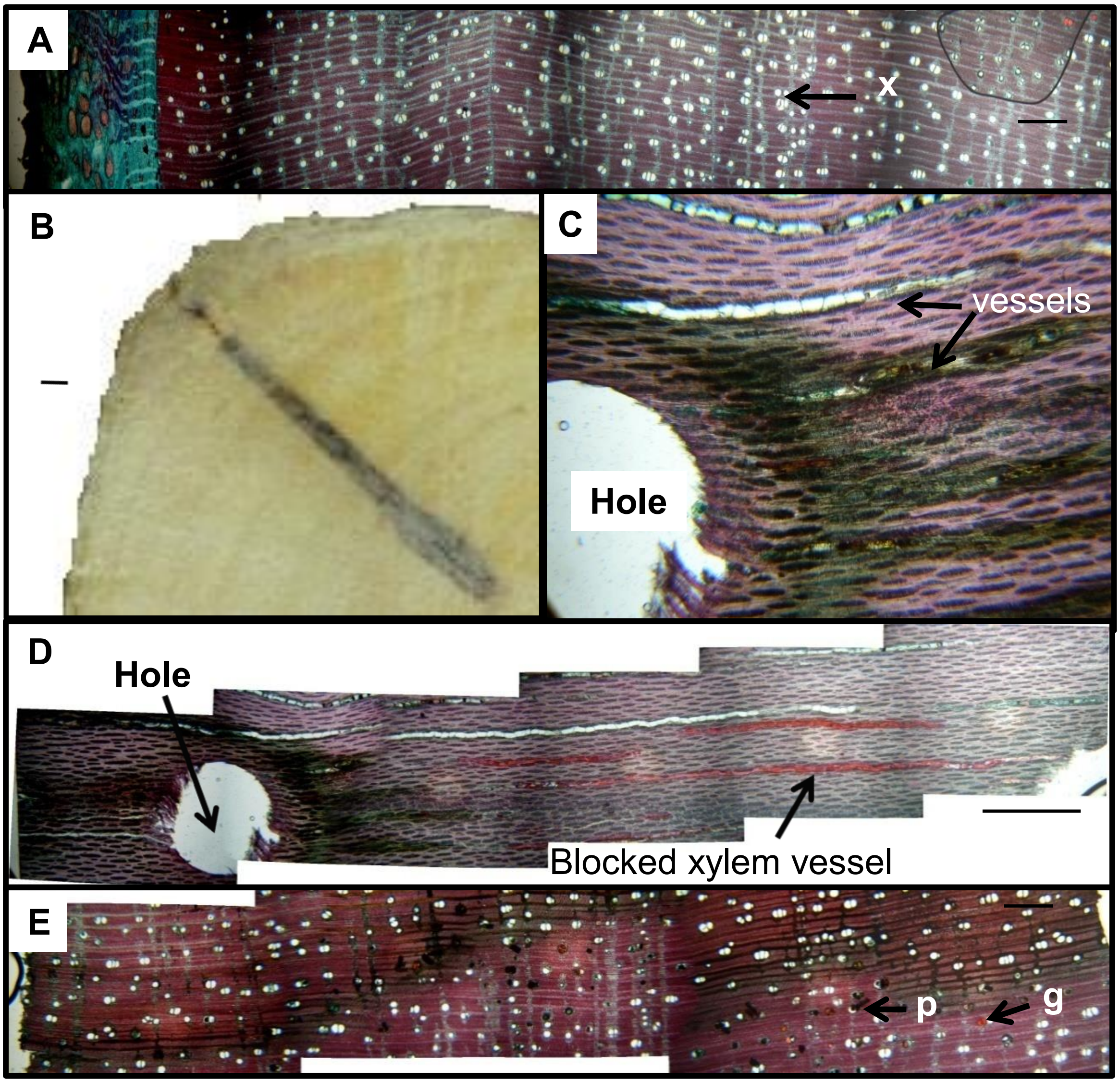

Figure 2.10. Photomicrographs of sapwood samples taken from a 'Valencia' orange tree. (A) A transverse section of the citrus sapwood prior to probe insertion showing the distribution of the xylem vessels (x) in the sapwood; (B) a transverse section of sapwood adjacent to one of the drilled holes made for insertion of a probe; (C) tangential section adjacent to one of the drilled holes showing the affected rays; (D) a transverse section showing the extent of blockage of xylem vessels by gum (g) and phenols (p); and (E) a transverse section of the sapwood approximately 1 mm above the downstream thermocouple showing extensive xylem blockage. Scale bars on each photograph are equal to 2 mm.

2.4 Discussion

Heat pulse velocity techniques have been used extensively to estimate transpiration of fruit trees (Nicolas *et al*., 2005; Rana *et al*., 2005; Pernice *et al*., 2009; Marin and Angelocci, 2011; Consoli and Papa, 2013). There is serious concern that this technique tends to underestimate transpiration (Green and Clothier 1988; Jones *et al*., 1988; Steppe *et al*., 2010), and species-specific calibration is therefore required (e.g., Green and Clothier, 1988; Green *et al*., 2003; Dragoni *et al*., 2005; Ferandez *et al*. 2006; Pernice *et al.*, 2009). This is because of the invasive nature of the methods that disrupts the sap stream and alters the thermal homogeneity of the sapwood surrounding the probes causing a systematic underestimation in the measured V_h's (Cohen *et al*., 1981; Green and Clothier, 1988). In this study sap flow measurements using the HRM were calibrated using eddy covariance measurements of ET_c under field conditions in an orchard planted with 'Delta' Valencia orange trees, when evaporation was considered to be negligible.

The small difference between the virtual wound widths determined during the two measurement periods used for calibration, which were nine months apart, indicates that limited changes occurred in the sapwood surrounding the probes during the measurements. As the initial calibration was performed immediately after the insertion of the probes it can be inferred that wounding in response to probe insertion in citrus occurs quickly and once established it does not change over time. As such a single calibration using this method is most probably sufficient for long-term measurement of transpiration using the HRM in citrus. In addition, the use of a virtual wound width of 3.2 mm resulted in very good agreement between transpiration determined by the HRM and ET_c suggesting that this is a reliable method for in-field calibration of sap flow systems. Constant wound widths or correction factors for long term sap flow measurements have also previously been reported. Dragoni *et al*. (2005) reported a constant wounding effect over a period of two and half months in apples. Rana *et al*. (2005) also used a constant correction factor over a period of one month in citrus trees. This is, however, in contradiction to earlier findings where changes in wound width were observed to occur with time (Swanson and Whitfield, 1981; Marshall *et al*., 1981; Zreik *et al*., 2003).

Although there are no reports of the calibration of the HRM in citrus in literature to draw comparisons with, similar calibrations of other V_h techniques do exist. The average virtual wound width of 3.2 mm that could be used to match orchard transpiration to ET_c for both measurement periods is similar to the range of values (2.8-3.2 mm) determined by Zreik *et al*. (2003) in citrus. However, it is greater than the virtual wound width of 2.4 mm determined in citrus by Fernández *et al*. (2006). Differences would be expected due to the fact that experimental conditions and analytical equations used by the authors are not the same as those used in this study. This includes the fact that they were using a different sap flow method (i.e. the compensation heat pulse technique) with different wound correction analytical models. In addition both experiments were not carried out under field conditions but were cut tree experiment (Fernández *et al*., 2006) and transpiration based on mass changes of potted plants (Zreik *et al*., 2003).

There are two possible explanations that could be drawn from the xylem anatomical assessments that could have led to a virtual wound width that is greater than what was observed with the naked eye. Firstly, the diameter of the xylem vessels and the distance between them is greater than 0.4 mm, which may cause the sapwood matrix of the citrus trees to depart from the assumption of thermal homogeneity and therefore may not adhere to the underlying principles of the V_h techniques as theorised by Huber and Schmidt (1937). Studies by Swanson (1983), Green and Clothier (1988) and Fernández *et al*. (2006) concluded that distances of non-conductive tissue greater than 0.4 mm tend to cause departures from thermal homogeneity such that an effective wound width greater than the largest hole drilled would be required to convert V_h's to transpiration. This is not taken into account in the wound correction process, based on the numerical models of Burgess *et al*. (2001) used in this study. Secondly, the greater virtual wound width is also probably due to the fact that besides the interruption of flow pathways (caused by mechanical damage during sensor installation) intact vessels had become occluded as the plant responded to wounding by deposition of gum and phenols. According to Burgess *et al*. (2001) such occlusions, which may not be visible to the naked eye, result in a region of non-conducting wood around the site of probe insertion, which has an effect of decreasing the heat ratio (v_1/v_2) and hence V_h in Equation 2.3.

2.5 Conclusions

The HRM was successfully calibrated under field conditions in a citrus orchard using ET_c estimated from the eddy covariance method. It was established that a virtual wound width of 3.2 mm can be used in the conversion of heat pulse velocities to tree transpiration for both measurement periods (winter 2008 and autumn 2009) so that average daily sap flow measurements of the sample trees matched daily ET_c measurements done using the eddy covariance method. The virtual wound width that was greater than the biggest hole drilled (2 mm) was probably due to the fact that citrus wood is not thermally homogeneous as indicated by the xylem anatomical assessments. This in-field calibration method was performed twice, with nine months of continuous heat pulse velocity measurements separating the measurement windows, indicating the likelihood that the wound width remained constant throughout this period. The use of a single virtual wound width during the two measurement periods resulted in a good match between transpiration and ET_c thereby suggesting that the HRM is reliable for long-term measurements of transpiration in citrus; and a single calibration using this method may be sufficient for long-term transpiration measurements. The development of a constant “virtual” wound width for citrus is a novel approach which will in future allow the online calculation of the sap flux density for potential real time monitoring of citrus tree transpiration.

Chapter 3: Measurement of long-term transpiration and transpiration coefficients in citrus orchards

3.1 Introduction

Irrigation plays a major role in meeting crop water requirements for evergreen citrus orchards, which require water all year round in semi-arid regions, such as South Africa (Bijzet, 2006). Micro-irrigation systems, such as drip, that allow for greater control over the quantity of water applied, have been adopted by citrus farmers in South Africa in recent years. The potential of drip irrigation systems to improve irrigation water use efficiency in orchards lies in their ability to supply near-to-exact the water required by the tree crops; and the fact that it applies water directly to the root system on small areas which are usually shaded, thereby limiting evaporation (Reinders *et al*., 2010)

However, there is a need to complement these systems with water management procedures that are system-specific, if their benefits are to be fully realized. Knowledge of the water use of crops and the factors that govern the actual process of water uptake are essential for developing models that are used for extrapolating such information for irrigation water management. Such knowledge is considered lacking under the relatively new micro-irrigation systems in South Africa (Pavel *et al*., 2003; Volschenk *et al*., 2003). The need to update such information is also necessitated by a change in rootstock choice from the more vigorous ‘Rough Lemon’ to the rootstocks of intermediate vigour which include ‘Carrizo’, ‘Troyer’ and ‘Swingle’. Thermometric sap flow techniques can be utilised to expedite the gathering of information on transpiration of citrus orchards to fill that knowledge gap. The heat ratio method (HRM) sap flow technique has been used to study transpiration dynamics in *Jatropha curcas L.* (Gush, 2008), olive (Williams *et al*., 2004; Er-Raki *et al.*, 2010), *Eucalyptus marginata* (Bleby *et al*., 2004) and *Prosopis* (Dzikiti *et al*., 2013).

The crop coefficient (K_c) approach proposed by Doorenbos and Pruitt (1977) that was later refined by Allen *et al*. (1998) has been used quite extensively in irrigation water management of various crops including citrus (e.g., Green and Moreshet, 1979; Hoffman *et al*., 1982; Rogers *et al*., 1983; Castel *et al*., 1987; Castel, 1997;

Allen *et al*., 1998; Yang *et al*., 2003; Rana *et al*., 2005; Fares *et al.,* 2008). This has been attributed to the relative simplicity of the method such that it is currently considered the standard method for determining crop water use (Pereira *et al*., 2015). One major advantage of the crop coefficient approach is that it considers the independent contributions of soil evaporation and crop transpiration towards crop evapotranspiration (ET_c) (Allen *et al*., 1998). This is done by using the dual crop coefficient approach in which K_c is split into two separate coefficients, i.e. a soil evaporation coefficient (K_e) and the crop transpiration coefficient (K_{cb}).

Recent studies have, however, revealed variability in crop coefficients of citrus among different growing regions (Carr, 2012; García Petillo and Castel, 2007) and the need to up-date crop coefficients has been highlighted (Snyder and O’Connell, 2006). One source of variation that is particular to K_{cb} values that are based on transpiration determined using sap flow methods (e.g., Rana *et al*. 2005; Villalobos *et al*., 2009; Marin and Angelocci, 2011; Villalobos *et al*., 2013) is that the K_{cb} values of Allen *et al*. (1998) represent the transpiration component of ET_c and a small evaporation component from soil that is visibly dry at the surface. Although the evaporation component is small, it is not determined by the sap flow methods. To distinguish the two forms, Villalobos *et al*. (2013) suggested that sap flow-based crop coefficients should be termed transpiration coefficients (K_t).

The aims of this work were to: (i) quantify the long-term transpiration of three well-irrigated citrus orchards using the HRM, (ii) determine K_t values of citrus orchards based on transpiration measured using the HRM, and (ii) verify the suitability of the K_{cb} values proposed for a generic citrus crop in the FAO56 to predict transpiration of citrus orchards.

3.2 Materials and methods

3.2.1 Experimental site and climate

Measurement of tree water use was conducted at Moosrivier Farm (Schoeman Boerdery Group) in commercial orchards planted with ‘Delta’ Valencia and ‘Bahianinha’ Navel oranges [*Citrus sinensis* (L.) Osbeck]. The description of the

‘Delta’ Valencia orange tree orchard and equipment setup is given in Section 2.2.1. Measurements were conducted during the 2008/9 season in the ‘Delta’ Valencia orchard and during the 2009/10 in the ‘Bahianinha’ Navel orchard. The ‘Bahianinha’ Navel orange trees were grafted on ‘Carrizo’ rootstocks and were planted in 2003. The row orientation was 51^o ENE, with north being 0^o. Tree spacing was 6 m x 2 m with the trees planted on ridges, pruned to an average height of 2.5 m each year after harvest. Measured leaf area index (LAI) of the orchard was 2.34 m^2 m^{-2}. The orchard was drip-irrigated, with one line per tree row and pressure compensating emitters with a discharge of 2.3 L h^{-1}, spaced 1 m apart. The soil type was sandy loam with an average of 5-10 % clay in the first 1 m depth.

Both orchards were managed according to commercial standards, as stipulated by the GLOBALG.A.P standards. Irrigation scheduling was done using a simple water balance approach checked with soil water content measurements performed using DFM capacitance probes (DFM Software Solutions, South Africa). Generally, both orchards received irrigation on a daily basis, with two to three 2-h pulses per day, which ensured that soil water content was maintained near to field capacity.

An additional data set of transpiration and ET_o measurements that was sourced from within the “Water use of fruit tree orchards” project, of which this study was part of, will also be reported on. The measurements were conducted in a commercial orchard planted with ‘Rustenburg’ Navels in the 2010/11 season at Patrysberg Farm in the Western Cape Province (32° 27’ 15.43’’ S and 18° 58’ 3.58’’ E, 149 m.a.s.l.) near Citrusdal, in the winter rainfall region of South Africa. The area receives an average annual rainfall of 200 mm and has average minimum and maximum temperatures of 10 °C and 24 °C, respectively. The ‘Rustenburg’ Navel trees were grafted on ‘Troyer’ citrange rootstocks and were planted in 1996. Tree spacing was 5 × 2.5 m with trees being pruned shortly after harvest to a height of 3.2 m, with selective limb removal, according to the industry standards of the production area. The orchard row orientation was 79° ENE. Average tree height was 3.3 m. Measured leaf area index (LAI) of the orchard was 3.40 m^2 m^{-2}. The orchard was drip-irrigated, with two drip lines per tree row using pressure compensating emitters spaced 0.8 m apart with a discharge of 1.8 L h^{-1}. The soil texture was a sandy loam with an average of 5–10 % clay in the top 1-m depth. The orchard was irrigated on a daily basis, with one 2 to 3 h pulse per day.

3.2.2 Estimation of transpiration

Heat pulse velocities (V_h) were measured using the HRM developed by Burgess *et al*. (2001) on three sample trees in the ‘Delta’ Valencia orchard, four sample trees in the ‘Bahianinha’ Navel orchard and six trees in the ‘Rustenburg’ Navel. Details of the instrumentation in the ‘Delta’ Valencia orchard were given in Section 2.2.2. Selection of the sample trees that were instrumented in the other orchards was also based on a tree stem circumference survey as described the ‘Delta’ Valencia orchard in Section 2.2.2. Table 3.1 shows circumference size classes established, the number of trees in each class, the sample tree representing each class, sample tree circumference and the percentage of the orchard represented by each sample tree in the ‘Bahianinha’ and ‘Rustenburg’ Navel orchards. No heartwood was detected on core samples taken from other trees in three orchards using an incremental borer. The details of the measurement procedure of the V_h’s and conversion to transpiration volumes are given in Section 2.2.2. The integrated sap flux density (assumed to be equal to transpiration) was calculated for every hour and then summed to obtain daily transpiration. The virtual wound width that was established for the ‘Delta’ Valencia orchard using micrometeorological measurements in Chapter 2 was used in the three orchards.

Table 3.1. Established circumference size classes (CSC), the number of trees in the class (*N*), the sample tree representing each class, sample tree circumference (S_c) and the percentage represented by each sample tree each orchard (P_t).

CSC (mm)	*N*	S_c (mm)	Probe depths (mm)	P_t
'Bahianinha' Navels				
≤282.7	24	222	7, 14, 22, 30	16.00
282.8-306.3	26	306	7, 20, 30, 40	18.00
306.4-342.4	55	313	7, 20, 30, 45	37.00
≥342.5	42	346	7, 20, 30, 40	29.00
'Rustenburg' Navels				
≤300	6	280	8, 15, 25, 30	21.10
300-350	15	345	8, 15, 25, 30	32.40
350-390	15	384	10, 18, 30, 40	8.45
350-390	11	392	10, 18, 30, 40	8.45
390-430	12	442	10, 18, 30, 40	21.10
>430	12	444	10, 18, 30, 40	8.50

Integrated volumetric sap flow of the individual trees (L day^{-1}) was converted to transpiration (mm day^{-1}) using the ground area allocated to each tree in the orchard, i.e. 12 m^2 in the 'Bahianinha' Navel orchard and 12.5 m^2 in the 'Rustenburg' Navel orchard. Orchard transpiration in the two orchards was calculated as a weighted average of sampled trees as suggested by Hultine *et al*. (2010), based on a stem circumference survey at the start of the study and the consistent relationship between seasonal water use and stem circumference (Figure 3.1). Transpiration of the 'Delta' Valencia orchard was calculated as an average of the sample trees as a result of the sandwich pruning method adopted in this orchard, which resulted in a significantly smaller canopy in every second tree. In the 'Bahianinha' and 'Rustenburg' Navel orchards where trees were pruned to almost an equal canopy size, it was thought that the stem diameter would have an influence on the transpiration rate.

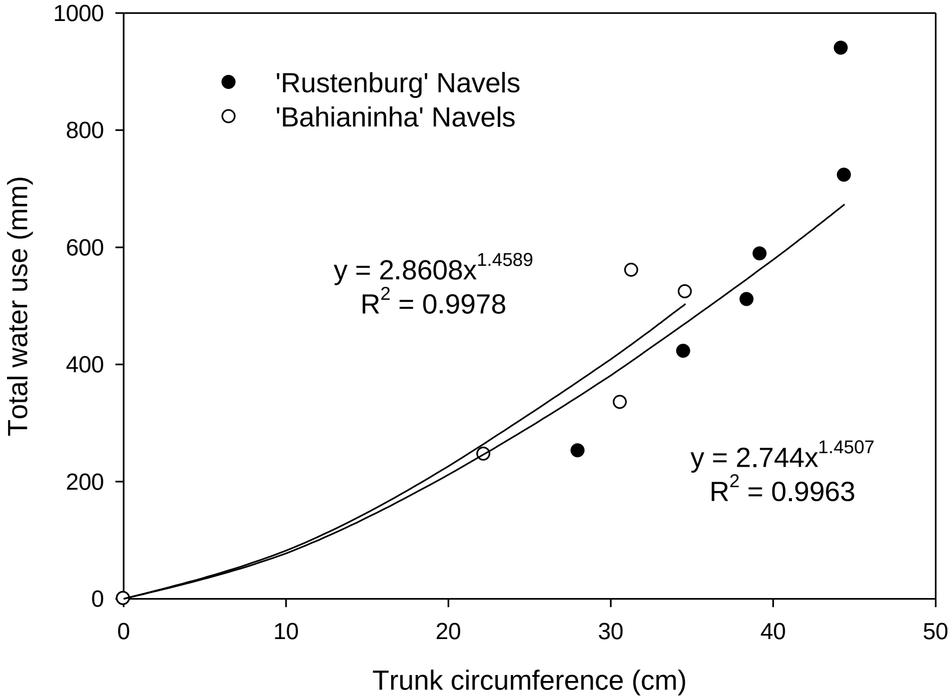

Figure 3.1. Relationship between trunk circumference and seasonal water use for the 'Bahianinha' and 'Rustenburg' Navel orchards

3.2.3 Reference evapotranspiration

Weather variables required for the determination of reference evapotranspiration (ET_o) were recorded using an automatic weather stations (AWS) installed at both sites. The weather variables that were recorded included wind speed, solar radiation, temperature, relative humidity and rainfall. The AWS at Groblersdal was located on an open stretch of mown, rain-fed grass and was 50 m west of natural vegetation, which consisted of sparse trees (2-3 m tall) and grasslands. There were buildings to the east, within 130 m of the AWS, and irrigated orchards within 300 m to the north. Under these fairly dry conditions, reference evapotranspiration (ET_o) is likely to be slightly overestimated, as compared to the reference surface (Allen, 2008). This is as a result of high VPD that occurs over the equilibrium boundary layer over a dry surface as compared to a well water grass surface theorised by Allen *et al*. (1998). The AWS at Citrusdal was located on the site of a recently top-worked (1 m height), ridged and drip irrigated orchard, with a short ground cover consisting of grass and weeds. It was 20 m east of an irrigated orchard with a height of 3 m, which would have reduced wind speed and therefore ET_o is likely to be somewhat underestimated, as compared to standard conditions (Allen 2008).

Quality assessment and quality control of the data was performed according to the procedures described by Allen (2008). The “upper” measured values of solar radiation (R_S) fell routinely below the clear-sky short wave radiation (R_{SO}) curve and R_S measurements were therefore adjusted upwards based on the average value of R_S/R_{SO} on clear days (Allen 2008).

Daily ET_o was determined using the FAO-56 Penman-Monteith equation following Allen *et al.* (1998):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_a + 273} u_2 (VPD)}{\Delta + \gamma(1 + 0.34 u_2)} \qquad \textit{Equation 3.1}$$

where ET_o is reference evapotranspiration (mm day^{-1}), R_n is net radiation at the crop surface (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), T_a is mean daily air temperature at 2 m height (°C), u_2 is wind speed at 2 m height (m s^{-1}), VPD is water vapour pressure deficit (kPa), Δ is slope of the vapour pressure curve (kPa °C^{-1}) and γ is the psychrometric constant (kPa °C^{-1}).

3.2.4 Determination of transpiration (K_t) crop coefficients

According to Villalobos *et al.* (2013) the basal coefficient of Allen *et al.* (1998) includes some soil evaporation which makes it difficult to separate the two components of ET_c effectively. An equivalent of the basal crop coefficient, termed the transpiration coefficient (K_t) as suggested by Villalobos *et al*. (2013), was determined from measured tree transpiration and ET_o as follows:

$$K_t = \frac{T}{ET_o} \qquad \textit{Equation 3.2}$$

where K_t is the basal crop coefficient and T is transpiration estimated from sap flow measurements. Monthly crop coefficients were calculated from monthly totals of measured daily orchard transpiration and ET_o. Monthly crop coefficients were calculated as citrus is an evergreen crop and significant changes in canopy size do not occur on a weekly basis.

3.3 Results and discussion

3.3.1 Measurement of long-term transpiration

Measured transpiration rates in the three orchards showed large day to day variations, which were largely determined by changes in atmospheric evaporative demand, defined in terms of ET_o (Figure 3.2). At Groblersdal the recorded ET_o in the 2008/9 season ranged from 0.93 mm day^{-1} to 8.04 mm day^{-1}. Transpiration in the 'Delta' Valencia orchard on the days when minimum and maximum ET_o were measured were 0.24 and 1.92 mm day^{-1} respectively. ET_o in the 2009/10 season ranged from 0.71 mm day^{-1} to 7.93 mm day^{-1}. Transpiration of 'Bahianinha' Navel orange trees on the days with minimum and maximum ET_o were 0.08 and 1.63 mm day^{-1}, respectively. ET_o in the 2010/11 season at Citrusdal ranged from 0.59 to 9.58 mm day^{-1} and; transpiration rates measured in the 'Rustenburg' Navel orchard on those respective days were 0.26 and 2.16 mm day^{-1}. Maximum transpiration rates recorded in all the orchards were not on days with the maximum ET_o.

Differences in transpiration measured in the orchards become more evident when the average rates for the different seasons (i.e. summer and winter) are considered (Table 3.2). Similar seasonal averages have also been calculated by other scientists (Moreshet and Green, 1983; García Petillo and Castel, 2007) for easy comparison with other data. Transpiration rates were generally higher in the 'Delta' Valencia orchard than in the 'Bahianinha' Navel orchard despite the close similarities in the atmospheric evaporative demand. This was largely attributable to the fact that the 'Delta' Valencia trees were bigger in size as compared to the 'Bahianinha' Navel trees. Furthermore, although higher atmospheric evaporative demands were observed in Citrusdal during the summer months (winter rainfall region), the 'Rustenburg' Navels did not use proportionally more water as compared to the 'Delta' Valencia orchard in Groblersdal (summer rainfall region), even though canopy size was similar. This has previously been noted by Kaufmann (1977), who observed that although evaporative demand was much higher under Arizona desert conditions, as compared to the humid conditions in Florida, citrus transpiration was very similar in summer in these two regions.

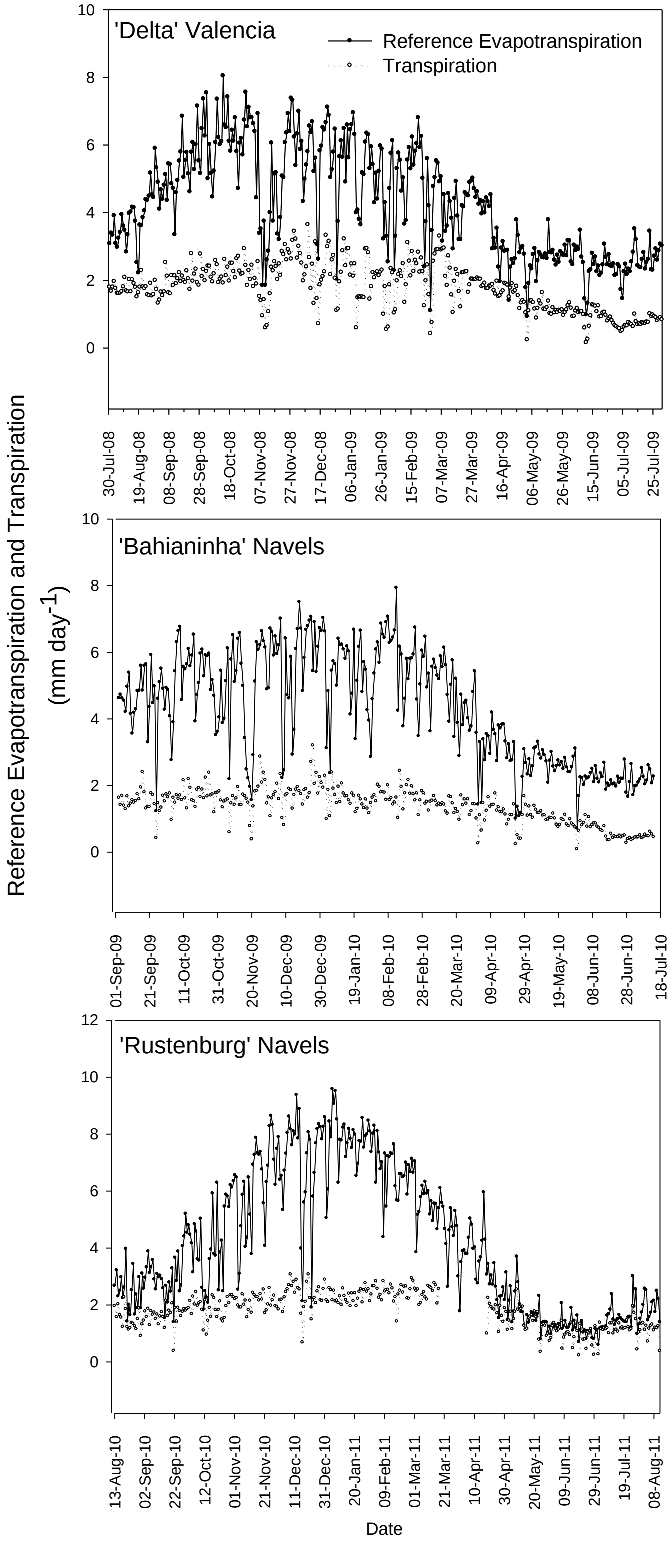

Figure 3.2. Daily transpiration and reference evapotranspiration determined in the 'Delta' Valencia, 'Bahianinha' and 'Rustenburg' Navel orchards.

Table 3.2. Average daily transpiration (T) and reference evapotranspiration (ET_o) for the summer and winter seasons in the three orchards.

Orchard	**T (mm day^{-1})**		**ET_o (mm day^{-1})**	
	Summer	**Winter**	**Summer**	**Winter**
‘Delta’ Valencia	2.30	1.16	5.75	2.57
‘Bahianinha’ Navel	1.90	0.65	6.09	2.53
‘Rustenburg’ Navels	2.26	2.08	6.42	1.62

Published work on seasonal water use of citrus orchards under South African conditions is available in the form of classic work done over two decades ago – a knowledge gap that prompted this study. Transpiration of a basin-irrigated 15-year old Valencia orchard measured by Green and Moreshet (1979) in weighing lysimeters ranged from 1.9 to 5.8 mm day^{-1}, with an average of 2 mm day^{-1} in winter and 4.97 mm day^{-1} in summer. The reference evapotranspiration measured using a class ‘A’ pan during the same period ranged between 2.5 and 7.6 mm day^{-1}, which is very similar to the environment in which this study was conducted. The seasonal transpiration figures were higher than the values in the current study partly because the trees were older and transpiration (mm) was calculated from the wetted area, instead of the area allocated to the tree. If these values are normalised using the area allocated to each tree, transpiration would range from 0.69 to 1.73 mm day^{-1} which is comparable to what was established in this study.

Daily transpiration measured in the three citrus orchards was within the range of ET_c (0.7 to 8.5 mm day^{-1}) reported in citrus tree species across the different growing regions of the world (García Petillo and Castel, 2007; Carr, 2012). However, there are few studies in which long-term transpiration of citrus orchards was measured using sap flow techniques in other regions that can be compared with this study. Transpiration rates measured in this study were lower than 4 mm day^{-1} in summer and 1 mm day^{-1} in winter reported by Rana *et al*. (2005) under Mediterranean conditions. The difference can most likely be ascribed to the manner in which transpiration volumes (L) are converted to mm, as described above. Rana *et al*. (2005) used the base of the tree crown to convert L to mm day^{-1}, whilst in this study the area allocated to each tree was used. Consoli and Papa (2013) also measured transpiration rates greater (0.5 to 6 mm day^{-1}) in semi-arid Mediterranean conditions than what was observed in this study likely because the trees were older and had a larger canopy (LAI ranging from 4.0 to 4.7) than those in this study.

Besides canopy size, an additional factor which may have contributed to the lower transpiration in the ‘Delta’ Valencia and ‘Bahianinha’ orchards used in this study than other orchards (including the ‘Rustenburg’ Navel orchard reported here), is the lower than average yields attained during the monitoring periods. The yields for the ‘Delta’ Valencia and ‘Bahianinha’ orchards of 28 and 15 t ha^{-1}, respectively, were considerably lower than the average yields for these orchards and much lower than the 75 t ha^{-1} recorded in ‘Rustenburg’ Navel orchard. There are reports of crop load impacting gaseous exchange (Syvertsen *et al*., 2003), as well as sap flow rates (Yonemoto *et al*., 2004), with lower crop yields having a negative feedback on photosynthesis and stomatal conductance, through carbohydrate accumulation in leaves. Differences in transpiration between Valencia and Navel trees may be due to different varietal, as well as the rootstock-scion combinations as reported previously (Yonemoto *et al*., 2004; Rodríguez-Gamir *et al*., 2010). However, despite all of these factors transpiration rates measured in this study are comparable to 0.4 to 2.3 mm day^{-1} that was reported by Marin and Angelocci (2011) in Southern Brazil, and 0.1 to 2.5 mm day^{-1} reported by Villalobos *et al*. (2013) in East and South Spain. It is therefore evident that citrus transpiration, on both a daily and seasonal basis, varies quite dramatically across the different growing regions of the world.

Transpiration was measured for periods of 364 days in the ‘Delta’ Valencia, 301 days in the ‘Bahianinha’ Navels and 365 days in the ‘Rustenburg’ Navels. Total transpiration for the measurement periods were 682 mm, 468 mm and 672 mm in the ‘Delta’ Valencia, ‘Bahianinha’ and ‘Rustenburg’ Navel orchards, respectively (Table 3.3). The total rainfall and irrigation volumes recorded for each orchard also shown in Table 3.3 exceeded transpiration suggesting that the trees were not water stressed. Irrigation management was assumed to be very good especially given the fact that these were the best growers producing export quality citrus. Rana *et al*. (2005) measured a seasonal transpiration totalling 766 mm using sap flow, which is higher than what was recorded in the 'Delta' Valencia orchard of similar age. Although cumulative transpiration could not be ascertained in the cases of either Marin and Angelocci (2011) or Villalobos *et al*. (2013) the close similarity of the daily magnitudes would most likely translate to the same effect on a seasonal basis. Total crop evapotranspiration, including evaporation in citrus orchards, has been estimated to be in the range of 767 mm yr^{-1} in Uruguay (García Petillo and Castel, 2007) to over 1400 mm yr^{-1} in Florida USA (Fares *et al*., 2008).

Table 3.3. Accumulated reference evapotranspiration (ET_o), rainfall, irrigation and transpiration for the measurement periods in each orchard.

Accumulated water (mm)	**'Delta' Valencia**	**'Bahianinha' Navel**	**'Rustenburg' Navels**
ET_o	1668	1423	1528
Rainfall	579	518	203
Irrigation	925	261	600
Transpiration	682	468	672

3.3.2 Determination of transpiration crop coefficients (K_t)

There was a lot of variation in the day-to-day K_t coefficients determined in the three orchards (Figure 3.3). The ranges for the K_t values determined were 0.14-0.78 in the 'Delta' Valencia orchard, 0.12-0.59 in the 'Bahianinha' Navel orchard and 0.22-1.21 in the 'Rustenburg' Navel orchard. Differences in the K_t values can be observed when average monthly K_t (Figure 3.4) and seasonal K_t (Table 3.4) values were determined. The monthly K_t coefficients were fairly constant in both summer and winter for the orchards at Groblersdal, which is in agreement with other reports in citrus (e.g., Kalma and Stanhill, 1969; Green and Moreshet, 1979; Allen *et al*., 1998). The K_t values established for the 'Rustenburg' Navels are significantly higher in winter than what was observed during the summer. Similar trends were reported by García Petillo and Castel (2007) in Uruguay and Villalobos *et al*. (2013) in Spain.

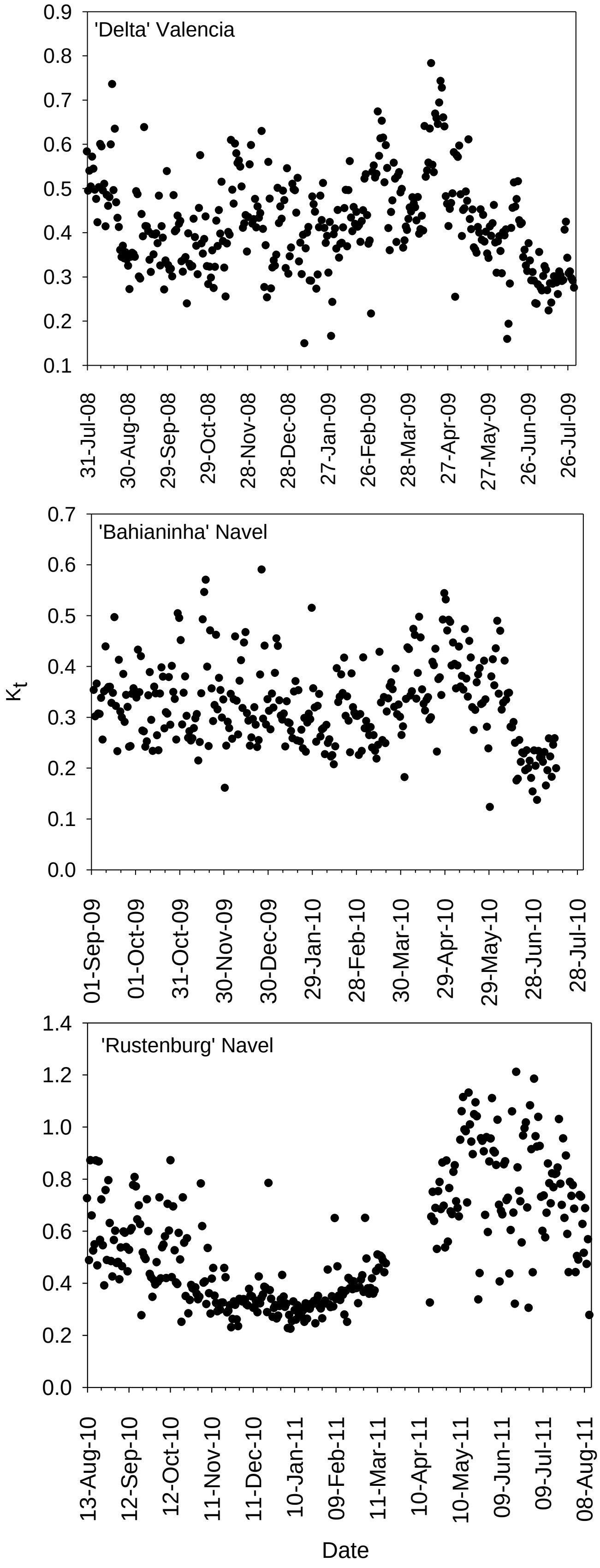

Figure 3.3. Transpiration coefficients (K_t) determined for the ‘Delta’ Valencia, ‘Bahianinha’ Navel and ‘Rustenburg’ Navel orchards.

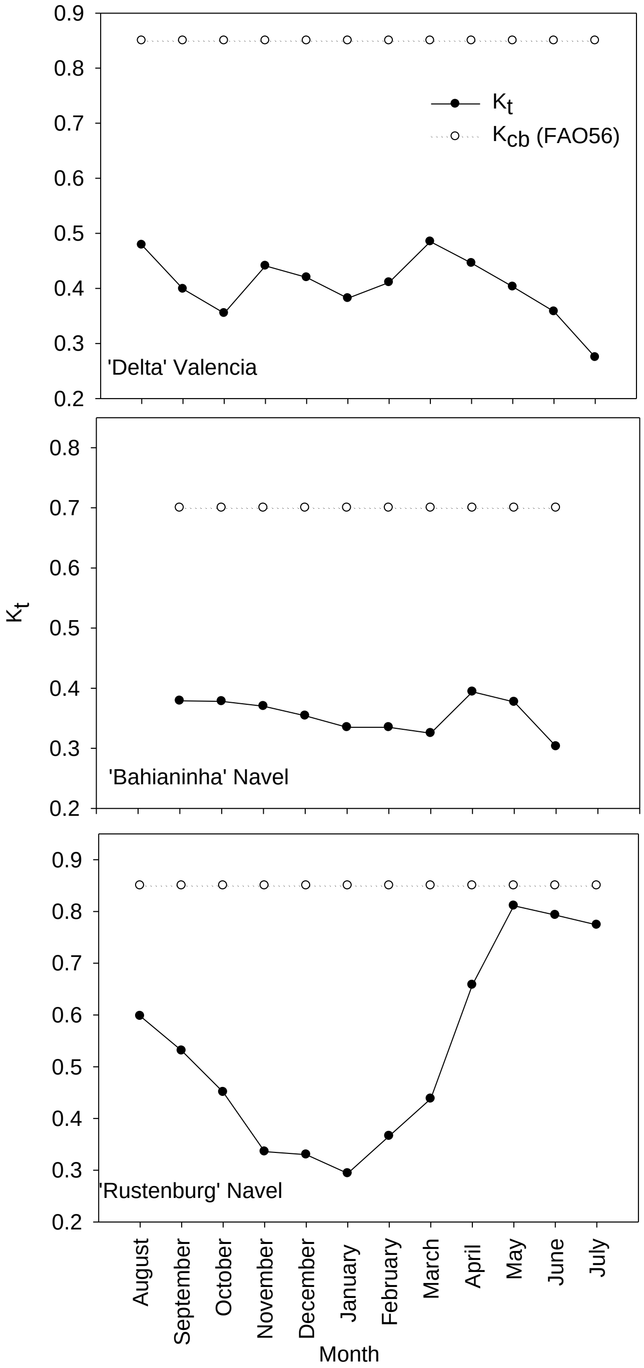

Figure 3.4. Average monthly transpiration coefficients (K_t) for the three orchards. Also shown are the FAO-56 standardised basal crop coefficients (K_{cb} FAO-56) for a citrus orchard with 70 % canopy cover (‘Delta’ and ‘Rustenburg’ orchards) and 50 % ground cover (‘Bahianinha’ orchard), all with no active ground cover, as given by Allen and Pereira (2009).

Table 3.4. Average transpiration crop coefficients (K_t) and water vapour pressure deficit (VPD) for the summer and winter seasons in the three orchards.

Orchard	**K_t**		**VPD (kPa)**	
	Summer	**Winter**	**Summer**	**Winter**
‘Delta’ Valencia	0.43	0.38	1.37	1.16
‘Bahianinha’ Navel	0.35	0.28	1.47	0.98
‘Rustenburg’ Navel	0.31	0.71	2.24	0.74

The most obvious difference in K_t values between orchards was found in the winter months, where values were considerably higher in the winter rainfall region, which is most likely attributable to the lower average vapour pressure deficit (VPD) (Table 3.4) and higher average transpiration rates at this time in this region (Table 3.2). Kriedemann and Barrs (1981) and Oguntunde *et al*. (2007) both reported that VPD is the dominant regulator of transpiration in citrus, when trees are well watered, with transpiration decreasing with an increase in VPD. The lower VPD was also reflected in lower ET_o in winter (Table 3.2) in the winter rainfall region than in the summer rainfall region.

A logical explanation for the trend of K_t values in the three orchards is that as ET_o increases during the summer months, tree transpiration does not increase at the same rate. Figure 3.2 suggests that the transpiration measured in both orchards does not always increase in proportion to the increase in ET_o. This suggests that there is a maximum transpiration rate for these citrus orchards, which is reached when ET_o exceeds approximately 5 mm day^{-1}. The maximum transpiration rate for the ‘Delta’ Valencia orchard is approximately 3 mm day^{-1}, in the ‘Bahianinha’ Navels approximately 2 mm day^{-1} and approximately 2.5 mm day^{-1} in the ‘Rustenburg’ Navels. The limited response to high ET_o values is more apparent when one considers the sharp responses that occur when ET_o falls to low values in the three orchards (Figure 3.2). The limited responses to high ET_o is despite the fact that trees are actively growing (in terms of flushes) and they have growing fruit on them. This is suggestive of the fact that citrus trees might only be able to supply a certain maximum amount of water to the canopy, irrespective of the atmospheric demand, as highlighted by Sinclair and Allen (1982).

Kriedemann and Barrs (1981) suggested that this could partly be explained by the low root:shoot ratio of citrus and the poorly developed root hairs that are not capable of supplying enough water to match atmospheric demand during the peak periods. Rodriguez-Gamir *et al*. (2010) working in young Valencia orange trees also confirmed that transpiration of citrus tree species is strongly influenced by the leaf to root ratio. This regulation mechanism has also been associated with stomatal closure under conditions of high atmospheric evaporative demand (Kaufmann, 1977; Kriedemann and Barrs 1981; Sinclair and Allen, 1982; García Petillo and Castel, 2007).

The K_t values obtained in the three orchards are much lower than the standardised values reported by Allen and Pereira (2009) (Figure 3.4). If standard values published by Allen *et al*. (1998) were to be applied over the measurement period in each orchard, transpiration would have been overestimated by 94 % in the ‘Delta’ Valencia orchard, 98 % in the ‘Bahianinha’ Navel orchard and 96 % in the ‘Rustenburg’ Navel orchard. The ranges of seasonal K_t coefficients in the three orchards compare very well to the range of 0.2-0.7 by Villalobos *et al.* (2013).

3.4 Conclusions

Average daily transpiration in the three orchards ranged from 0.77 mm day^{-1} to 2.26 mm day^{-1} depending on canopy size, season and climate (summer versus winter rainfall areas). Total seasonal transpiration for the two orchards in which measurements covered an entire production season, i.e. ‘Delta’ Valencia and ‘Rustenburg’ Navel orchards were 682 mm and 672 mm, respectively. Transpiration coefficients derived from the measured data were lower than the standardised values published in the FAO56. Differences in K_t values obtained amongst the three orchards, as well as compared to values from other growing regions, means that this kind of information is of significance to the commercial growers on whose farms the research was conducted. Such information is not always applicable and readily transferrable to many other regions within South Africa or across citrus growing regions of the world, or even for different seasons. This emphasizes the need to develop a relatively simple method for estimating site-specific crop coefficients, in order to improve water management. Sap flow-based measurements of transpiration obtained in this study present a valuable data set for developing models of citrus transpiration that can be used to extrapolate measured water use to other growing regions of the world.

Chapter 4: Estimation of transpiration crop coefficients from ground cover and height in citrus orchards

4.1 Introduction

Knowledge of crop water use is the fundamental basis for efficient irrigation water management strategies. The term irrigation water management encompasses activities such as irrigation systems planning, irrigation scheduling and issuing of water rights/permits. Measurements undertaken to gather information of crop water use are time consuming, expensive and require specialised expertise, which is not always available. The high variability between different orchards and the perennial nature of orchards exacerbates the difficulty in obtaining water use estimates for orchard crops (Hoffman *et al.*, 1982; Castel *et al*., 1987). Consequently a number of crop water use models have been developed which have proved very useful in extrapolating measured data and predicting crop water use under a range of conditions.

The use of the dual crop factor approach (Allen *et al*., 1998) has proved very useful in micro-irrigated orchards, with discontinuous canopies, as it allows the separate estimation of transpiration and evaporation. However, in tree crops, a linear relationship between the evapotranspiration from a short, smooth and uniform grass surface and a tall, very rough, clustered orchard canopy may not always hold true (Annandale and Stockle, 1994; Testi *et al*., 2004). This probably explains the large variation in K_t values determined among the three citrus orchards in this study (Chapter 3), as well as crop coefficients (K_c and K_{cb}) reported in other citrus orchards across the different growing regions of the world (see Table 1.3). This means that K_c values derived in one location may not be readily transferable to other locations, which limits their extrapolation to different climatic zones, with different orchard management practices.

In an attempt to make crop coefficients more transferrable between different orchards, Allen and Pereira (2009) developed a procedure for estimating crop coefficients where vegetation density and height varies between orchards. These authors found that under such conditions, K_c and basal crop coefficient (K_{cb}) values can be estimated more accurately by taking into account fraction of ground covered or shaded by the vegetation, the height of the vegetation and the degree of stomatal regulation under wet soil conditions. An adjustment can also be made for climate by taking into account the average relative humidity and wind speed of the climate, which accounts for the differences in roughness between the grass reference surface and the tall orchard canopy. According to the authors the leaf resistance term that accounts for stomatal regulation requires further investigation in order to improve the accuracy of the method in orchards. The aim of this chapter was to evaluate this procedure for the derivation of orchard specific K_t values in three citrus orchards in different climatic regions of South Africa (summer and winter rainfall regions), by comparing derived K_t values with actual K_t values determined from transpiration measurements using sap flow. It was hypothesized that a dynamic estimate of leaf resistance is needed to predict daily and seasonal changes of transpiration in citrus orchards.

4.2 Materials and Methods

The long-term transpiration measured in the ‘Delta’ Valencia, ‘Bahianinha’ and ‘Rustenburg’ Navel orchards was used together with weather data that was measured simultaneously at the site to determine transpiration crop coefficients (K_t). Transpiration crop coefficients, as suggested by Villalobos *et al*. (2013), were chosen as K_{cb} includes some evaporation when the soil surface is dry and only transpiration was measured in this study. Details of the three orchards and the measurement of transpiration are given in Section 2.2.4.1 and 3.2.2. Measurement of weather variables and determination of reference evapotranspiration (ET_o) were presented in Section 3.2.3.

4.2.1 Model description

Allen and Pereira (2009) published a method of estimating orchard specific crop coefficients from measurements of effective ground cover and tree height.

In drip-irrigated orchards the K_t coefficients, which correlate with transpiration of planted trees, can be expressed in terms of a density coefficient (K_d) as:

$$K_t = K_{c\,min} + K_{\mathrm{d}}(K_{\mathrm{t\,full}} - K_{c\,min})$$ *Equation 4.1*

where K_{t} is an approximation for transpiration crop coefficients for conditions represented by the density coefficient, K_{d}; $K_{\mathrm{t\,full}}$ is the transpiration coefficient during peak plant growth for conditions having nearly full ground cover (or LAI > 3) and $K_{\mathrm{c\,min}}$ is the minimum crop coefficient for bare soil. The $K_{\mathrm{c\,min}}$ was set to zero, as only transpiration from the trees measured using the heat ratio method sap flow technique was considered.

The basal crop coefficients calculated following this approach apply to standard conditions as stipulated in the FAO56 publication. As such it is recommended that crop coefficients be adjusted for climates with minimum relative humidity (RH_{min}) greater than or less than 45 % and/or with mean wind speeds at 2 m over grass (u_2) that are more or less than 2.0 m s^{-1}. According to Allen *et al.* (1998) for large stand size (greater than about 500 m^2), $K_{\mathrm{t\,full}}$ for use with ET_o can be approximated as a function of mean plant height and adjusted for climate as:

$$K_{\mathrm{t\,full}} = F_{\mathrm{r}}\left(\min(1.0 + 0.1h, 1.20) + [0.04(u_2 - 2) - 0.004(RH_{\min} - 45)]\left(\frac{h}{3}\right)^{0.3}\right)$$

Equation 4.2

where F_r [0-1] is a relative adjustment factor for stomatal control and h is the mean maximum plant height (m) during the mid-season period, or full cover period. Parameter F_r applies a downward adjustment ($F_r \leq 1.0$) if the vegetation exhibits more stomatal control on transpiration than is typical of most annual agricultural crops, a situation that is typical of citrus (Kriedemann and Barrs, 1981).

Allen and Pereira (2009) suggested the following calculation for F_r for full cover vegetation, based on the FAO Penman-Monteith equation and assuming full cover conditions:

$$F_r \approx \frac{\Delta + \gamma(1 + 0.34u_2)}{\Delta + \gamma\left(1 + 0.34u_2\frac{r_l}{100}\right)}$$ *Equation 4.3*

where r_l is the mean leaf resistance (s m^{-1}); Δ is the slope of the saturation vapour pressure versus air temperature curve (kPa $°C^{-1}$) and γ is the psychrometric constant (kPa $°C^{-1}$).

The density factor (K_d) was determined according to Allen and Pereira (2009) as follows:

$$K_\mathrm{d} = \min\left(1, M_L f_{\mathrm{c\ eff}}, f_{\mathrm{c\ eff}}^{\left(\frac{1}{1+h}\right)}\right) \qquad \textit{Equation 4.4}$$

where f_{ceff} is the effective fraction of ground covered or shaded by vegetation [0.01-1] near solar noon, M_L is a multiplier of f_{ceff} describing the effect of canopy density on shading and on maximum relative evapotranspiration per fraction of ground shaded [1.5-2.0], with a value of 1.5 recommended for citrus (Allen and Pereirra, 2009).

Effective fraction cover was calculated as the ratio of tree canopy width to inter-row spacing or the ratio of ground shaded area by the crop at solar noon to the total area available to the tree, following Allen *et al*. (1998) in the ‘Delta’ Valencia orchard with a north-south orientation. In the ‘Bahianinha’ and ‘Rustenburg’ Navel orchards, provision had to be made for row orientation. In these orchards, $f_{\mathrm{c\ eff}}$ was calculated according to Allen *et al*. (1998) as follows:

$$f_{c\ \mathrm{eff}} = \frac{fc}{\sin(\beta)} \leq 1 \qquad \textit{Equation 4.5}$$

where f_c is the observed fraction of soil surface that is covered by vegetation as seen from directly overhead. $f_{c\ \mathrm{eff}}$ is usually calculated at solar noon, such that β (mean elevation angle of the sun above the horizon during the period of maximum evapotranspiration) can be calculated as:

$$\beta = \arcsin[\sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)] \qquad \textit{Equation 4. 6}$$

where φ is latitude and δ is solar declination in radians. The average $f_{c\ \mathrm{eff}}$ values determined during the measurement period were 0.63, 0.61 and 0.88 for the ‘Delta’ Valencia, ‘Bahianinha’ and ‘Rustenburg’ Navel orchards, respectively.

4.2.2 Model calibration

Model calibration consisted of establishing parameters which provided for minimal differences from measured K_t values on a monthly basis in all the orchards. Initially the parameters recommended by Allen and Pereira (2009) for a generic citrus orchard were used to estimate K_t values in the study orchards. Average monthly values of r_l were then estimated by inverting Equation 4.4, after solving for F_r by inverting Equation 4.3, using known monthly values of $K_{t\ full}$. Average monthly r_l values were determined based on the daily values and used to estimate K_t. Measurements of leaf resistance in the 'Rustenburg' Navel orchard were performed with a SC-1 leaf porometer (Decagon Device Inc, Pullman, WA, USA) on 5 sunlit leaves per tree instrumented with sap flow equipment. Measurements were made every hour from sunrise to sunset for a minimum of 3 days and an average was obtained for each measurement period.

4.2.3 Model validation

Monthly K_t coefficients developed using the different approaches were used to estimate transpiration in each orchard. The performance of the model was tested by comparing the predicted and observed transpiration values. The statistical parameters used to test the goodness of fit for the model were the coefficient of determination (R^2), root mean square error (RMSE) and mean absolute error (MAE) (de Jager, 1994). The total error of estimating water use over the season was also considered.

4.3 Results and discussion

Transpiration coefficients determined using the parameters given by Allen and Pereira (2009) ($K_{t\ \text{Allen and Pereira}}$) were higher than the measured K_t values in the three orchards (Figure 4.1). The overestimation of transpiration coefficients and crop water use using the given citrus parameters is likely a reflection of the greater stomatal control of transpiration in citrus than in most other crops, which is attributed to high resistances to water transport within the plant (van Bavel *et al*. 1967; Kriedemann and Barrs 1981; Sinclair and Allen 1982). Whilst Allen and Pereira (2009) account for this by including their F_r parameter, which is used as a downward adjustment on crop coefficients for crops which exhibit more stomatal control on transpiration than most other agricultural crops, the r_l value of 420 s m^{-1} suggested by the authors may be too low, especially during hot summer months, when VPD increases.

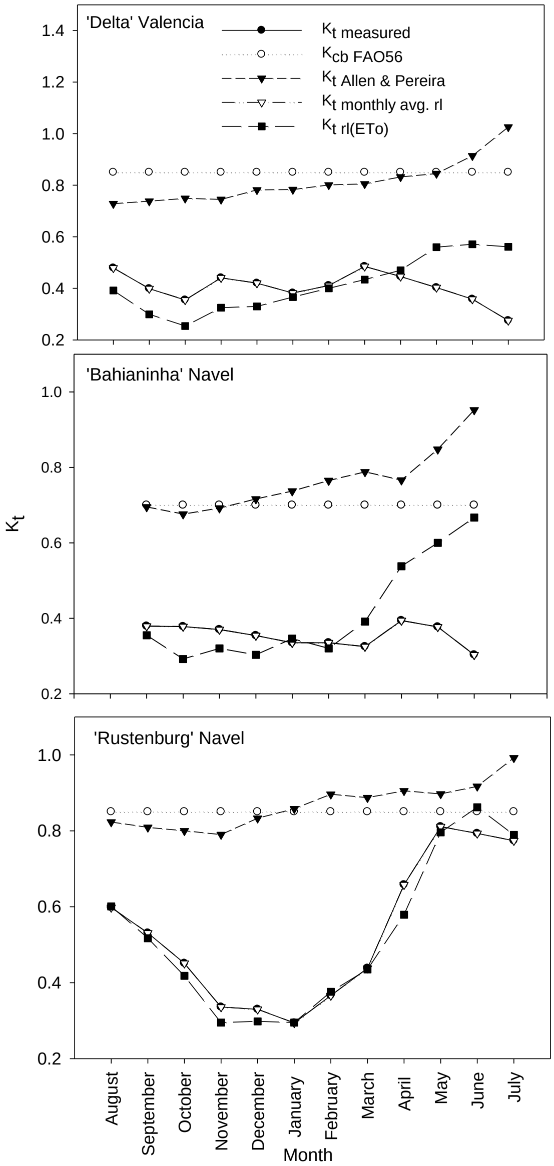

Figure 4.1. Derived monthly transpiration crop coefficients (K_t) for the three orchards. Transpiration crop coefficients were determined using measured transpiration ($K_{t\ \mathrm{measured}}$), the method described in Allen and Pereira (2009) using the parameters given for citrus ($K_{t\ \mathrm{Allen\ and\ Pereira}}$), using estimates of monthly average rl values from transpiration data ($K_{t\ \mathrm{monthly\ avg.\ rl}}$) and using r_l estimated from the relationship with ET_o ($K_t\ r_l$ (ET_o)). Also shown are FAO-56 standardised basal crop coefficients ($K_{cb\ FAO\text{-}56}$) for a citrus orchard with 70% canopy cover (‘Delta’ and ‘Rustenburg’ orchards) and 50% ground cover (‘Bahianinha’ orchard), all with no active ground cover, as given by Allen and Pereira (2009)

More appropriate values for r_l were therefore estimated following a procedure recommended by Allen and Pereira (2009), using measured transpiration data. Following their approach r_l values were estimated by inverting Equation 4.3, after solving for F_r by inverting Equation 4.2 using known values of $K_{t\ \mathrm{full}}$. Monthly, $K_{t\ \mathrm{full}}$ values were obtained by scaling measured monthly K_t values with the appropriate K_d value and were used to calculate a mean monthly r_l (Figure 4.2). There was a very good agreement between measured K_t values ($K_{t\ \mathrm{measured}}$) estimated using the calculated r_l values ($K_{t\ \mathrm{monthly\ avg.}\ rl}$) (Figure 4.1) with the two plots sitting perfectly on top of one another. The perfect similarity between the measured and estimated K_t values is expected since there is a high level of circularity involved in the estimation process.

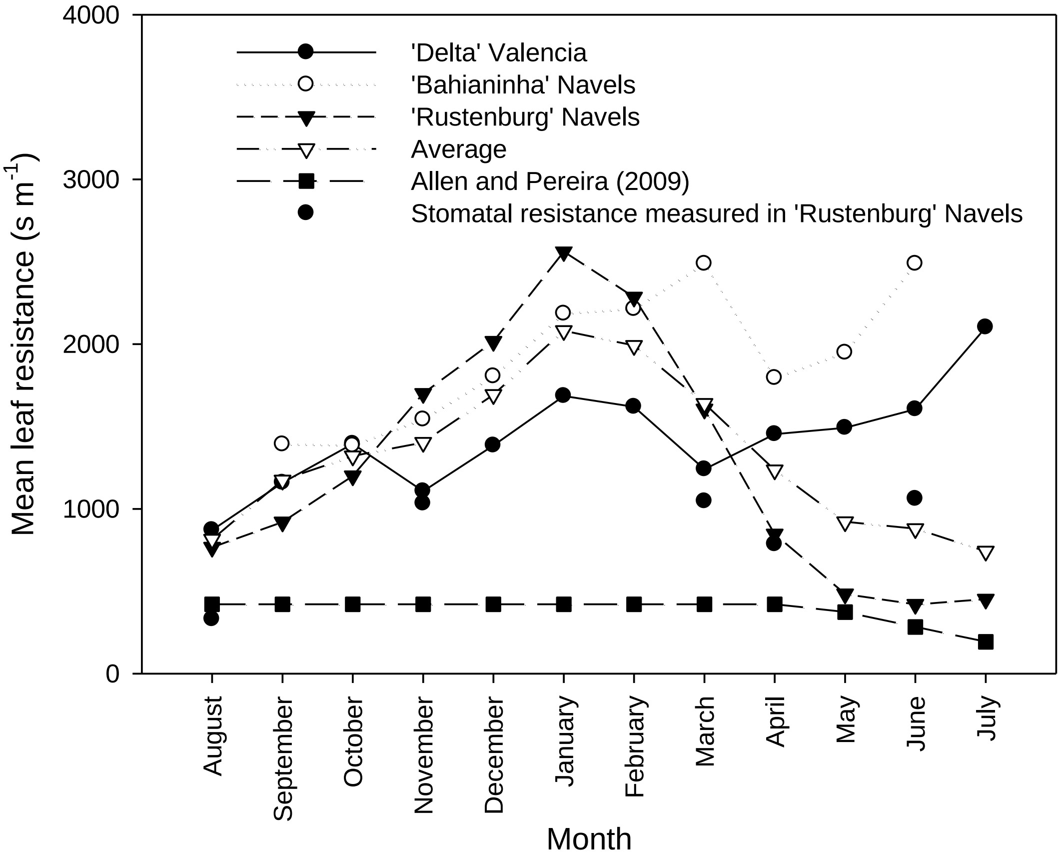

Figure 4.2. Monthly mean leaf resistances calculated following the procedure outlined by Allen and Pereira (2009), compared with the values suggested by Allen and Pereira (2009) for citrus and daily stomatal resistance measure in the 'Rustenburg' Navel orchard in Citrusdal.

It is the magnitude and trend of r_l values estimated following this method suggested by Allen and Pereira (2009) that are of interest in as far as this result is concerned. The r_l values estimated in the three orchards ranged from 419 to 2 694 s m^{-1}, which is higher than the values suggested by Allen and Pereira (2009). Although Allen and Pereira (2009) emphasised that the values of r_l obtained using this procedure should only be used in the estimation of F_r, these values were not too dissimilar to published stomatal resistance data for citrus. Stomatal resistances in Shamouti orange varied between 500 and 2000 s m^{-1} (Cohen and Cohen 1983); in young Navel orange trees they varied between 200 to 8280 s m^{-1} (Dzikiti *et al.,* 2007) and in oranges 295 and 830 s m^{-1} (Pérez-Pérez *et al.*, 2008). The r_l values in Figure 4.2 may therefore be reasonable, and may not be heavily biased by the procedure outlined by Allen and Pereira (2009), indicating that measured leaf resistances could potentially be used to derive crop coefficients. However, average daily stomatal resistance, measured in the various citrus orchards in Citrusdal, was between 300 and 1 000 s m^{-1} (Figure 4.2), which was considerably lower than the r_l values of between 530 and 2,694 s m^{-1} for this period, but generally the trend was very similar. Contrary to a constant value of 420 s m^{-1}, suggested by Allen and Pereira (2009), the average r_l values increased during the summer months in all three orchards. The increase in r_l values during the summer months, which are characterised by high atmospheric evaporative demands, is evidence of strong stomatal control of transpiration in citrus.

The accurate estimation of K_t values and subsequent prediction of transpiration in the three orchards using the method of Allen and Pereira (2009) hinged on the back-calculation of r_l. It is the estimation of mean r_l, without measured transpiration, that really hinders the ease with which this approach can be used to accurately estimate crop coefficients for different citrus orchards. An independent methodology for estimating this parameter was therefore sought by the parameterization of a relationship between r_l and routinely measured weather variables such as relative humidity, VPD or ET_o. A simple reproducible relationship with an excellent coefficient of determination ($R^2 = 0.97$) was found for the Citrusdal site during the 2010/11 season between r_l and ET_o (Figure 4.3).

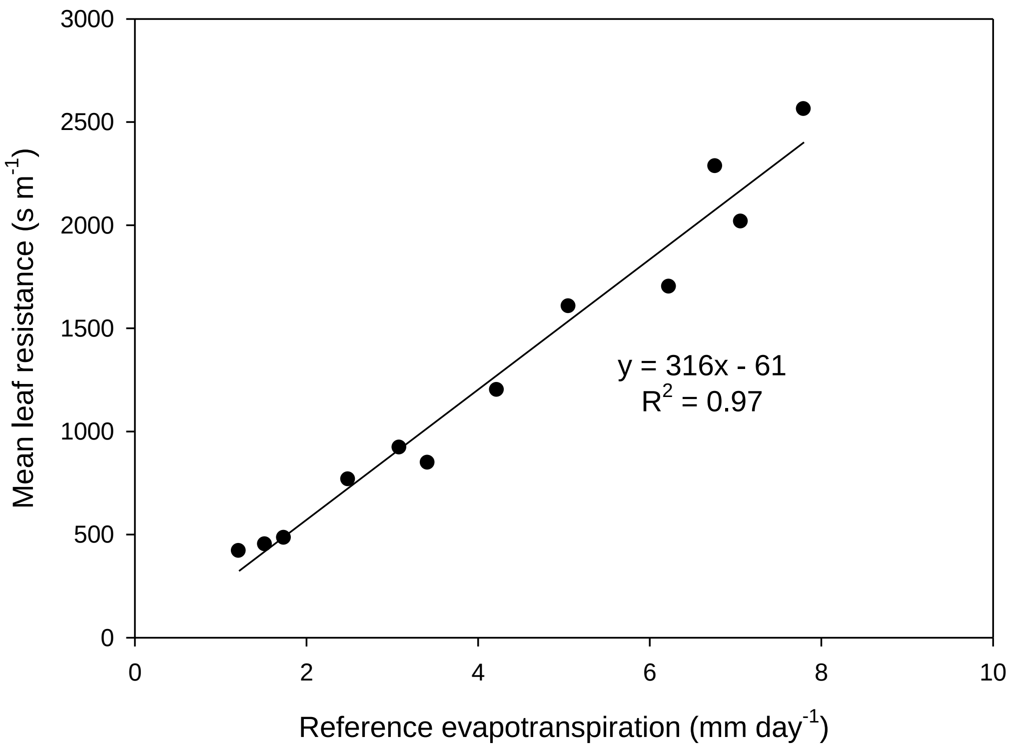

Figure 4.3. Relationship between reference evapotranspiration (ET_o) and mean leaf resistance for the 'Rustenburg' Navel orchard

Monthly transpiration estimates obtained in all the orchards, using the relationship between ET_o and r_l, are presented in Figure 4.4. In the 'Delta' Valencia and 'Bahianinha' orchards, transpiration was underestimated at the beginning of the season and overestimated at the end of the season. The underestimation at the start of the season was more pronounced in the 'Delta' Valencia orchard, whilst the overestimation at the end of the season was more pronounced in the 'Bahianinha' Navel orchard. In the 'Rustenburg' Navel orchard, in the 2010/11 season, good estimates of water use were obtained throughout the season. The performance of the model, as determined by statistical parameters, was good in the orchard in Citrusdal, as the MAE was <20 % and *D* greater than 0.8. It did not, however, perform as well in the orchards in the summer rainfall region with an MAE of 23 and 24 % and *D* of 0.55 and 0.63.

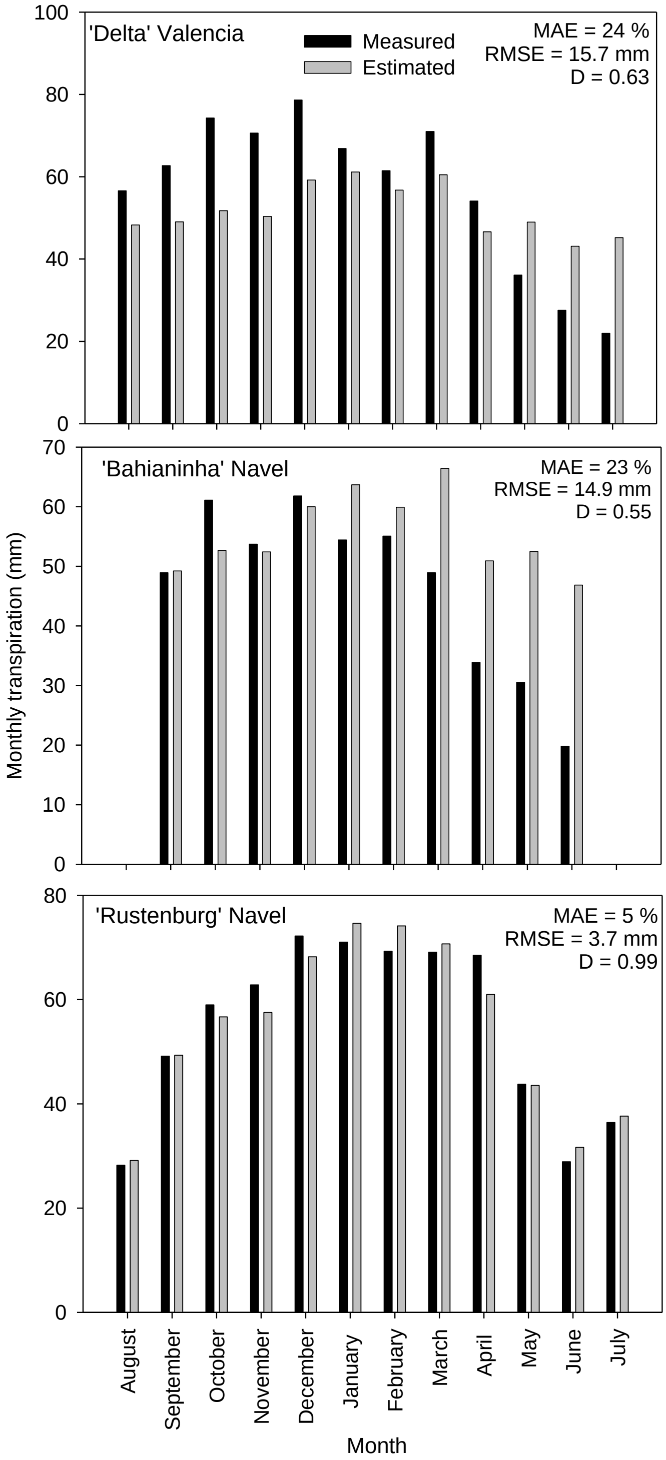

Figure 4.4. Monthly measured and estimated transpiration using K_t values derived from mean leaf resistance, estimated from the relationship between reference evapotranspiration and mean leaf resistance in the three orchards. Statistical parameters shown include mean absolute error (MAE), root of the mean square error (RMSE) and index of agreement (D)

Cumulative transpiration for the measurement periods was underestimated by 0.1 % in the ‘Rustenburg’ Navels, and overestimated by 9 % in the ‘Delta’ Valencia orchard and 18 % in the ‘Bahianinha’ Navel orchard when using the estimated K_t values ($K_{t\ rl\ (ETo)}$ (Figure 4.5). Given the empirical nature, the performance was fairly good, especially compared to using the parameters stipulated by Allen and Pereira (2009) for citrus. If derived K_t values using the parameters stipulated by Allen and Pereira (2009), were to be applied over the measurement periods, they would have resulted in a 139 % over-estimation of transpiration in the ‘Delta’ Valencia orchard, a 172 % over-estimation in the ‘Bahianinha’ Navel orchard and a 95 % over-estimation in the ‘Rustenburg’ Navel orchard (Figure 4.5).

The accuracy of using the method of Allen and Pereira (2009) coupled with a relationship between r_l and ET_o provided seasonal estimates within an acceptable error range. This method could therefore be used for irrigation planning purposes and for the issuing of water permits. However, the inability to predict water use accurately on a monthly basis for most of the season limits the use of this procedure for irrigation scheduling, which will require more reliable estimates of r_l. This is not unexpected, as stomatal conductance is known to be regulated by a number of factors, which includes solar irradiance, ambient CO_2 concentration, leaf to air water vapour pressure deficit, leaf temperature, leaf water status and hydraulic limitations to leaf water supply (Jarvis 1976; Sperry *et al*., 2002), and it is usually a combination of these factors that determines stomatal conductance. This creates uncertainty when only using climatic data to predict stomatal responses. In this respect, reduced sink activity or accumulation of carbohydrates in leaves could also lead to decreases in stomatal conductance (Iglesias *et al*., 2002; Syvertsen *et al*., 2003; Duan *et al*. 2008), which may be a contributing factor to the increased leaf resistance in the Groblersdal orchards at the end of the season, as both these orchards experienced lower than average yields during the monitoring period. As a result of the reduced number of fruit on trees, and therefore sink strength, feedback inhibition of photosynthesis through carbohydrate accumulation in leaves may have occurred. Although Nebauer *et al*. (2013) attributed the lack of difference in photosynthetic rates between high and low-yielding citrus trees, in alternate bearing cycles, to an unsaturable sink in the root system of perennial fruit trees, their evidence is not compelling enough to suggest that changes in fruit load have no impact on overall tree sink demand and canopy conductance. Further research is therefore required to determine the relationship between yield and water use, as this has implications for predicting seasonal water use. The solution for better prediction of leaf resistances may be to use more mechanistic models which can predict canopy conductance based on canopy size, environmental variables and sink strength or potential yield. Similar approaches have been undertaken by Oguntunde *et al*. (2007) and Villalobos *et al*. (2009, 2013) and have shown some promise, but the ability of these models to predict citrus water use need to be verified in orchards with different canopy sizes and in different climatic regions.

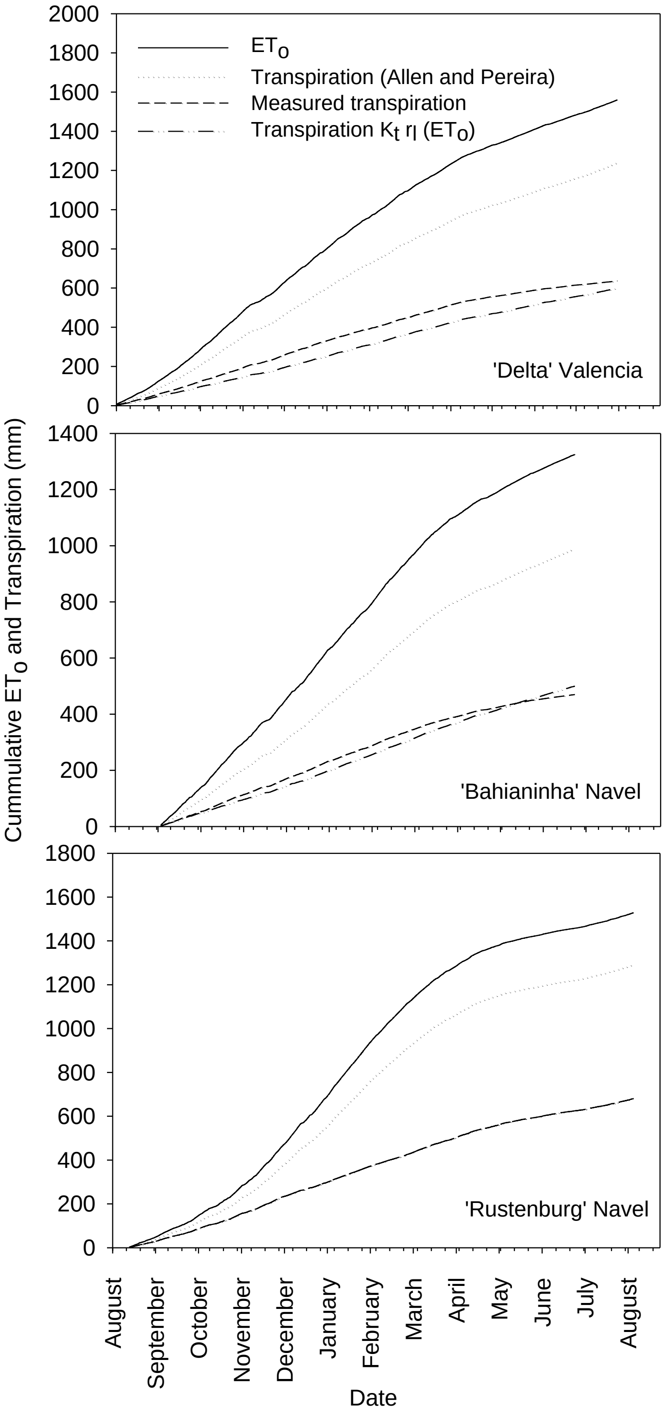

Figure 4.5. Cumulative ET_o, measured transpiration and transpiration estimated from the derived crop coefficients in the ‘Delta’ Valencia orange orchard (1 August 2008 to 31 July 2009), the ‘Bahianinha’ Navel orchard (3 September 2009 to 30 June 2010) and the ‘Rustenburg Navel orchard (13 August 2010 to 12 August 2011)

4.4 Conclusions

The development of transpiration coefficients from ground cover and crop height published by Allen and Pereira (2009) was evaluated. Due to the greater stomatal control of transpiration in citrus than in most other crops, crop coefficients that are constant or are based on parameters that are constant are not suitable for accurate predictions of water use, as crop coefficient models assume atmospheric demand-limited conditions and transpiration in citrus is often water-supply limited, even in well-watered orchards. Good agreement between measured and predicted transpiration was obtained by using leaf resistances back-calculated from the measured transpiration coefficient values. A relationship between monthly reference evapotranspiration and mean leaf resistance provided a means of estimating a dynamic leaf resistance which gives crop coefficients with a reasonable degree of accuracy.

Chapter 5: Predicting transpiration of citrus orchards using the Penman-Monteith equation coupled with a Jarvis-type multiplication canopy conductance model

5.1 Introduction

Transpiration coefficients determined according to Allen and Pereira (2009), based on ground cover and crop height and using a dynamic estimate of leaf resistance, provided good seasonal estimates of transpiration, but could not provide reasonable monthly estimates throughout the season (Chapter 4). The leaf resistances calculated using the measured transpiration data were higher than that suggested by Allen and Pereira (2009) for citrus. This reiterates the strong stomatal control over transpiration that has been reported in citrus (Kriedemann and Barrs, 1981; Meyer and Green, 1981; Sinclair and Allen, 1982). A mechanistic approach that incorporates the intra-annual dynamics of canopy conductance may therefore hold the solution for improved modelling and/or simulation of citrus transpiration (Villalobos *et al*., 2013; Taylor *et al*., 2015).

When measurements of transpiration are available, the bulk canopy conductance of a vegetated surface can be obtained using the top-down approach by inversion of the Penman-Monteith equation (Baldocchi *et al*., 1991). Such data sets have been used to develop canopy conductance models, as a function of environmental variables, for predicting transpiration using the Penman-Monteith equation (e.g., Granier and Loustau 1994; Green and McNaughton 1997; Zhang *et al*., 1997; Oguntunde *et al*., 2007; Villalobos *et al*., 2009; Villalobos *et al*., 2013). Jarvis-type models, i.e. multiplicative models of similar form to that originally proposed by Jarvis (1976), have been parameterised using weather variables to model the variations in canopy conductance with satisfactory accuracy in a number fruit trees e.g., olives (Villalobos *et al*., 2000; Testi *et al*., 2006), cashew (Oguntunde and van de Giesen, 2005) and citrus (Cohen and Cohen, 1983; Oguntunde *et al*., 2007).

Besides being based on strong physiological relationships between stomatal responses and environmental variables, the other advantage of the Jarvis model (Jarvis, 1976) is that weather data available from a standard automatic weather station is used to predict canopy conductance. This approach therefore does not require any additional input data than what is required for the FAO56 approach. Whilst the use of the Penman-Monteith equation coupled with a Jarvis-type conductance model by Oguntunde *et al*. (2007) in citrus showed some promise, it was only evaluated for a short period of time in a single orchard. Whitley *et al*. (2009) showed that the Penman-Monteith equation coupled with the Jarvis model with a single set of parameters was able to accurately predict transpiration in a forest species over an annual cycle. The ability of this approach, to estimate long-term transpiration in citrus and its transferability amongst orchards with varying canopy sizes and in different climatic regions, still needs to be verified.

The aims of this study were to: (i) Use sap flow-based transpiration measurements to parameterise a Jarvis-type conductance model for inclusion in the Penman-Monteith equation for predicting long-term transpiration of citrus orchards and (ii) To test the transferability of the parameters of a Jarvis-type model obtained in an orchard in the summer rainfall area to predict transpiration in orchards situated in the summer and winter rainfall areas of South Africa. The hypothesis that a dynamic estimate of canopy conductance is needed to predict daily and seasonal changes of transpiration in citrus orchards was further tested.

5.2 Materials and methods

Long-term orchard transpiration and weather data measurements that were conducted in the ‘Delta’ Valencia, ‘Bahianinha’ and ‘Rustenburg’ Navel orchards were used in the modelling approach conducted in this chapter. Details of the measurement of long-term transpiration and weather parameters are given in Chapters 2 and 3. The weather parameters used included wind speed, solar radiation, air temperature and relative humidity.

5.2.1 Calculation of canopy conductance

Bulk canopy conductance (g_c) was calculated from transpiration measurements using the inversion of the following Penman-Monteith equation (Monteith and Unsworth, 1990):

$$\lambda E_c = \frac{\Delta(R_n - G) + \rho_a C_p g_a VPD}{\Delta + \gamma\left(1 + \frac{g_a}{g_c}\right)}$$ *Equation 5. 1*

where λ is the latent heat of vaporization of water (J kg^{-1}), E_c is canopy transpiration (kg m^{-2} s^{-1}), Δ is slope of the water vapour pressure curve versus temperature (kPa K^{-1}), R_n is net irradiance at the crop surface (W m^{-2}), G is soil heat flux (W m^{-2}), taken as 10 % of R_n, ρ_a is the density of dry air (kg m^{-3}), C_p is the specific heat capacity of the air (J kg^{-1} K^{-1}), VPD is saturation vapour pressure deficit (kPa), γ is the psychrometric constant (kPa K^{-1}), g_a is the aerodynamic conductance (m s^{-1}) and g_c is the canopy conductance (m s^{-1}). R_n was estimated from solar irradiance measured at the automatic weather stations according to Allen *et al*. (1998) using measurements of citrus reflection coefficient obtained using an albedometer in the 'Delta' Valencia orchard.

Leaf boundary conductance (g_a) was calculated from an empirical relation derived by Landsberg and Powell (1973), which accounts for the mutual sheltering of clustered leaves as:

$$g_a = 0.172 p^{-0.56} \left(\frac{u}{d}\right)^{0.5}$$ *Equation 5. 2*

where *d* is a characteristic leaf dimension, equal to 8 mm for citrus leaves (Dzikiti *et al*., 2011), *u* is the mean wind speed (m s^{-l}) across the leaf surface, and *p* is a measure of foliage density to wind given by the ratio of total leaf plane area to the area of the foliage projected onto a vertical plane. Leaf area was determined using a leaf area density of 2.5 m^2 m^{-3} and tree canopy volume was determined according to a cone shape following Annandale *et al*. (2003).

5.2.2 Modelling canopy conductance

Canopy conductance was modelled using a Jarvis-type multiplicative model (Jarvis 1976), similar to the one used by Oguntunde *et al*. (2007), on an hourly basis with weather data as follows:

$$g_{c,j} = g_{c\,max} f(S_R) f(VPD) f(T)$$ *Equation 5.3*

where $g_{c,j}$ is the canopy conductance predicted by the Jarvis model, $g_{c\,max}$ is the maximum canopy conductance (m s^{-1}), $f(S_R)$ is a function of solar radiation, $f(VPD)$ is a function of water vapour pressure deficit and $f(T_a)$ is a function of air temperature. The functions have values ranging between 0 and 1. A response function for soil water content has been included in the Jarvis-type model in some studies, particularly native forests (e.g. Whitley et al. 2008), but as the orchards in this study were well-irrigated this function was set to one. The control functions of air temperature and solar irradiance were similar to those of Oguntunde *et al*. (2007) and took the following forms:

$$f(S_R) = \frac{S_R}{R_m}\left(\frac{R_m+k_R}{S_R+k_R}\right) \qquad \textit{Equation 5. 4}$$

$$f(T_a) = \frac{(T_a-T_L)(T_H-T_a)^t}{(k_T-T_L)(T_H-k_T)} \qquad \textit{Equation 5.5}$$

$$t = \frac{T_H-k_T}{k_T-T_L} \qquad \textit{Equation 5.6}$$

where k_R and k_T are model parameters for the respective functions in which they are used, T_L and T_H are the lower and upper temperature limits to transpiration fixed at 0 and 45 ^{o}C, respectively (Wright *et al*., 1995; Oguntunde *et al*., 2007). R_m is an arbitrary radiation constant, often fixed at 1000 W m^{-2} (e.g. Wright *et al*., 1995; Sommer *et al*., 2002). For the control function for water vapour pressure deficit the equation derived by Zhang *et al*. (1997) was used. The equation is stated as:

$$f(VPD) = \frac{1+k_{D1}VPD}{1-k_{D2}VPD} \qquad \textit{Equation 5.7}$$

where k_{D1} and k_{D2} are model parameters.

5.2.2.1 Model parameterisation

Parameters $g_{c\ max}$, k_R, k_T, k_{D1} and k_{D2} were optimised by minimising the sum of squares of the residuals of the measured and modelled canopy conductance as:

$$S^2(k) = \sum_{i=1}^{n}\left(g_{ci} - g_{cj}(k, x_i)\right) \qquad \textit{Equation 5. 8}$$

where g_{ci} is the i^{th} value of canopy conductance calculated using transpiration data by inverting Equation 5.1, $g_{c,j}$ is the corresponding canopy conductance value predicted by the Jarvis model, k represents the model parameters (k_R, k_T, k_{D1} and k_{D2}) and x_i is the input variables of the i^{th} model value. Minimisation of S^2 was carried out by optimising *k* using the Marquardt and Simplex iterative procedures in the ModelMaker 3rd Edition software package (Cherwell Scientific Publishing Ltd, UK). Days with the highest g_c values (10 to 15 December 2008) were used.

5.2.2.2 Model validation

Validation of the model was performed by calculating canopy conductance using the optimised parameters of the Jarvis model and using these values in the Penman-Monteith equation to estimate hourly transpiration. Only transpiration values for the day-time (0800 h to 1700h) period were used to evaluate the performance of the model. These values were compared to the day-time transpiration measured using the HRM technique from16 December 2008 to 26 June 2009, to assess the ability of the model to predict long-term transpiration in the 'Delta' Valencia orchard.

The transferability of the parameters optimised in the 'Delta' Valencia orchard was evaluated in a 'Bahianinha' Navel orchard at the same location and in a 'Rustenburg' Navel orchard in the winter rainfall area of South Africa. Maximum canopy conductance ($g_{c\ max}$) required in Equation 5.3 was calculated for these orchards according to Whitehead (1998), which was also used by Whitely *et al*. (2009):

$$g_{c\,max} = LAI \times g_{s\,max} \qquad \textit{Equation 5. 9}$$

where LAI is leaf area index and $g_{s\ max}$ is the maximum stomatal conductance. LAI in the three orchards was measured using an AccuPAR Ceptometer (model LP-80 Decagon Devices, Inc, Pulman, WA, USA). The $g_{c\ max}$, estimated through the optimisation process based on the g_c data calculated by inverting the Penman-Monteith equation in the 'Delta' Valencia orchard, was used to determine $g_{s\ max}$ for citrus using the LAI of the orchard. The response parameters of the weather variables (i.e. k_R, k_T, k_{D1} and k_{D2}) were applied in their original forms, as determined for the 'Delta' Valencia orchard.

5.2.3 Statistical analysis

The statistical parameters used to test the predicted values against the observed data for the model are linear regression models, the coefficient of determination (R^2), root mean square error (RMSE), mean absolute error (MAE) and the index of agreement of Willmott (D) (de Jager, 1994). The model reliability criteria recommended by de Jager (1994) are that R^2 should be greater than 0.5, D should be greater than 0.8 and MAE should be less than 20 %.

5.3 Results

5.3.1 Canopy conductance

A typical diurnal trend of g_c in the ‘Delta’ Valencia orchard, calculated from the inversion of the Penman-Monteith equation on a clear sky day (27 January 2009), and weather variables are presented in Figure 5.1. The g_c on this particular day reached a maximum value of 5.7 m s^{-1} in the morning (0800 to 1100 h) and gradually decreased to a minimum value of 1.9 mm s^{-1} at 1500 h. The high g_c in the morning is in response to an increase in solar irradiance, which causes a sudden increase in the VPD on the evaporating leaf surface; whilst later on in the day the responses of g_c are controlled by a combination of variables VPD, S_R, and T_a. This trend of high and low values of g_c in the early morning and late afternoon, which was observed on most clear-sky days, is consistent with measurements of stomatal conductance of citrus (Cohen and Cohen, 1983).

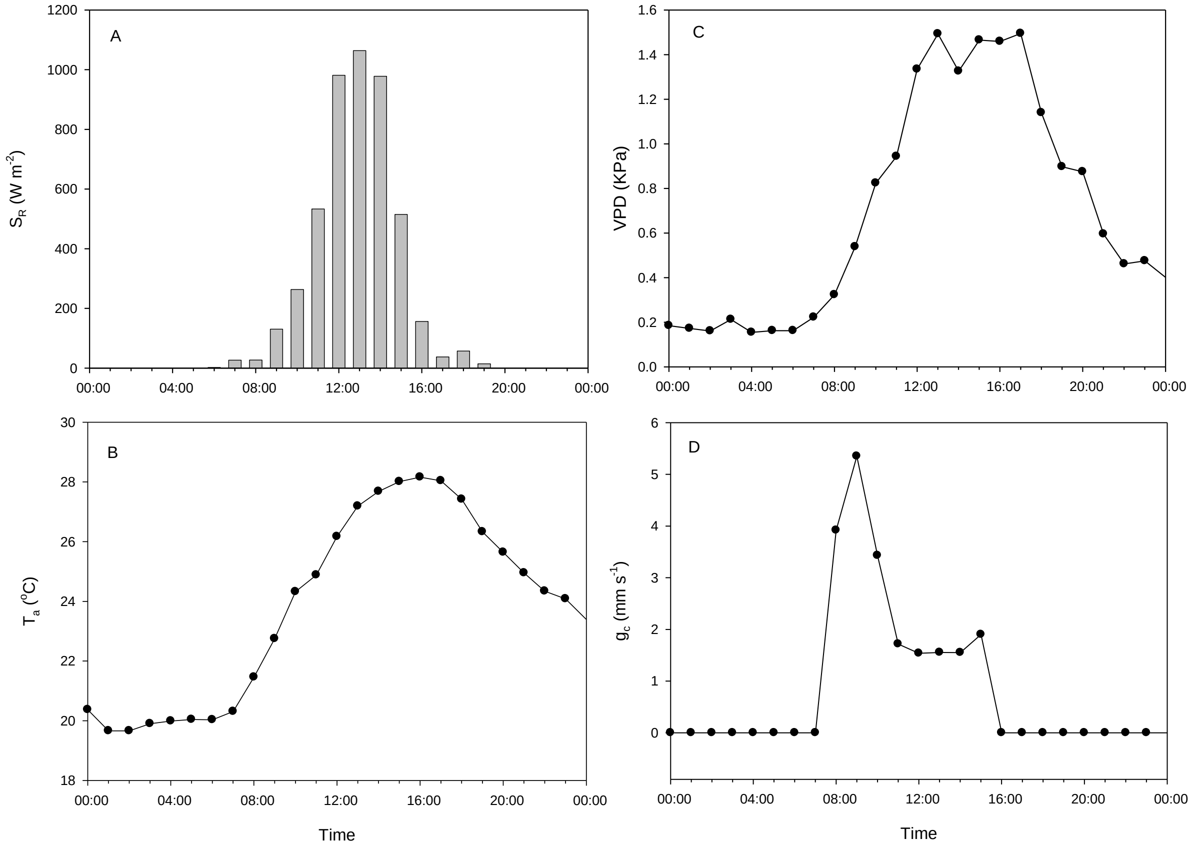

Figure 5.1. Typical diurnal trend of A) solar irradiance (S_R), B) air temperature (T), C) vapour pressure deficit (VPD) and D) canopy conductance (g_c), calculated from the inversion of the Penman-Monteith, in the 'Delta' Valencia orchard on a clear sky day, 27 January 2010.

Considerable scatter, signifying the stomatal response to weather variables, is exhibited by the g_c values when plotted over the measurement period in each orchard (Figure 5.2). The g_c values show a similar trend in the 'Delta' Valencia and 'Bahianinha' Navel orchards, where the highest values were observed in summer and lowest values were at the end of the winter months. The highest g_c values recorded in the 'Delta' Valencia and 'Bahianinha' Navel orchards were approximately 12 mm s^{-1} and 9 mm s^{-1}, respectively. In contrast, maximum canopy conductance (10 mm s^{-1}) in the 'Rustenburg' Navels orchard remained relatively constant throughout the measurement period.

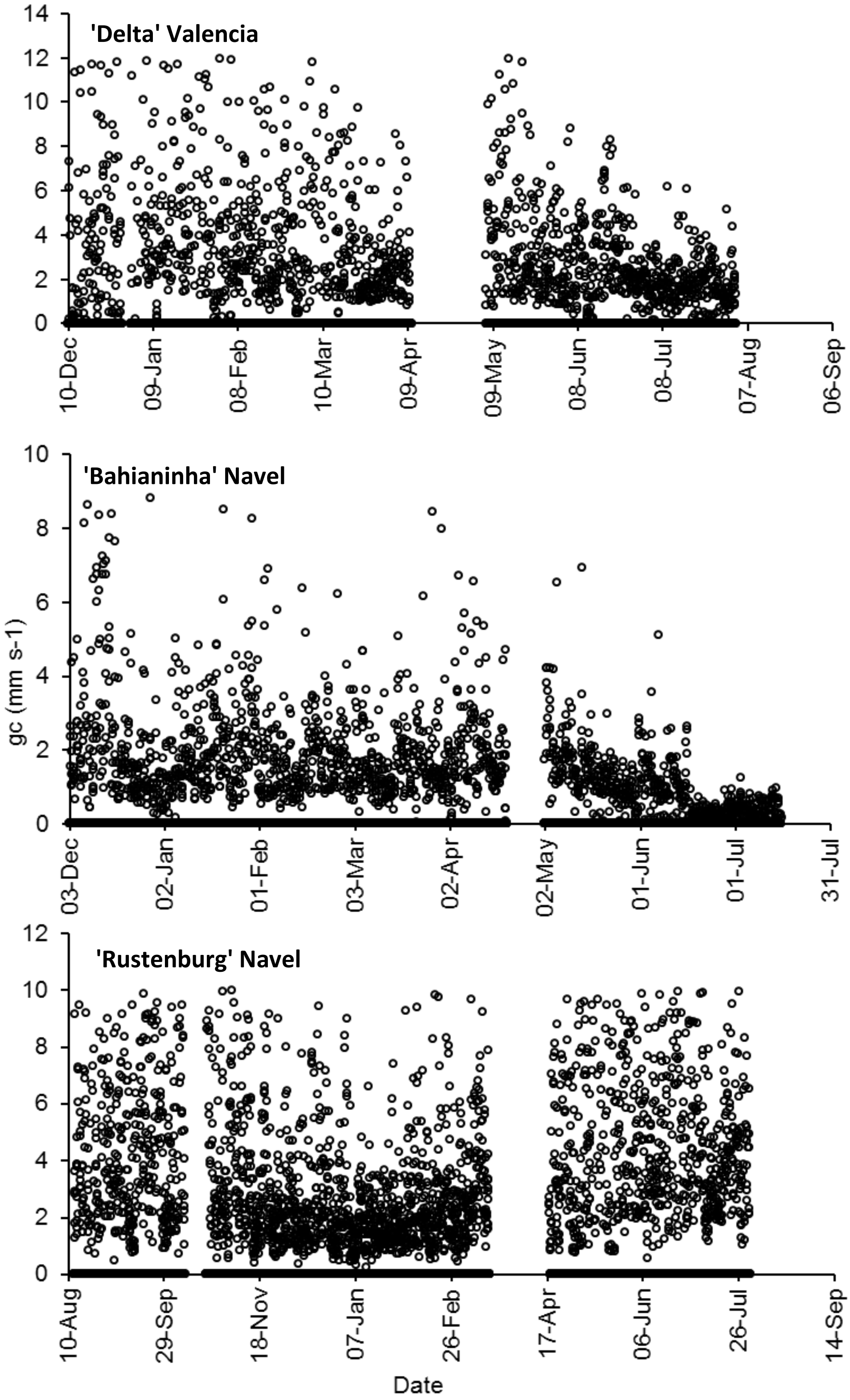

Figure 5.2. Hourly canopy conductance (g_c) calculated using the measured transpiration and inverting the Penman-Monteith equation in the three orchards. Gaps in the plotted data were due to missing hourly weather data caused by power failure to the weather stations.

5.3.2 Parameterisation of the Jarvis model

The five parameters, i.e. $g_{c\ max}$, k_{D1}, k_{D2}, k_T and k_R, which describe the seasonal response of canopy conductance to S_R, VPD and T_a, obtained in the ‘Delta’ Valencia orchard through the Marquardt and Simplex iterative procedures on an hourly basis, are shown in Table 5.1. A very good correlation, R^2 value of 0.97, was observed between the measured and predicted canopy conductance during the optimisation process in the ‘Delta’ Valencia orchard (Table 5.1). The three functions of S_R, VPD and T_a therefore explained over 97 % of the variation in canopy conductance in the orchard and all parameter values were statistically significant ($P<0.001$). Figure 5.3 shows the normalised canopy conductance ($g_c/g_{c\ max}$) plotted against the functions of weather variables (i.e. solar radiation; VPD and temperature) for the orchard. The functional forms of the equations fit very well to the boundary regions described by the data (Figure 5.3).

Table 5.1. Optimised parameters for the Jarvis model used to predict canopy conductance with water vapour pressure deficit, solar irradiance and air temperature as response functions in the ‘Delta’ Valencia orchard.

Parameter	**Value**
g_{cmax} (mm s^{-1})	14.0380
k_{D1} (kPa)	0.0477
k_{D2} (kPa)	-0.1799
k_T (^oC)	18.6410
k_R (W m^{-2})	350.1700
R^2	0.9700
P value	<0.0010

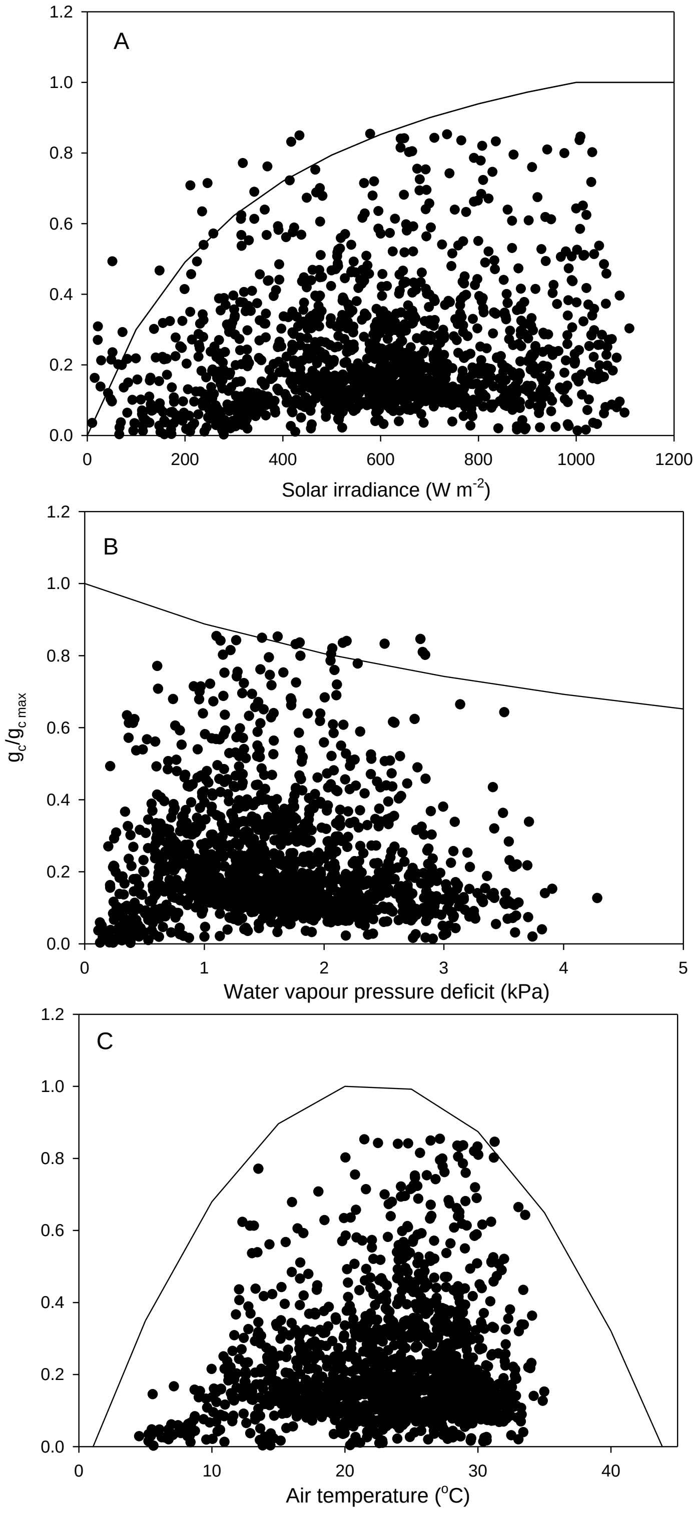

Figure 5.3. Normalised canopy conductance in the ‘Delta’ Valencia orchard plotted against (A) solar radiation (B) vapour pressure deficit and (C) temperature. The forms of the model functions, based upon the optimised parameters, are shown as solid lines.

5.3.2 Predicting transpiration using the Penman-Monteith equation coupled with the Jarvis-type model

Figure 5.4 shows the relation between the g_c predicted by the Jarvis model and g_c obtained from sap flow data by inverting the Penman-Monteith equation. The predicted values were scattered around the 1:1 line with a reasonable correlation ($R^2 = 0.56$). There is high variance between predicted and measured values at higher values of g_c. Despite the disparities between measured and estimated hourly g_c, when using these values in the Penman-Monteith equation fairly good predictions of the observed range of daily transpiration volumes were obtained (Figure 5.5A). Both the day-to-day variation in transpiration and the gradual decline daily transpiration rates as winter approached were captured by the model. Regression analysis resulted in a slope of close to 1 (y = 1.13) between predicted and measured transpiration in the ‘Delta’ Valencia orchard (Figure 5.5B) and the statistical parameters were within the ranges stipulated for good model performance by de Jager (1994).

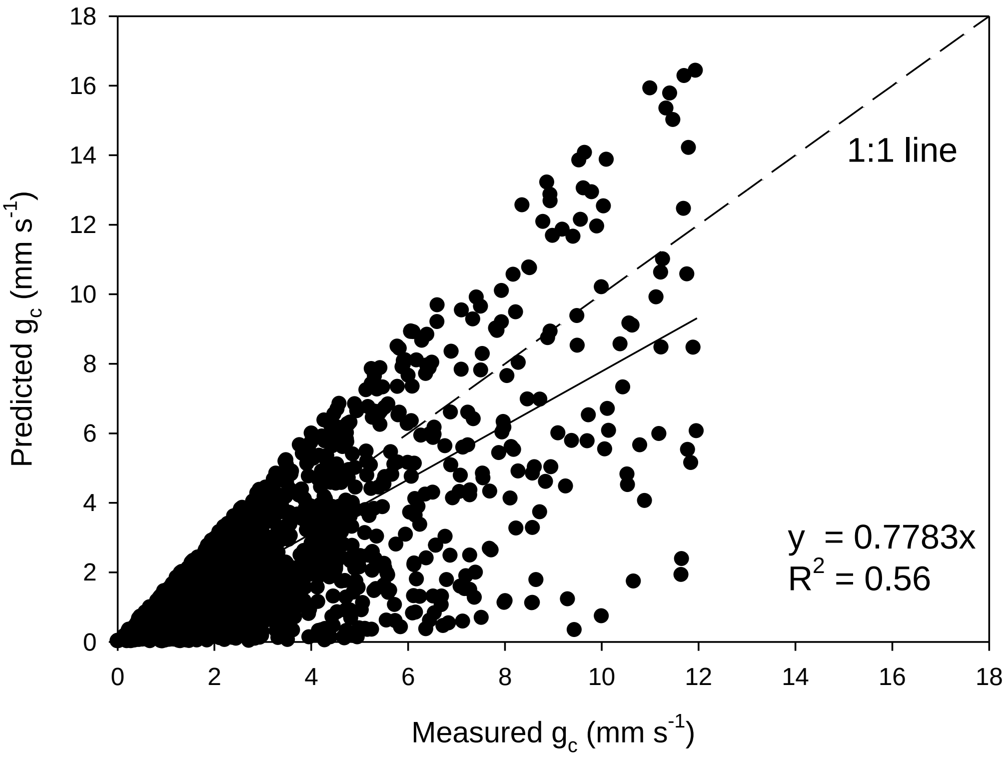

Figure 5.4. Relationship between hourly g_c predicted by the Jarvis model and g_c obtained from sap flow data by inverting the Penman-Monteith equation in the ‘Delta’ Valencia orchard.

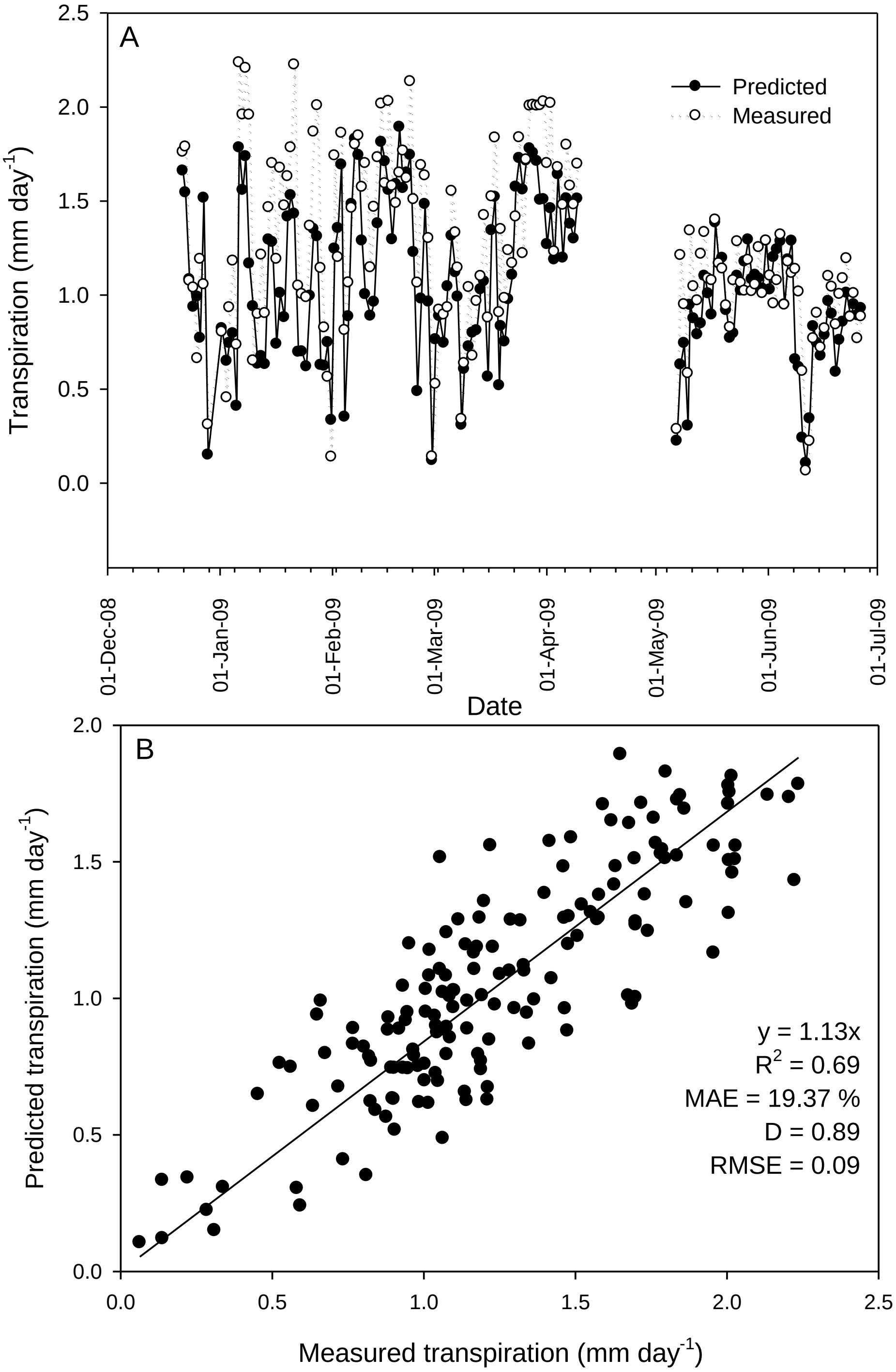

Figure 5.5. Measured and predicted daily transpiration in the ‘Delta’ Valencia orchard for A) the period 16 December 2008 to 26 June 2009 and (B) regression analysis. Statistical parameters include slope of regression equation, coefficient of determination (R^2), mean absolute error (MAE), Willmot coefficient of agreement (D) and root mean square error (RMSE). The missing data were due to missing hourly weather data caused by power failure to the weather station.

Whilst the model performed very well in the ‘Delta’ Valencia parameterisation orchard using independent validation data, it is important that the model is transferable and can be used to predict long-term transpiration in a wide range of citrus orchards. The transferability of the parameters for the Jarvis-type canopy conductance model was therefore evaluated in a ‘Bahianinha’ Navel orchard at the same location and in a ‘Rustenburg’ Navel orchard in the winter rainfall region of South Africa. The value for $g_{s\ max}$ for the ‘Delta’ Valencia orchard was 4.92 mm s^{-1}, and was used together with orchard LAI to determine $g_{c\ max}$ in the ‘Bahianinha’ and ‘Rustenburg’ Navel orchards using Equation 5.9. Following this approach hourly g_c was poorly estimated in both of these orchards (Figure 5.6), with an R^2 value of 0.47 for the ‘Bahianinha’ Navel orchard (Figure 5.6A) and 0.41 ‘Rustenburg’ Navel orchard (Figure 5.6B). In the ‘Bahaininha’ Navel orchard g_c tended to be overestimated (slope = 1.34), whilst in the ‘Rustenburg’ Navel orchard g_c tended to be underestimated (slope = 0.64). As a result transpiration was overestimated in the ‘Bahianinha’ Navel orchard throughout the measurement period and underestimated in the ‘Rustenburg’ Navel orchard (Figure 5.7). Three of the four statistical parameters (i.e. MAE, D and RMSE) indicated that the parameters for the Jarvis-type model determined in the ‘Delta’ Valencia orchard did not predict transpiration adequately in both the ‘Bahianinha’ and ‘Rustenburg’ Navel orchards (Figure 5.8).

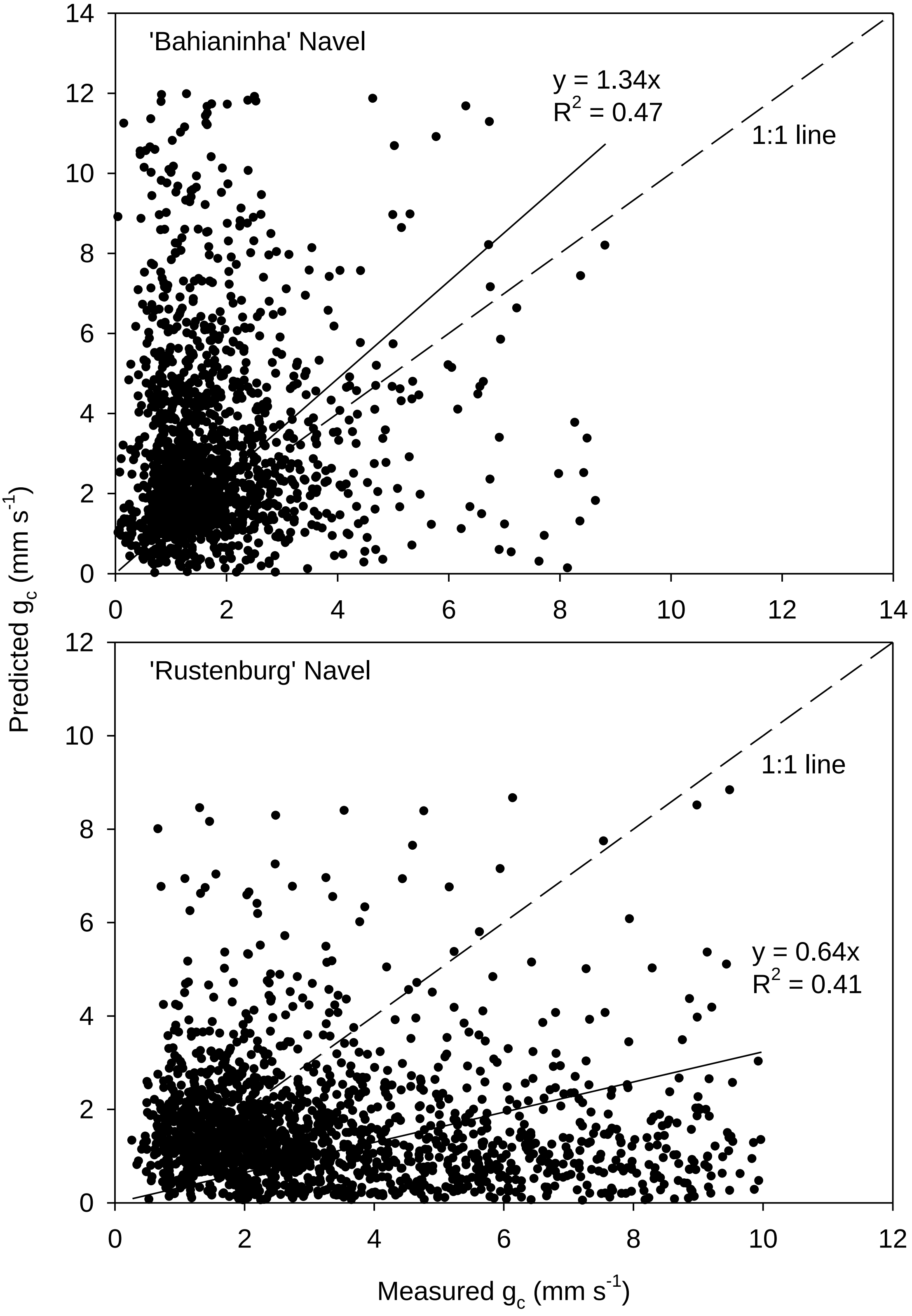

Figure 5.6. Relationship between g_c predicted by the Jarvis model using parameters of the 'Delta' Valencia orchard and g_c obtained from sap flow data by inverting the Penman-Monteith equation in the 'Bahianinha' and 'Rustenburg' Navel orchards.

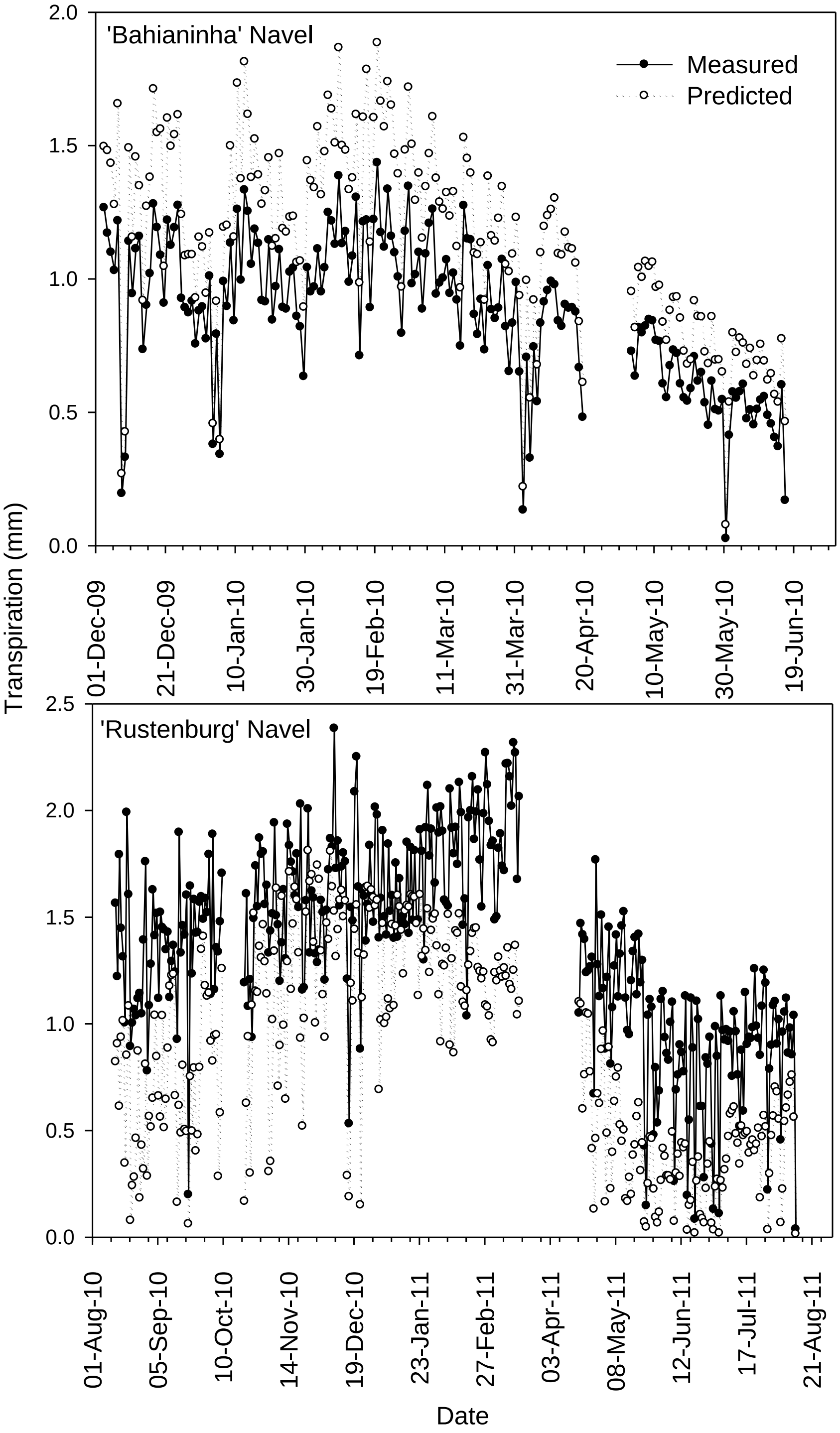

Figure 5.7. Time series of measured and predicted transpiration in the 'Bahianinha' and 'Rustenburg' Navel orchards using Jarvis parameters optimised in the 'Delta' Valencia orchard.

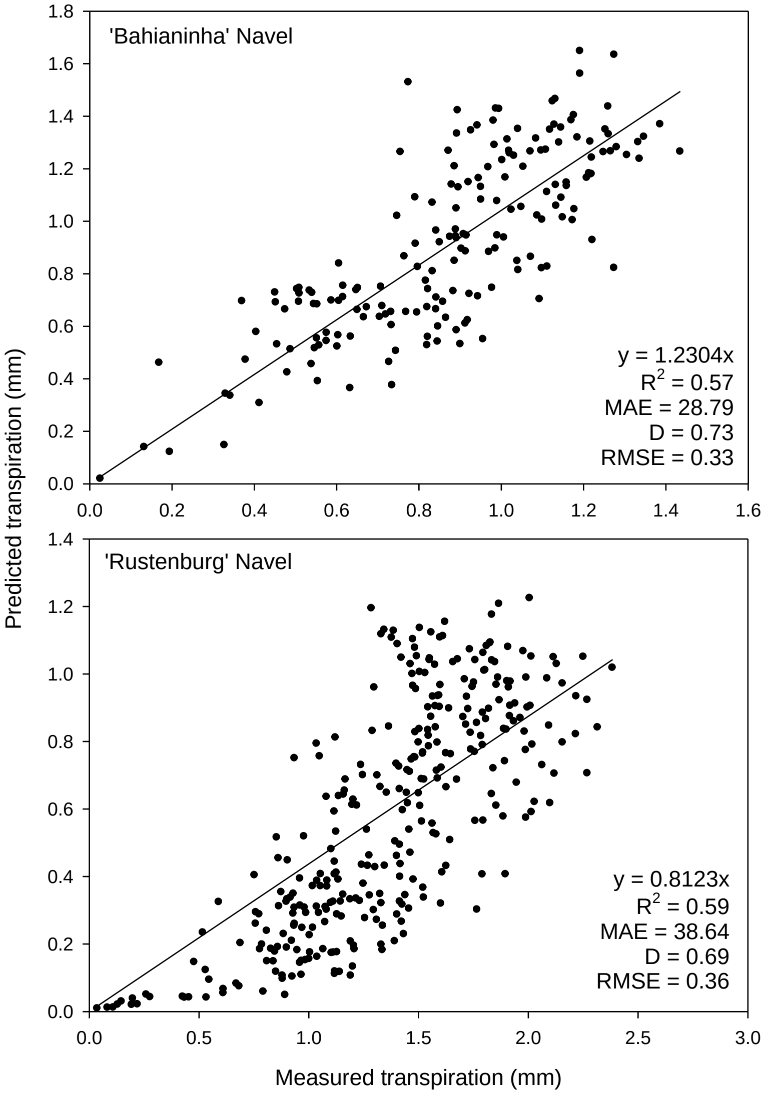

Figure 5.8. Regression analysis between measured and predicted transpiration in the 'Bahianinha' and 'Rustenburg' Navel orchard using parameters determined in the 'Delta' Valencia orchard. Statistical parameters used include slope of regression equation, coefficient of determination (R^2), mean absolute error (MAE), Willmot coefficient of agreement (D) and root mean square error (RMSE).

As transpiration was poorly predicted in the 'Bahianinha' and 'Rustenburg' Navel orchards when using the parameters for the 'Delta' Valencia orchard, it was decided to parameterise the Jarvis model in the 'Bahianinha' and 'Rustenburg' Navel orchards following the same procedure as in the 'Delta' Valencia orchard. Parameterisation of the Jarvis model was done using data measured during the period of 3 to 9 December 2009 in the 'Bahianinha' Navel orchard; and 13 to 17 August 2010 in the 'Rustenburg' Navel orchard. A very good correlation (R^2 >0.9) was once again observed between the measured and predicted canopy conductance during parameterisation, such that over 90 % of the variation in canopy conductance in the two orchards was explained by the three functions of S_R, VPD and T_a (Table 2). All parameter values were found to be statistically significant (P<0.001). Most of the normalised canopy conductance data points were below the ideal situation described by the functional forms in both the 'Bahianinha' Navel (Figure 5.9) and Rustenburg Navel orchards (Figure 5.10).

Table 5.2. Parameters for the response functions of water vapour pressure deficit, solar irradiance and air temperature for the Jarvis model determined through the optimisation process in the 'Bahianinha' and 'Rustenburg' Navel orchards.

Parameter	**'Bahianinha' Navel**	**'Rustenburg' Navel**
$g_{c\ \mathrm{max}}$ (mm s^{-1})	12.2970	18.0260
k_{D1} (kPa)	0.0503	0.0502
k_{D2} (kPa)	-0.3083	-0.2673
k_T (^{o}C)	18.4871	19.3670
k_R (W m^{-2})	363.2290	356.6990
R^2	0.9900	0.9200
P value	<0.0010	<0.0010

There were close similarities between the optimum parameters of the Jarvis-type model obtained in the 'Bahianinha' and 'Rustenburg' Navel orchards (Table 5.2) and those of the 'Delta' Valencia orchard (Table 5.1). Maximum differences amongst the k_{D1}, k_{D2}, k_T and k_R parameters in respect of the 'Delta' Valencia orchard parameters for the three orchards were 8.6, 33.9, 4.8 and 11.2 %, respectively. There were also differences in the values of $g_{c\ \mathrm{max}}$ that were obtained during the optimisation process (Table 5.2) and those calculated using Equation 5.9 for the two orchards. The $g_{c\ max}$ values obtained for the different orchards seem to reflect the sizes of the tree canopies as they increase with measured LAI.

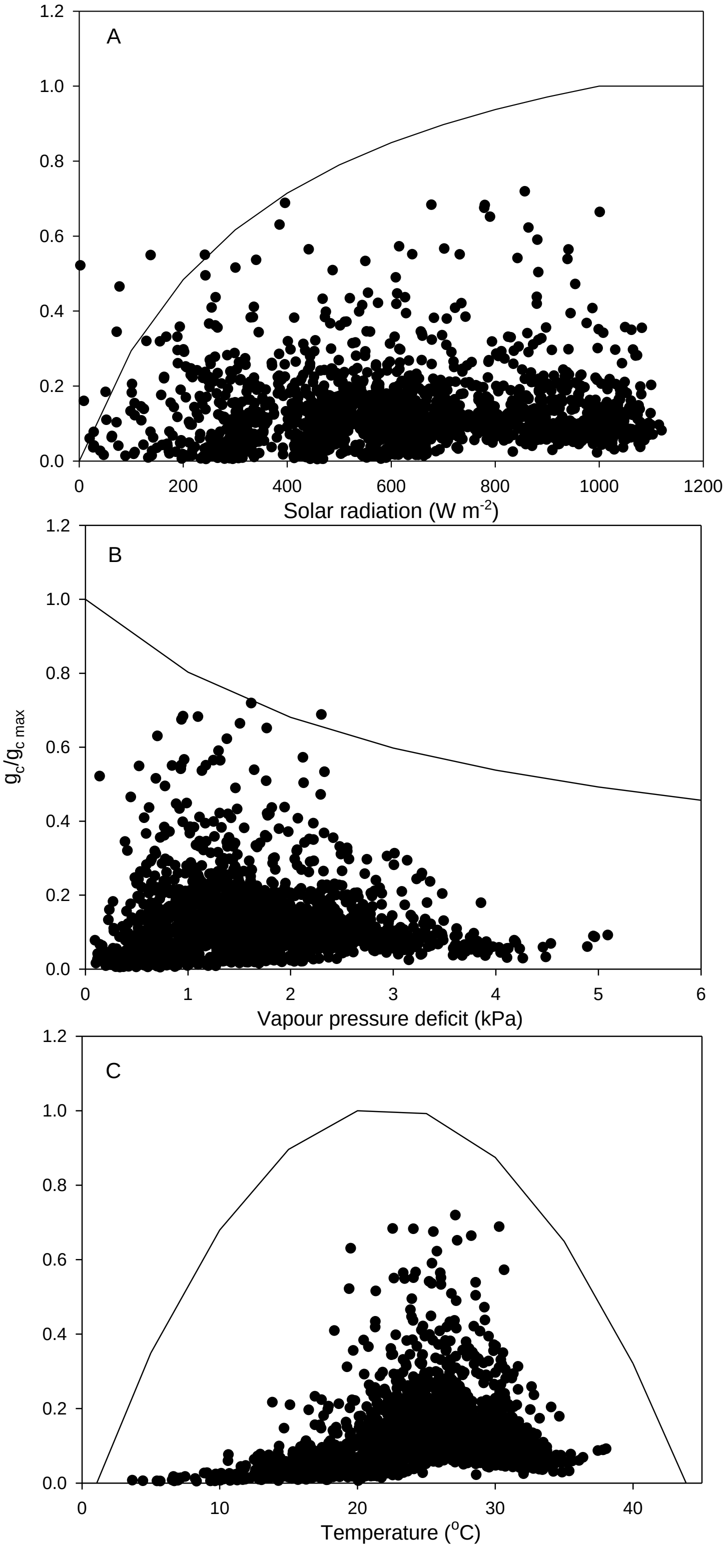

Figure 5.9. Normalised canopy conductance in the 'Bahianinha' Navel orchard plotted against (A) solar radiation (B) water vapour pressure deficit and (C) air temperature. The forms of the model functions based upon the optimised parameters are shown as solid lines.

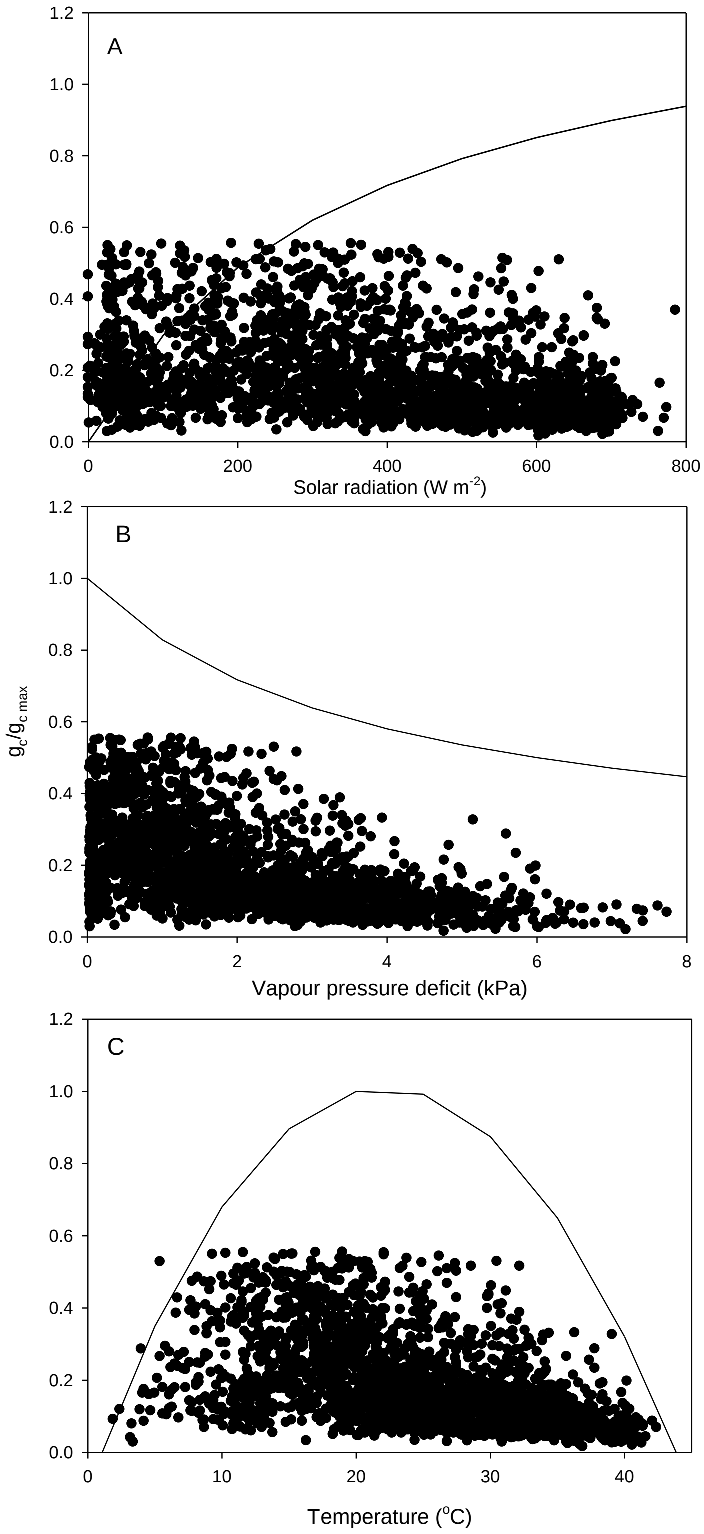

Figure 5.10. Normalised canopy conductance in the 'Rustenburg' Navel orchard plotted against (A) solar radiation, (B) water vapour pressure deficit and (C) air temperature. The forms of the model functions based upon the optimised parameters are shown as solid lines.

Improved correlations were observed between g_c predicted by the Jarvis-type model, using orchard specific parameters (Table 5.2) and measured g_c in the 'Bahianinha' and 'Rustenburg' Navel orchards (Figure 5.11). While there was a good agreement between predicted and measured transpiration in the 'Bahianinha' Navel orchard using parameters for the Jarvis model specific to this orchard, there were periods of underestimation of transpiration in the 'Rustenburg' Navel orchard during spring of 2010 (August to October) and winter 2011 (April to August) (Figure 5.12).

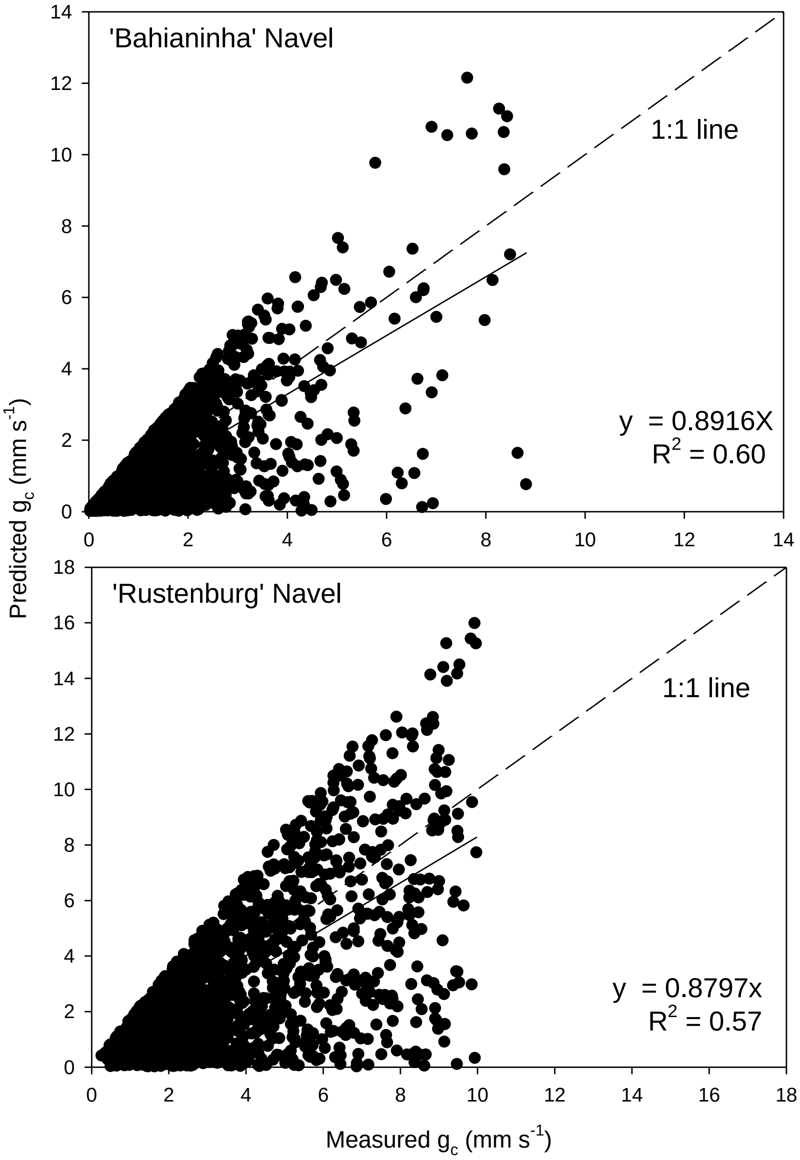

Figure 5.11. Relationship between hourly g_c predicted by the Jarvis model and g_c obtained from sap flow data by inverting the Penman-Monteith equation in the 'Bahianinha' and 'Rustenburg' Navel orchards.

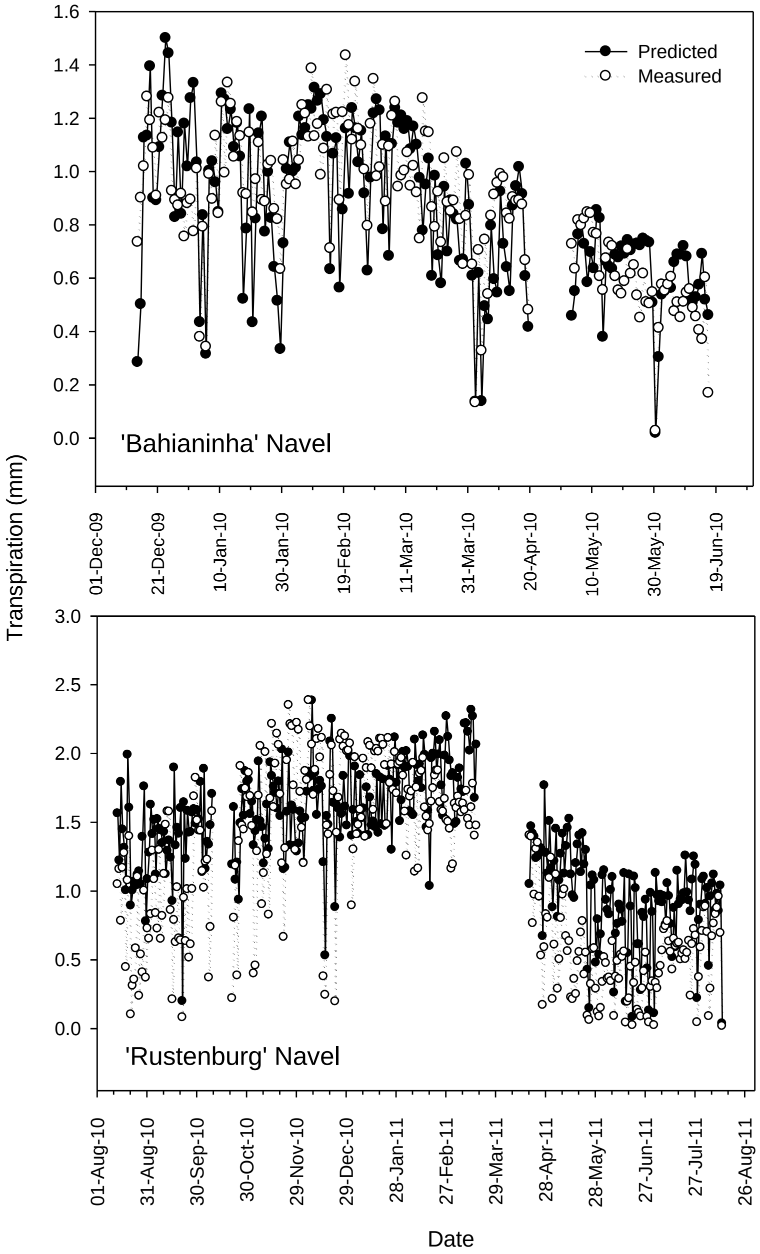

Figure 5.12. Time series plot of measured and predicted transpiration in the ‘Bahianinha’ and ‘Rustenburg’ Navel orchards. The gaps in the plotted data were due to missing hourly weather data caused by power failure to the weather stations.

Regression analysis revealed reasonable linear relationships between predicted and measured transpiration in both the ‘Bahianinha’ and ‘Rustenburg’ Navel orchards (Figure 5.13). The model predicted transpiration reasonably well as almost all the statistical parameters, except for MAE in the ‘Rustenburg’ Navel orchard, are within the ranges stipulated by de Jager (1994) for good model performance (Figure 5.13).

The MAE, which was greater than 20 % in the ‘Rustenburg’ Navel orchard, was probably a reflection of the underestimation of transpiration by the model in autumn and winter (Figure 5.12). The Penman-Monteith equation coupled with Jarvis canopy conductance model (using orchard specific parameters) underestimated cumulative transpiration by 13 % in the ‘Delta’ Valencia, 2 % in ‘Bahianinha’ and 18% in the ‘Rustenburg’ Navel orchards over the measurement period (Figure 5.14).

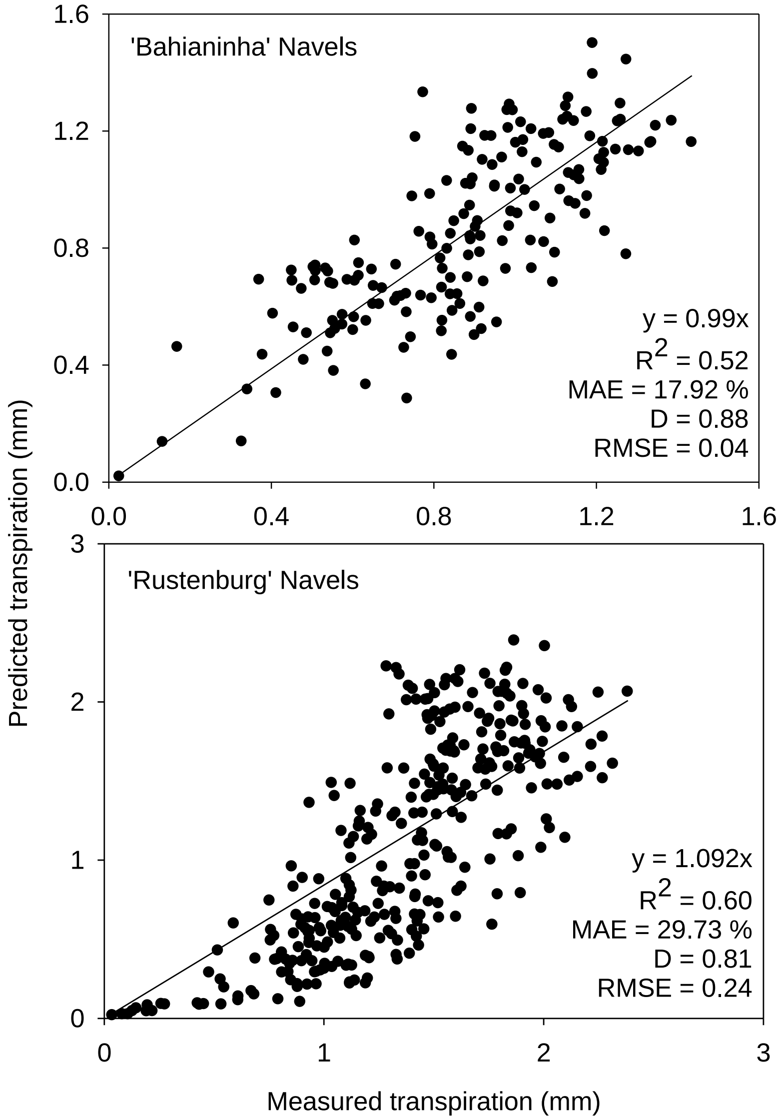

Figure 5.13. Regression analysis between predicted and measured transpiration in the ‘Bahianinha’ and ‘Rustenburg’ Navel orchards. Statistical parameters used include slope of regression equation, coefficient of determination (R^2), mean absolute error (MAE), Willmot coefficient of agreement (D) and root mean square error (RMSE).

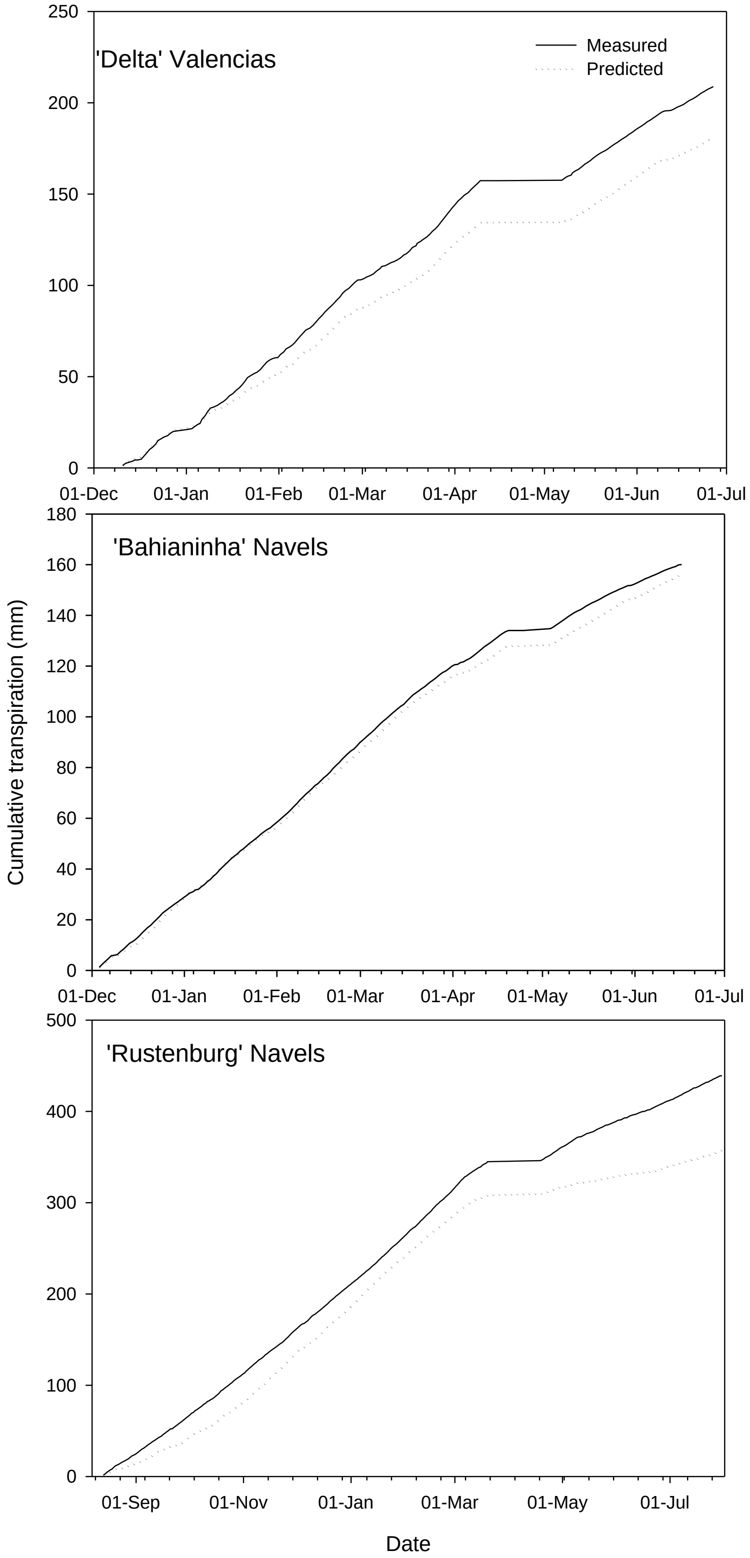

Figure 5.14. Cumulative measured transpiration and transpiration predicted using a Jarvis-type model parameterised in the respective orchards for the measurement periods. The plateau in water use graphs occurring around April/May in the three graphs is due to periods of missing data.

5.4 Discussion

The optimised hourly values of $g_{c\ max}$ obtained in the three orchards were higher than the maximum values calculated by inverting the Penman-Monteith equation. The value of $g_{c\ max}$ represents the ideal situation at which all functions are equal to one. In fact the Jarvis model predicts $g_{c\ max}$ values under conditions of low VPD and high S_R and such conditions do not normally occur in the field (Whitley *et al*., 2009). These values were also higher than the 6.98 to 7.96 mm s^{-1} that was reported by Oguntunde *et al*. (2007) in sweet oranges which might mean that this parameter is not conservative for citrus. However, the $g_{c\ max}$ obtained for the different orchards by the optimisation process, followed in this instance, contains artefacts of the g_c data used as well as the parameters of the response functions that were attained.

The parameter k_{D1} is much lower than the values of 0.116 and -0.229 kPa reported in poplar trees by Zhang *et al*. (1997), who used a similar form of the VPD function, most probably indicating the differences in response of the two species to VPD. The optimised value for the parameter k_T, for optimum temperature, obtained in all three orchards was slightly lower than 25.5 ^{o}C that was established by Oguntunde *et al*. (2007). Despite the differences in canopy sizes and different environmental conditions experienced in the orchards the response functions obtained in three orchards in this study were very similar.

When the parameters of the Jarvis model were used to predict conductances, derived from the sap flow data, the model was only able to account for a small proportion (56 to 60 %) of the variance in g_c. The modelling approach first suggested by Jarvis (1976) has been widely used to predict conductances in fruit trees, including citrus. The level at which these weather variables were able to explain the variability in canopy conductance is slightly lower than the 83 % reported by Oguntunde *et al*. (2007) in sweet oranges under semi-arid Tropical Monsoon climate, but higher than 11 % obtained by Cohen and Cohen (1983) after fitting a similar Jarvis-type model to measured leaf conductance of Shamouti orange trees under Mediterranean conditions.

The Penman-Monteith equation coupled with the Jarvis model (with one set of parameters) was able to predict transpiration successfully in the three orchards over a relatively long period. This is despite the limitations of Jarvis-type models on days when the crop canopy is wet, or in cloudy or overcast conditions, that most studies such as Oguntunde *et al*. 2007 tend to eliminate from the data set when testing the approach. A similar modelling approach by Whitely *et al*. (2009) gave fairly reasonable results in forest species over a period of 109 days. This modelling approach may be applicable to semi-arid sub-tropical conditions where wetting of the canopy by rainfall and occurrence of cloudy/overcast conditions are both infrequent.

The parameters of the Jarvis-type model obtained in the 'Delta' Valencia orchard did not predict transpiration accurately in either the 'Bahianinha' or 'Rustenburg' Navel orchards even though they were similar. The multiplicative form of the Jarvis model means that the differences observed in the parameters are multiplied, hence the large differences between measured and predicted values when using such an approach. The fact that transpiration was overestimated in the 'Bahianinha' Navel orchard and underestimated in the 'Rustenburg' Navel orchard, although with a reasonable correlation, might mean that transferring such an approach amongst orchards is not as straight-forward as proposed previously by Whitehead (1998). For instance Villalobos *et al*. (2013) argued that LAI may not be the best parameter to use when up-scaling transpiration in fruit tree orchards since it is a reflection of the available, rather than the conducting leaf area. In order for this approach to work a methodology for determining the leaf area active in transpiration would need to be formulated.

There are a few possible reasons for the failure of the Jarvis-type parameters obtained in the 'Delta' Valencia to accurately predict transpiration in both the 'Bahianinha' and 'Rustenburg' Navel orchards. There is evidence that stem hydraulic conductance varies among rootstock/scion combinations in citrus (Rodríguez-Gamir *et al*., 2010), which would have a direct bearing on the variations of canopy conductance values calculated using the Penman-Monteith equation based on sap flow measurements. Cultivar effects are probably partly reflected by the fact that largest difference observed between the k_{D2} parameters of the VPD response function was between the 'Rustenburg' Navel and 'Delta' Valencia trees. The thickness and composition of epicuticular waxes found on citrus that help to suppress cuticular transpiration vary amongst citrus species, such that the sensitivity of the cultivars to environmental conditions is also expected to differ (Baker *et al*., 1975). Although the findings of Baker *et al*. (1975) were at species level, the occurrence of such difference in cultivars and their effect on the regulation of transpiration (and hence conductance) would be worthy of investigation.

It is also important to note that the response functions of Jarvis-type model depend upon the physiological condition of the plants, the previous and current season in which measurements were conducted (Jarvis, 1976). The differences in leaf resistance brought about by the differences in crop load of these orchards that were discussed in Chapter 4 would also be expected to manifest at canopy level. The highest VPD recorded at the Citrusdal site is almost twice that observed at Groblersdal during the measurement period. Citrus transpiration on which the g_c values were based has been shown to be sensitive to VPD (Oguntunde *et al*., 2007) which may mean that the response of the trees under these conditions may have differed. In addition the maximum solar radiation recorded at the Groblersdal site was above 1000 W m^{-2} in both seasons as compared to a maximum of approximately 800 W m^{-2} recorded at the Citrusdal site. The ability of citrus trees to acclimatize to different levels of solar radiation, as reported by Syvertsen (1984), may also have an effect on the responses of the citrus leaves. Since measurements of transpiration were conducted for only one season in each orchard, the effects of conditions in the previous seasons could not be evaluated.

5.5 Conclusion

The use of the Penman-Monteith equation coupled with a Jarvis-type model for predicting transpiration in citrus orchards was tested. The Jarvis model had response functions of solar radiation, temperature and vapour pressure deficit. The model was able to predict long-term variations of citrus transpiration reasonably well only when parameterized using data from that specific orchard. However, transferability of the optimised parameters from one orchard to an orchard in a similar or different region was not possible.

Chapter 6: General conclusions and recommendations

6.1 Overview of study

Citrus is a one of the most important fruit crops grown across the world, as well as in South Africa. Production of this evergreen crop in semi-arid countries, which receive seasonal rainfall, is made possible through irrigation. The advent of micro-irrigation systems, such as drip, provides an opportunity to match crop water requirements and irrigation amounts, but needs to be coupled with appropriate water management techniques (Jones, 2004). Insufficient knowledge of fruit tree water use, under these relatively new systems, has been identified as a major factor hindering the application and further development of existing irrigation water management tools in South Africa (Pavel *et al*., 2003; Volschenk *et al*., 2003). This is probably because measurements of crop water use are time consuming, expensive and require specialized expertise, which are not always available. The situation is made worse in orchards, where tree size is variable between different orchards and by the long time needed to obtain good estimates (Hoffman *et al.*, 1982; Castel *et al*., 1987). Water use models have proved very useful in extrapolating measured data and predicting water use of different crops.

The aims of this study were two-fold: i) to measure long-term transpiration of well managed micro-irrigated citrus orchards and; ii) to test physically–based models that can be used to predict transpiration across different citrus growing regions. This study concentrated on the transpiration component since it forms the larger portion of orchard water use in micro-irrigated fruit tree orchards (Reinders *et al*., 2010) and is directly related to productivity (Villalobos *et al*., 2013). In order to meet the objectives, sap flow measurements were performed using the heat ratio method (HRM) as described by Burgess *et al*. (2001) in two orchards in South Africa. The two orchards planted with ‘Delta’ Valencia and ‘Bahianinha’ Navel orange trees were located in the summer rainfall area. A data set from an orchard planted with ‘Rustenburg’ Navel orange trees that was located in the winter rainfall area was sourced for model validation. Weather variables, which include solar radiation, temperature, relative humidity and wind speed, were measured using automatic weather stations close to the orchards for modelling purposes.

6.2 Calibration of the heat ratio method (HRM) sap flow technique for long-term transpiration measurement in citrus orchards

The HRM was calibrated against eddy covariance measurements in winter (31July to 3 August 2008) and autumn (21 to 25 May 2009) in the 'Delta' Valencia orchard, when soil evaporation was considered negligible (Chapter 2). Calibration was done by adjusting the wounding width to ensure that average transpiration of sample trees matched crop evapotranspiration (ET_c) measured above the orchard using the eddy covariance method. The virtual wound widths that matched mean transpiration of sample trees to ET_c for winter and autumn periods were 3.3 and 3.1 mm, respectively. The similarity of the virtual wound widths obtained during the two measurement periods (winter and autumn) and the subsequent successful use of an average value (3.2 mm) suggests that wounding does not increase with time and a single field calibration of the HRM using eddy covariance measurements is sufficient for measuring transpiration in citrus orchards. The requirement for a wound width greater than the observed 2 mm width in citrus was necessitated by the fact that citrus had non-homogeneous functional wood as determined by the anatomical assessments. Non-homogeneity of wood means that the ideal heat pulse theory will not apply to this wood and a correction factor is therefore required. This is in agreement with previous studies in kiwifruit (Green and Clothier, 1988) and citrus (Fernández *et al*., 2006). In addition citrus wood reacted to drilling and heating by deposition of phenols and gums that caused xylem blockages which extended beyond what could be seen by the naked eye, as revealed by the anatomical assessments in this study. Once the calibration of the HRM was performed, the method was then used to quantify transpiration in the three orchards.

6.3 Measurement of long-term transpiration and transpiration coefficients in citrus orchards

In order to address the problem of lack of information of water use in citrus orchards, which was previously highlighted (Pavel *et al*., 2003; Volschenk *et al*., 2003), the HRM was employed to quantify long-term transpiration rates in three citrus orchards (Chapter 3). Average daily transpiration in the three orchards ranged from 0.77 mm day^{-1} to 2.26 mm day^{-1} depending on canopy size, season and climate (summer versus winter rainfall areas). Total seasonal transpiration for the two orchards in which measurements covered an entire production season, i.e. ‘Delta’ Valencia and ‘Rustenburg’ Navel orchards were 682 mm and 672 mm, respectively. This study confirmed the variations of transpiration in citrus orchards as previously reported (García Petillo and Castel, 2007). Whilst the measurement of transpiration in the three orchards is not exhaustive of all orchard conditions in South Africa, it does provide a basis for the understanding of the drivers of transpiration. Sap flow-based measurements of transpiration obtained in this study presented a valuable data set for testing models of citrus transpiration that can be used to extrapolate measured transpiration to other growing regions of the world.

Transpiration coefficients (K_t) determined in the three orchards ranged between 0.28 and 0.71. The K_t values were almost constant throughout the seasons in the summer rainfall area, and significantly higher in the winter months than in the summer months in the winter rainfall area. This indicated that transpiration does not increase at the same rate as reference evapotranspiration (ET_o) during the summer months and confirmed the existence of strong regulation mechanisms within the citrus tree hydraulic path that was previously reported (van Bavel *et al*. 1967; Kriedemann and Barrs 1981; Sinclair and Allen 1982). It is also indicative of fact that citrus trees are only able to supply a certain maximum amount of water to the canopy at high ET_o ($\geq$ 5 mm day^{-1}), even when soil water is not limiting, as suggested by Sinclair and Allen (1982).

Differences in measured K_t values between the orchards in Groblersdal, despite similar ET_o in both years, suggests an effect of canopy size on transpiration. On the other hand differences in the trends of K_t values between the two orchards located in Groblersdal and the one in Citrusdal in winter could be linked to differences in VPD. Vapour pressure deficit was reported as the dominant regulator of transpiration of citrus by Kriedemann and Barrs (1981) and Oguntunde *et al*. (2007) when soil water is not limiting. The clear differences between K_t values in the three orchards and those published in literature (including the FAO56) indicate that the K_t values are orchard specific. This result confirmed the variation of K_t values of citrus orchards reported previously (Rana *et al*. 2005; Villalobos *et al*., 2009; Marin and Angelocci, 2011; Villalobos *et al*., 2013). Crop coefficients determined in one orchard can therefore not be directly applied or transferred to different growing regions of the world. This emphasizes the need to develop an easy method for estimating site-specific crop coefficients, in order to improve water management in citrus orchards.

6.4 Estimation of transpiration coefficients from plant height and canopy cover

The significance of the role of the resistance to water transport within the citrus tree transpiration stream was highlighted during the development K_t values based on crop height and canopy cover following the method suggested by Allen and Pereira (2009) (Chapter 4). Good agreements between measured and estimated K_t values were only obtained after back-calculating leaf resistance (r_l) using measured transpiration values, as recommended by Allen and Pereira (2009). This study established that the leaf resistance of citrus may be higher than what was suggested by Allen and Pereira (2009) for a generic citrus orchard. The r_l values of ranging from 419 to 2 694 s m^{-1} obtained through this procedure were comparable to those ranging from 200 to 8 280 s m^{-1} reported in literature (Cohen and Cohen 1983; Dzikiti *et al.* 2007; Pérez-Pérez *et al.*, 2008). It was also established that contrary to the constant r_l value (420 s m^{-1}) suggested by Allen and Pereira (2009), leaf resistance increased for all orchards during the summer period. Allen and Pereira (2009) recommended that improvements in estimating the r_l term are needed to improve the accuracy of the methodology. In that regard a relationship between mean monthly r_l and ET_o in the 'Rustenburg' Navel orchard provided a means of estimating mean leaf resistance, which estimated K_t values with a reasonable degree of accuracy in the three orchards. However, this relationship only provided good seasonal estimates of transpiration, which means that it can only be useful for irrigation planning. A more mechanistic model capable of capturing the dynamics of the canopy conductance in citrus varieties is required to predict transpiration of citrus trees on day-to-day basis for purposes such as irrigation scheduling.

6.5 Predicting transpiration of citrus orchards using the Penman-Monteith equation coupled with a Jarvis-type canopy conductance model

The use of a more mechanistic approach that incorporates a dynamic canopy conductance term was also tested (Chapter 5). This was in the form of the Penman-Monteith equation, coupled with the estimation of canopy conductance using a Jarvis-type model, as proposed by Oguntunde *et al*. (2007). It was demonstrated that once optimised a single set of response functions for canopy conductance, obtained in each orchard, can be used to predict transpiration accurately in the respective orchard for periods over six months. This approach may be applicable to sub-tropical conditions where wetting of the canopy by rainfall and occurrence of cloudy/overcast conditions are both infrequent. This result is similar to what was established by Whitely *et al*. (2009) who also reported that this approach could be applied in a forest species for a fairly long time. The ability of a single set of response functions to predict transpiration when the Jarvis-type model was parameterized using data in the respective orchards does put hope in the method as a way of mechanistically predicting citrus transpiration. It was also shown that the parameters of the Jarvis model obtained in an orchard in the summer rainfall are not suitable for predicting conductance (and hence transpiration) in the same or different region. This was attributed to the fact that the parameters obtained in one orchard contain artifacts of the measured data that may not exist in the other orchards. The factors that could potentially influence these parameters and hinder the transferability of the Jarvis-type model, which could not be ascertained in this study, include differences in varieties, climatic conditions and crop load. This approach will only be applicable if parameterized with measured data.

6.6 Recommendations for future research

Knowledge of water use of citrus orchards is crucial for irrigation planning and management. In this study transpiration of three citrus orchards was measured, and; the data was used to test some of the models that can be used to estimate water use in these orchards. Nevertheless, questions related to water use of citrus orchards still remain unanswered. Measurements of transpiration in three orchards presented in this study are not exhaustive on how much water use is used by citrus under all environmental conditions and management strategies in South Africa. Measurement of transpiration should be conducted in different growing regions under the different strategies to consolidate the base information of citrus orchard transpiration attained in this study. Such monitoring experiments should aim to address water use of the trees in relation to factors possibly impacting transpiration e.g. canopy size, rootstock/scion combinations and crop load. Citrus water use measurements should be conducted simultaneously with environmental monitoring to allow for further improvement of the modelling approaches that were evaluated in this study. There is room for improvement in the estimation of the r_l term so as to use the method predicting transpiration on daily time scale. The approach for transferring the Jarvis-type model amongst orchards needs further research. A starting point would be to determine a maximum canopy conductance value of citrus that is independent of the measured transpiration data for parameterization of such a model. Information on water use of specific rootstock/scion combinations obtained for long periods covering consecutive seasons can also be used to answer question pertaining to the transferability of Jarvis-type canopy conductance model amongst different varieties that arose in this study. The exploration of other modelling approaches such as a combination of a crop coefficient and a maximum transpiration rate as envisaged by Sinclair and Allen (1982) should be considered as well. Using such a model, it will be important to be able to determine what the maximum transpiration rate would be for a certain sized canopy, which may be addressed by way of extensive measurements mentioned above.

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