Crop coefficient approaches based on fixed estimates of leaf resistance are not appropriate for estimating water use of citrus

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Abstract

The estimation of crop water use is critical for accurate irrigation scheduling and water licenses. However, the direct measurement of crop water use is too expensive and time consuming to be performed under all possible conditions, which necessitates the use of water use models. The FAO-56 procedure is a simple, convenient and reproducible method, but as canopy cover and height vary greatly among different orchards, crop coefficients may not be readily transferrable from one orchard to another. Allen and Pereira (2009) therefore incorporated a procedure into the FAO-56 approach which estimates crop coefficients based on a physical description of the vegetation and an adjustment for relative crop stomatal control over transpiration. Transpiration crop coefficients derived using this procedure and fixed values for citrus, did not provide good estimates of water use in three citrus orchards. However, when mean monthly leaf resistance was taken into account,

good agreement was found with measured values. A relationship between monthly reference evapotranspiration and mean leaf resistance provided a means of estimating mean leaf resistance which estimated transpiration crop coefficients with a reasonable degree of accuracy. The use of a dynamic estimate of mean leaf resistance therefore provided reasonable estimates of transpiration in citrus.

Introduction

Citrus is one of the most important fruit tree crops in the world, with over 5.4 million ha currently under cultivation. Many of these orchards are planted in semi-arid regions or subtropical regions where rainfall is seasonal and as a result the vast majority of these evergreen, perennial orchards are under irrigation. This represents a significant irrigation requirement and with more pressure being placed on agriculture to reduce water use and with the increase in pollution of natural water resources, it is becoming increasingly important to accurately estimate water use of cultivated crops. Citrus is also an important crop in South Africa, where an additional driver for improved water management is an increase in electricity tariffs, where growers aim to schedule irrigation more efficiently to reduce pumping costs. It was as a result of the need for more definitive information on water use of fruit tree crops that the Water Research Commission of South Africa solicited, managed and funded a project for determining fruit tree water use, with co-funding from the South African Department of Agriculture, Forestry and Fisheries (Water Research Commission 2008).

Water use measurements are too expensive and time consuming to perform in all crops under all conditions and as a result various water use models have proved very useful in extrapolating measured data and predicting water use. The crop coefficient (K_c) approach described by Allen et al. (1998) has been used extensively in irrigation water management and is currently considered the standard method for determining crop water use, due largely to its relative simplicity. However, in tree crops, a linear relationship between the evapotranspiration (ET) 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 often means

Table 1. Seasonal crop coefficients determined in citrus orchards across the growing regions of the world

Reference	Region	ET method	f_c (%)	ET_o (mm day^{-1})				K_c			
				Summer[b]	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
Marin and Angelocci (2011)	Brazil	Aerodynamic method		4.4		2.7		0.7		0.26	
Villalobos et al. (2009)	Spain	Eddy covariance			4.99		5.88		0.44		0.43
Snyder and O'Connell (2007)	USA	Surface renewal	66-70	6.27	3.03	1.10	4.13	1.00	1.07	1.15	1.13
Alves et al. (2007)	Brazil	Lysimeter	22-42	4.40	3.49	2.90	4.30	1.13	1.02	0.60	0.86
García Petillo and Castel (2007)	Uruguay	Water balance	50	4.99	1.77	1.45	4.06	0.64	0.77	0.84	0.83
Rana et al. (2005)	Italy	Eddy covariance						1.04	0.77	0.81	1.16
Castel (1997)	Spain	Lysimeter	27	4.78	2.69	2.06	3.75	0.40	0.62	0.42	0.28
Castel et al. (1987)	Spain	Water balance	70	4.93	2.57	1.53	3.43	0.70	0.77	0.65	0.61
Rogers et al. (1983)	USA	Water balance	70	4.1	3.13	2.37	4.37	1.04	1.01	0.93	0.81
Hoffman et al. (1982)	USA	Water balance	70	7.7	4.1	2.27	5.27	0.85	0.83	0.77	0.80
Green and Moreshet (1979)	South Africa	Lysimeter	100	6.86	3.15	2.62	4.59	0.80	1.28	0.79	0.62
van Bavel et al. (1967)	USA	Water balance		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. Values presented are the average for each three month period.

that K_c values derived in one location may not be readily transferable to other locations, which limits the extrapolation of such data to different climatic zones, with different orchard management practices. This is evident in the wide range of published K_c values for citrus (Table 1), where variation is attributed to 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). Snyder and O'Connell (2007) illustrate the site specific nature of their citrus crop coefficients by including the following proviso that these recommendations are for "clean-cultivated, microsprinkler irrigated, mature orchards in the San Joaquin Valley of California or in regions with similar climatic conditions". As much of the variation in K_c values is also attributed to evaporation from the soil, as a result of different irrigation systems and rainfall patterns (Villalobos et al. 2009), the measurement of transpiration should allow improved estimates of transpiration crop coefficients (K_t) of citrus orchards and reduce the need to perform costly measurements of tree water use under different environmental conditions and management practices. Villalobos et al. (2013) also stress the importance of determining transpiration, as this is related to tree assimilation and productivity and it allows accurate partitioning of ET between transpiration and soil evaporation.

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. The aim of this paper was therefore 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. K_t values, 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.

Materials and Methods

Experimental Site

Measurements of citrus [*Citrus sinensis* (L.) Osbeck] water use were conducted in three orchards in the summer and winter rainfall regions of South Africa over three consecutive seasons (Table 2). Measurements in the summer rainfall region were conducted in the Limpopo Province at Moosrivier Farm (Schoeman Boerdery Group) near Groblersdal, in commercial orchards planted with „Delta" Valencia (25° 02" 32.69" S and 29° 22" 09.76" E, 900 m.a.s.l., orchard area of 11 ha) and „Bahianinha" Navel trees (25° 01" 42.53"" S and 29° 22" 46.16"" E, 870 m.a.s.l., orchard area of 2.4 ha) in the 2008/09 and 2009/10 seasons. The area receives an average annual rainfall of 535 mm and has average minimum and maximum temperatures of 12°C and 25°C. In the winter rainfall region measurements were conducted at Patrysberg Farm in the Western Cape Province (32° 27" 15.43"" S and 18° 58" 3.58"" E, 149 m.a.s.l., orchard area 3.9 ha) near Citrusdal, in a commercial orchard planted with „Rustenburg" Navels in the 2010/11 season. The area receives an average annual rainfall of 200 mm and has average minimum and maximum temperatures of 10°C and 24°C.

The 11 year-old „Delta" Valencia trees, in the summer rainfall region, were grafted on „Swingle" citrumelo rootstocks and were planted in 1997, in a north-south orientation (0° N). Tree spacing was 5.5 x 2.75 m and every alternate tree was "sandwich" pruned, meaning this tree was pruned narrower every year to allow 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 and average effective fraction of ground covered or shaded by vegetation ($f_{c\ eff}$) was 0.6 (calculated as described in the section on the estimation of crop coefficients and was an average for the season).

Table 2 Details of the three study orchards in which sap flow measurements were performed. ET_o = reference evapotranspiration, $f_{c\ eff}$ is the effective fraction of ground covered or shaded by the vegetation at solar noon

Orchard	'Delta' Valencia	'Bahianinha' Navel	'Rustenburg' Navel
Location	Groblersdal	Groblersdal	Citrusdal
GPS co-ordinates	25° 02' 32.69" S, 29° 22' 09.76" E	25° 01' 42.53'' S, 29° 22' 46.16'' E	32° 27' 15.43'' , 18° 58' 3.58'' E
Start	01-08-2008	03-09-2009	13-08-2010
End	30-07-2009	30-06-2010	12-08-2011
Duration (days)	364	301	365
Age (years)	11	6	14
Planting pattern (m)	5.5 x 2.75 m	6 x 2 m	5 x 2.5 m
$f_{c\ eff}$	0.60	0.63	0.88
Height (m)	4.1 m	2.3 m	3.3 m
ET_o (mm)[a]	1668	1423	1528
Rainfall (mm)[a]	579	518	203
Irrigation (mm)[a]	925	261	600
Transpiration (mm)[a]	682	468	672

[a]Accumulated total for the period of measurement

Yield for the 2008/09 season was disappointing (28 t ha^{-1}) due to fruitlet abscission during hot and dry conditions shortly after fruit set. The orchard was drip irrigated with one line per tree row with pressure compensating emitters with a discharge of 2 L h^{-1} spaced 1 m apart. Typically the orchard received irrigation on a daily basis, with two to three 2 h pulses per day. The soil texture was a sandy loam, with an average of 7-12 % clay in the top metre.

The 6 year-old „Bahianinha" Navel trees, also in the summer rainfall region, were grafted on „Carrizo" citrange rootstocks and were planted in 2003 on ridges. The row orientation was 51° ENE, with north being 0°. Tree spacing was 6 x 2 m, with trees pruned to a constant average height of 2.3 m and width within the row of 1.8 m every year after harvest, such that a complete hedgerow was not formed. Average tree height was 2.5 m and average $f_{c\ eff}$ was 0.63. Yield for the 2009/10 season was well below the average for this orchard (15 t ha^{-1}), as a result of poor flowering associated with a late harvest in the previous season. The orchard was drip irrigated with one line per tree row using pressure compensating emitters spaced 1 m apart with a discharge of 2.3 L h^{-1}. Typically the orchard received irrigation on a daily basis, with three to four 1 h pulses per day. The soil texture was a sandy loam with an average of 5-10 % clay in the top metre.

The 14 year-old „Rustenburg" Navel trees, in the winter rainfall region, were grafted on „Troyer" citrange rootstocks and were planted in 1996 on ridges. The row orientation was 79° ENE. Tree spacing was 5 x 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. Average tree height was 3.3 m and average $f_{c\ eff}$ was 0.88. Yield for the 2010/11 season was 75 t ha^{-1}. 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}. Typically the orchard was irrigated on a daily basis, with one 2-3 h pulse per day. The soil texture was a sandy loam with an average of 5-10 % clay in the top metre.

All orchards were managed according to GLOBALG.A.P standards and were selected based on a history of excellent production and on advice received from extension officers of Citrus Research International. Irrigation scheduling was

performed by the growers by monitoring soil water content with capacitance probes and adjusting a daily irrigation schedule to maintain the soil water content within limits determined based on soil texture and experience in each irrigation block. Profile pits were dug at the start of the measurement period in each orchard to install soil water monitoring equipment and at this time root distribution and any evidence of waterlogging was visually assessed. None of the orchards showed any typical mottling of the soil associated with waterlogging and there was ample evidence of a healthy root system. Daily irrigation volumes were determined by placing two tipping bucket rain gauges under drippers in each orchard. In addition, in line water meters were read every two weeks and provided a check on volumes estimated using the tipping buckets. In Groblersdal the area along the tree rows, with a width of 1 m, was kept clear of weeds through the use of herbicides, with a grass cover between rows. In Citrusdal the orchard was mostly free of vegetation between rows, largely as a result of a significant dry period in summer.

Sap flow and Transpiration

Sap flow measurements were performed using the heat ratio method as described by Burgess et al. (2001) on four trees in each orchard at Groblersdal and six trees at Citrusdal. Trees were selected in the centre of each block. In the „Delta" Valencia orchard the four sample trees included two sandwich pruned trees. Four heat pulse probe sets were inserted to four different depths in each tree trunk to account for the radial variation in sap flux within the conducting sapwood (Table 3). These probe sets were inserted above the rootstock in the scion and below the first branch, with the probes being equally spaced around the trunk and randomly arranged, taking care to avoid any abnormalities in the trunk. Each probe set consisted of two Type T (copper/constantan) thermocouples (embedded in 2 mm outside diameter PFTE tubing) placed equidistantly (0.5 cm) upstream and downstream of the stainless steel heater probe (1.8 mm). The heat pulse velocity (V_h) in cm h^{-1} for each probe set was calculated following Marshall (1958) as:

$$V_h = \frac{k}{x} \ln\left(\frac{v_1}{v_2}\right) * 3600 \qquad (1)$$

Table 3 Trunk circumference (mm) and probe insertion depths for trees selected for **sap flow measurements** in the three orchards.

Orchard	Stem circumferences (mm)	Insertion depths of probes (mm)
'Delta' Valencia	327; 382; 394; 477,	10; 20; 30; 40
'Bahianinha' Navel	313; 346; 306 222	7; 20; 30; 40 7; 14; 22; 30
'Rustenburg' Navel	345; 280 392; 444; 384; 442	8; 15; 25; 30 10; 18; 30; 40

where k is the thermal diffusivity of green (fresh) wood (assigned a nominal value of 2.5×10^{-3} cm^2 s^{-1}, (Marshall 1958)), x is distance in cm between the heater and either the upper or lower thermocouple, v_1 and v_2 are increases in temperature after the 0.4 s 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 or CR1000 data logger and an AM16/32B multiplexer (Campbell Scientific Ltd, Logan, Utah, USA). Conversion of heat pulse velocities to sap flux densities, taking into account wounding, were performed according to Burgess et al. (2001). Whole stem sap flux (assumed to be equal to transpiration) was calculated as a product of sap flux density and weighted sapwood cross-sectional area represented by each probe set. The presence of heartwood was determined by taking wood cores with an incremental borer. As there was no change in colour of the wood from the outside (youngest wood) to the centre of the core (oldest wood) in any of the samples taken in each orchard, it was assumed that no heartwood was present. 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. 15.125 m^2 in the „Delta" Valencia orchard, 12 m^2 in the „Bahianinha" Navel orchard and 12.5 m^2 in the „Rustenburg" Navel orchard. 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 other two orchards orchard transpiration 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 (Fig. 1).

Orchard transpiration was calibrated against micrometeorological measurements of ET during periods of negligible evaporation from the soil and cover crop in the „Delta" Valencia orchard using a empirically determined wound correction coefficient, which was determined to be 3.2 mm (Fig. 2). Although calibration focused on the wound width, it will also account for possible uncertainties in sapwood moisture content, sapwood density and the upscaling from individual trees to orchard scale. Similar sap flow calibrations have been performed by Williams et al. (2004) in an olive orchard assuming evaporation from the soil is negligible and by using a combination
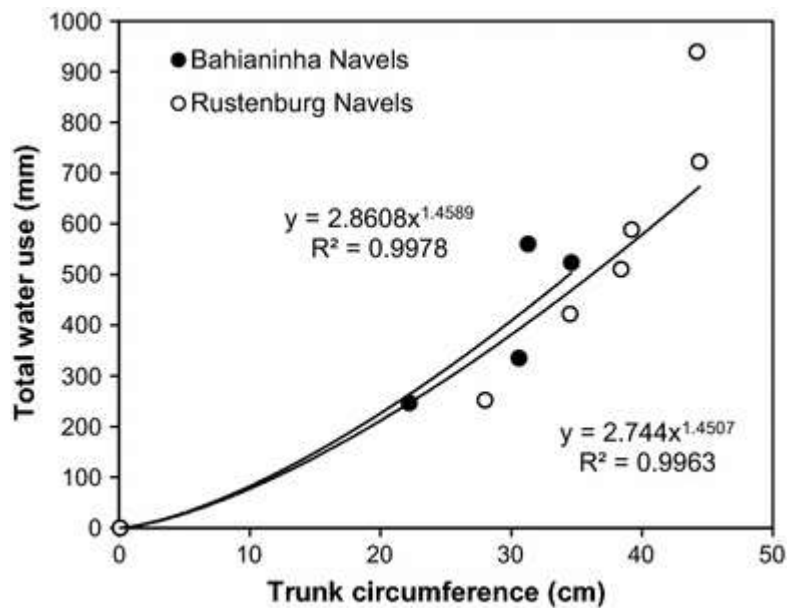
Fig. 1 : Relationship between trunk circumference and seasonal water use for the „Bahianinha" and „Rustenburg" Navel orchards
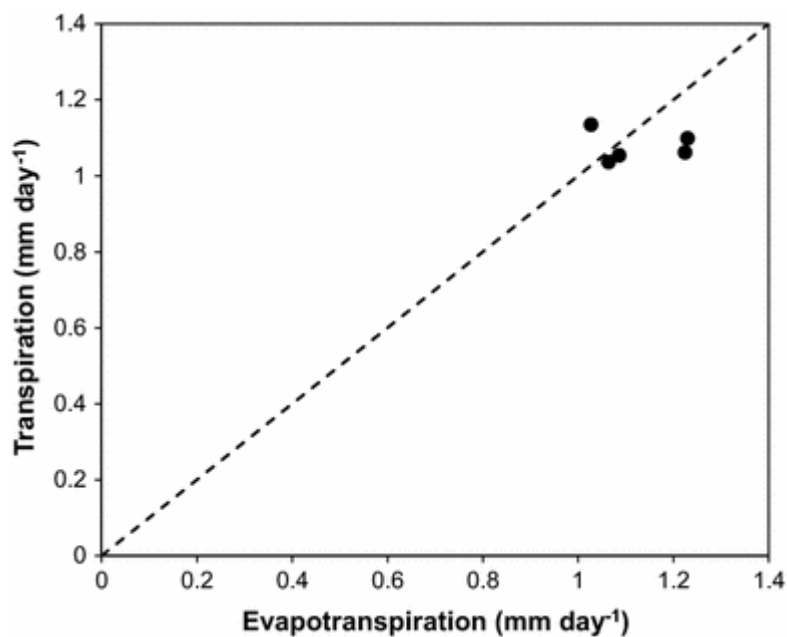

Fig. 2 : Comparison of daily crop evapotranspiration, measured with an eddy covariance system, with calibrated transpiration, determined using the heat ratio method, for the autumn measurement window in the „Delta" Valencia orchard in May 2009, when evaporation from the soil was negligible

of eddy covariance and micro-lysimeter measurements in a vineyard (Poblete-Echeverría et al. 2012), pear orchard (Conceição and Ferreira 2008) and broad-leaved forest (Köstner et al. 1992). The advantage of this method of calibration is that it can be performed in field without the use of weighing lysimeters, which although ideal, are expensive to install and require a number of years for the tree planted in the lysimeter to reach an adequate size for measurement. It is also non-

destructive as compared to stem perfusion and potometer calibration methods. However, eddy covariance measurements can be associated with some degree of error, but these can be assessed and minimised through careful analysis of the data (Allen et al. 2011a). In addition, whilst water use of a single tree is determined in a lysimeter, eddy covariance measurements represent a much larger area and a number of trees. The size and the shape of the area sampled are not fixed in time and vary with wind speed and direction (Horst and Weil 1992; Baldocchi 1997). However, there was adequate fetch and as measurements in this study were conducted in a large orchard of clonal trees this variation is expected to be minimal. As the need for calibration arises largely due to the variation in the distribution of sap conducting vessels within the sapwood (Green and Clothier 1988), which is assumed to be conservative for a species, a single calibration for a species for a specific sap flow technique should be sufficient (Smith and Allen 1996) and it should be transferable to other citrus orchards. In addition, a single calibration should also be sufficient as Pernice et al. (2008), Fernández et al. (2001), Giorio and Giorio (2003) and Poblete-Echeverría et al. (2012) showed no reduced sensitivity due to injury effects caused by probe implantation over a period of 2 months to 3 years.

Micrometeorological measurements

Micrometeorological measurements for the estimation of ET, via the eddy covariance method, were performed for short window periods in each orchard, due to restrictions on the availability of equipment. Calibration of the heat ratio method for citrus was performed during a window period in May 2009 in the „Delta" Valencia orchard, when no rainfall occurred, the grass cover between the tree rows was dormant and evaporation from the soil was considered negligible. Fluxes of latent (LE) and sensible heat (H) were measured with an extended open path eddy covariance (OPEC) system, comprising a CSAT3 three-dimensional sonic anemometer (Campbell Scientific Inc., Logan, Utah, USA) and an LI-7500 open path infrared gas analyser (LiCor Inc., Lincoln, Nebraska, USA), which was mounted on a lattice mast 6.2 m above the soil surface (2 m above the canopy). Upwind fetch of the prevailing northerly winds was 300 m. 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 radiation (R_n) was measured using two net radiometers (Model 240-110 NR-Lite, Kipp & Zonen, Delft, Netherlands), one above the trees, 7.1 m above ground, and the other between the rows, placed 8.0 m from the ground surface. Accuracy of the R_n measurements were compared against R_n estimated using standard equations (Allen et al. 1998) based on solar radiation from an automatic weather station (AWS) located at the site (Allen et al. 2011b). Four soil heat flux plates (model HFT-S, REBS, Seattle, Washington, USA) were used to measure soil heat flux (G) at a depth of 80 mm under the trees and between the rows, and four TCAV-L soil temperature averaging probes (Campbell Scientific Inc., Logan, Utah, USA) 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 of the soil surface was measured using a time domain reflectometer (CS616, Campbell Scientific Inc., Logan, Utah, USA). These sensors were connected to a CR23X datalogger (Campbell Scientific Inc., Logan, Utah, USA) and measurements were performed at 10 Hz frequency and averages obtained every 30 minutes. Energy balance closure for the measurement period varied between 0.3 and 6%, indicating good closure (Fig. 3).
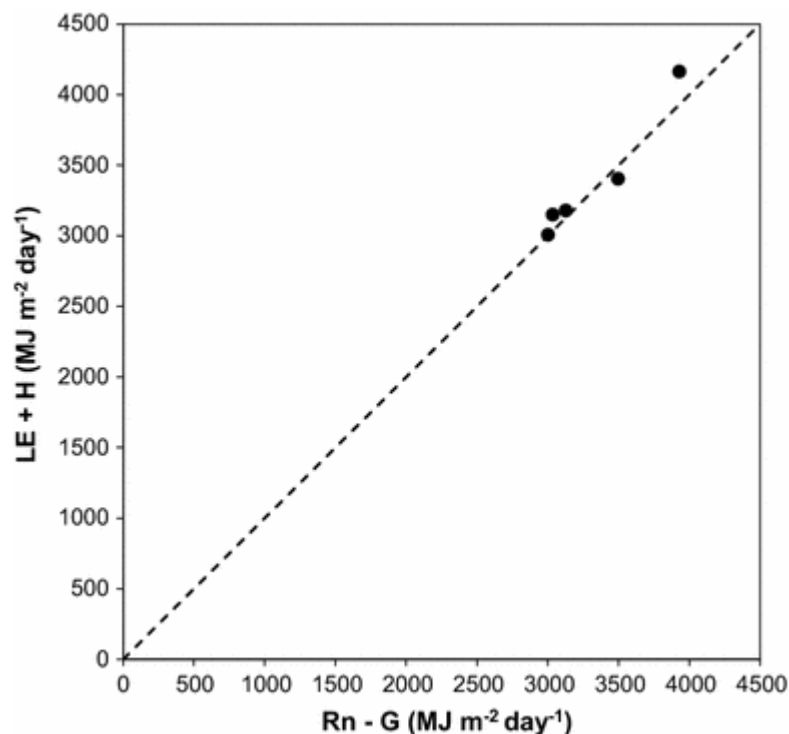

Fig. 3 : Daily energy balance closure for the eddy covariance measurements in the „Delta" Valencia orchard in May 2009

Reference evapotranspiration

Reference evapotranspiration (ET_o) was determined using the FAO Penman-Monteith equation (Allen et al. 1998) from weather data obtained from an AWS located on each farm (within 2 km of the orchards). 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, calculated ET_o is likely to be slightly overestimated, as compared to calculations made using weather data collected over a reference surface (Allen 2008). 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 slightly underestimated, as compared to standard conditions (Allen 2008). The weather parameters recorded were wind speed, solar radiation, temperature, relative humidity and rainfall. 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 for both weather stations and R_s measurements were therefore adjusted upwards based on the average value of R_s/R_{so} on clear days (Allen 2008).

Transpiration crop coefficients

Transpiration crop coefficients were determined from measured tree transpiration and reference evapotranspiration:

$$K_t = \frac{T}{ET_o} \qquad\qquad (2)$$

where K_t is the transpiration crop coefficient, T is transpiration estimated from sap flow measurements and ET_o is computed reference evapotranspiration. 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.

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

The procedure described by Allen and Pereira (2009) was used to estimate transpiration crop coefficients in the three orchards from measurements of fractional ground cover, tree height and daily weather data. K_t was adjusted for variation in vegetative cover by using a density coefficient (K_d) as follows:

$$K_t = K_d(K_{t\,full}) \tag{3}$$

where $K_{t\,full}$ is defined as the transpiration crop coefficient during peak plant growth for conditions having nearly full ground cover (or LAI > 3).

According to Allen et al. (1998), for large stand size (greater than about 500 m^2), $K_{t\,full}$ for use with ET$_o$ can be approximated as a function of mean plant height and adjusted for climate as:

$$K_{t\,full} = F_r\left(\min(1.0 + 0.1h, 1.20) + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3}\right) \tag{4}$$

where F_r [0-1] is a relative adjustment factor for stomatal control, h is mean monthly plant height (m), u_2 is average monthly wind speed (m s^{-1}) at 2 m for a particular growth period and RH_{min} is the average monthly minimum relative humidity in per cent. 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:

$$F_r \approx \frac{\Delta + \gamma(1 + 0.34u_2)}{\Delta + \gamma\left(1 + 0.34u_2\frac{r_L}{100}\right)} \qquad (5)$$

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. Values of mean monthly r_l for the study orchards were estimated by inverting Eq. 5, after solving for F_r by inverting Eq. 4, using known monthly values of $K_{t\,full}$. $K_{t\,full}$ values were calculated using average monthly K_t (Eq. 2) and K_d values (Eq. 6), both determined from measured data, and inverting Eq. 3. 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.

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

$$K_d = \min\left(1, M_L f_{c\,eff}, f_{c\,eff}^{\left(\frac{1}{1+h}\right)}\right) \qquad (6)$$

where $f_{c\,eff}$ is the effective fraction of ground covered or shaded by vegetation [0.01-1] near solar noon, M_L is a multiplier on $f_{c\,eff}$ and is an attempt to simulate hydraulic resistances within the plant and is expected to range between 1.5 and 2.0, with a value of 1.5 recommended for citrus (Allen and Pereira 2009). $f_{c\,eff}$ 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, $f_{c\,eff}$ was calculated according to Allen et al. (1998) as follows:

$$f_{c\ eff} = \frac{fc}{\sin(\beta)} \leq 1 \qquad (7)$$

where f_c is the observed fraction of soil surface that is covered by vegetation as seen from directly overhead. $f_{c\ eff}$ 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:

$$\beta = \arcsin[\sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)] \qquad (8)$$

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

Statistical analysis

The evaluation of model performance was done with the aid of statistical parameters including coefficient of determination (R^2), mean absolute error (MAE), root of the mean square error (RMSE) and index of agreement (D) of Willmott (1982). Model performance was considered satisfactory when $R^2 > 0.8$, MAE < 20% and D > 0.8 (de Jager 1994).

Results and Discussion

Transpiration in all orchards showed large day to day variation, which was largely determined by the prevailing climatic conditions, as seen from the ET_o data (Fig. 4a, b and c). However, it is evident that even though the atmospheric evaporative demand was highest during summer in all three regions, there was no proportional increase in transpiration at this time. 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 compared to the orchards 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.
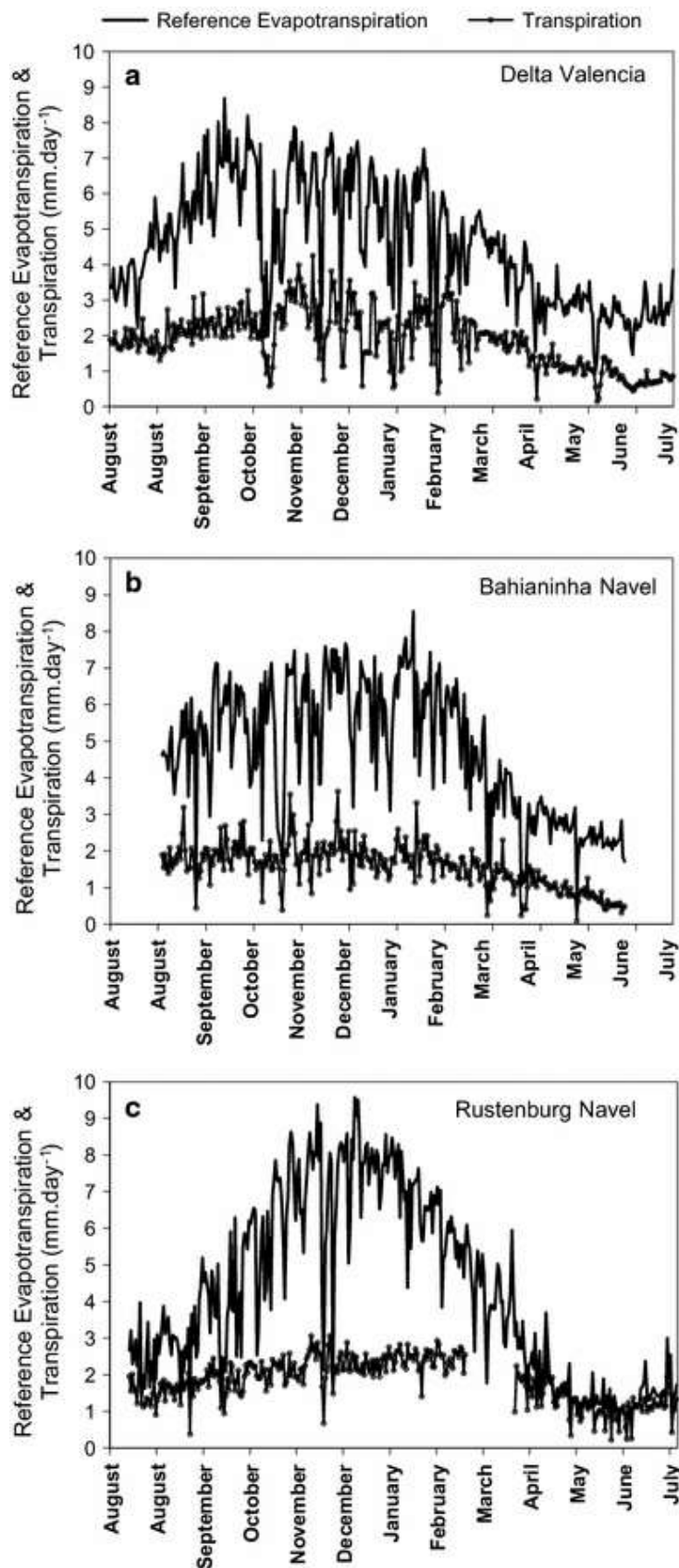
Fig. 4 : Daily transpiration (mm day^{-1}) and reference evapotranspiration (mm day^{-1}) for a the „Delta" Valencia orchard from 1 August 2008 to 31 July 2009, b the „Bahianinha" Navel orchard from 3 September 2009 to 30 June 2010 and c the „Rustenburg" Navel orchard from 13 August 2010 to 12 August 2011 (transpiration data from 18 March to 17 April 2011 is missing as a result of a power failure)

Table 4 Summary of average canopy size for the three orchards and average transpiration (T), transpiration crop coefficients (K_t), reference evapotranspiration (ET_o) and vapour pressure deficit (VPD) for the summer and winter periods of measurements. $f_{c\ eff}$ is the effective fraction of ground covered or shaded by the vegetation at solar noon

Rainfall region	Crop	Canopy size		T (mm day^{-1})		K_t		ET_o (mm day^{-1})		VPD (kPa)	
		Height (m)	$f_{c\ eff}$	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
Summer	Valencia	4.1	0.60	2.30	1.16	0.43	0.38	5.75	2.57	1.37	1.16
	Navel	2.3	0.63	1.90	0.65	0.35	0.28	6.09	2.53	1.47	0.98
Winter	Navel	3.3	0.88	2.26	1.08	0.31	0.71	6.42	1.62	2.24	0.74

Differences in transpiration between seasons and rainfall regions become more evident when averages for summer and winter are compared between the different rainfall regions (Table 4). In the summer rainfall region, despite large differences in average daily ET_o during the year, the average K_t for both orchards remained relatively constant throughout the year, which agrees with the single crop coefficient for citrus suggested by Allen and Pereira (2009). However, in the winter rainfall region there was a significant difference in K_t values between the two seasons, with the winter K_t being significantly larger than the summer K_t, as observed by García Petillo and Castel (2007) in Uruguay and Villalobos et al. (2013) in Spain. K_t values in this current study compare well to those reported by Villalobos et al. (2013), who reported summer K_t values ranging between 0.3 and 0.4 and in autumn between 0.4 and 0.6. 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) and higher average transpiration rates at this time in this region (Table 4). 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. VPD during the winter months in the winter rainfall region averaged 0.74 kPa, whilst in the orchards in the summer rainfall region, VPD averaged 1.11 kPa. The lower VPD was also reflected in lower ET_o in winter in the winter rainfall region than in the summer rainfall region.

Whilst this kind of information is of significance to the commercial growers on whose farms the research was conducted, it is not always applicable and readily transferrable to many other regions within South Africa or across citrus growing regions the world over, or even for different seasons. However, direct measurements of transpiration, using a sap flow technique, are an improvement on traditional soil water balance approaches, as these have proved problematic as a result of the two or three dimensional variability in soil water components found in hedgerow crops under micro-irrigation systems (Cohen 1991; Rana and Katerji 2000; Annandale et al. 2003; Testi et al. 2006; Villalobos et al. 2009) and therefore presents a valuable data set for modelling citrus water use. The relatively simple and convenient crop coefficient approach of Allen et al. (1998) relates water use of various crops to evapotranspiration from a well-watered hypothetical short grass reference surface.

However, reports on crop coefficients from different citrus orchards in different parts of the world have yielded very different crop coefficients (Table1). The adjustment of crop coefficients following the procedure of Allen and Pereira (2009) from measurements of canopy dimensions could therefore prove extremely useful in predicting water use in different orchards and citrus growing regions.

K_t values for the measurement orchards were initially derived using parameters for citrus provided by Allen and Pereira (2009), where the value for M_L was set to 1.5, apparent effective r_l for the initial and midseason periods was 420 s m^{-1} and r_l at the end of the season was 150 s m^{-1}, and measured canopy dimensions and weather data were used. However, these transpiration coefficients (K_t Allen and Pereira) did not compare well with the measured K_t values from the three orchards, and were at times in the season higher than the FAO-56 K_{cb} values for citrus given by Allen and Pereira (2009) (Fig. 5 a, b and c). If derived K_t values using the published fixed values of r_l, (Estimated transpiration from K_t Allen and Pereira) were to be applied over a season, they would have resulted in a 94% over estimation of transpiration in the „Delta" Valencia orchard, a 127% overestimation in the „Bahianinha" Navel orchard and a 95% overestimation in the „Rustenburg" Navel orchard (Fig. 6 a, b and c).

The fixed parameters for citrus orchards given by Allen and Pereira (2009) were therefore not able to generate accurate transpiration crop coefficients for the orchards in this study, where specific orchard inputs were effective fractional cover, height and monthly averaged daily weather data. The overestimation of transpiration
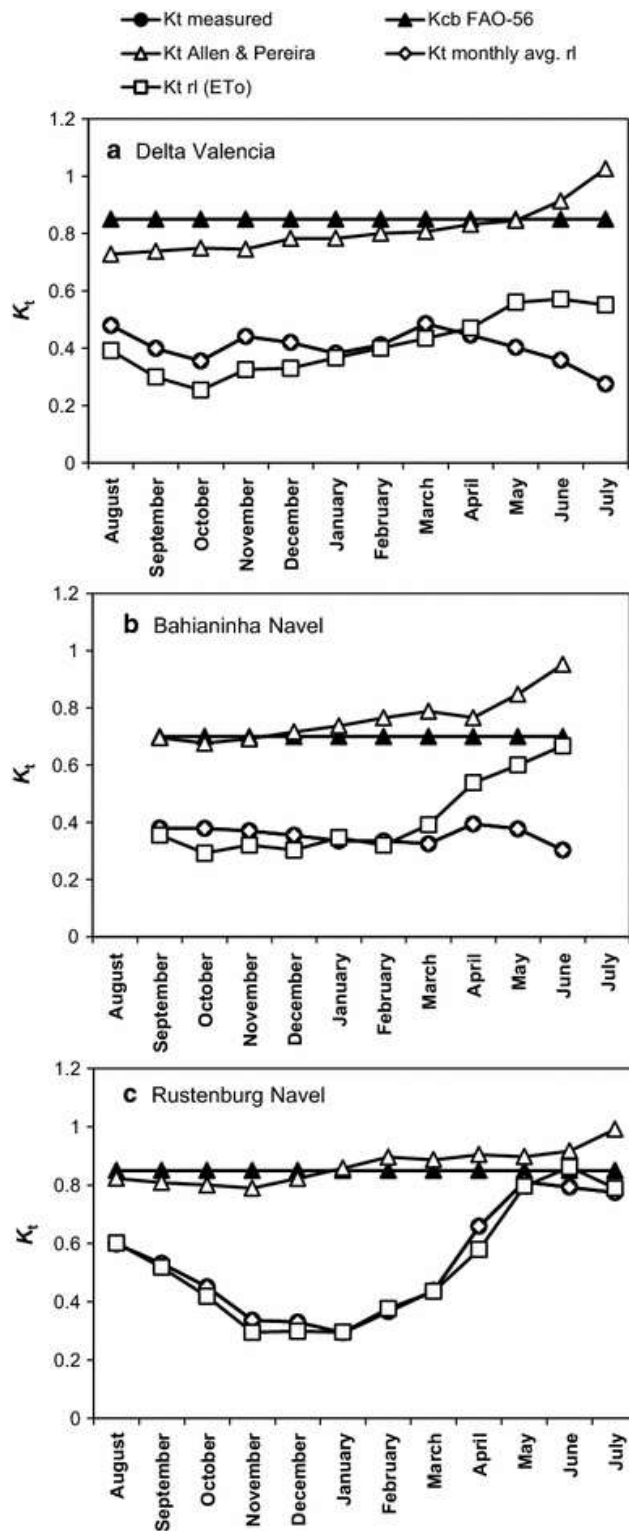
Fig. 5 : Derived monthly transpiration crop coefficients (K_t) for a the „Delta" Valencia orchard, b „Bahianinha" Navel orchard and c „Rustenburg" Navel orchard. Transpiration crop coefficients were determined using measured transpiration (K_t measured), the method described in Allen and Pereira (*2009*) using the parameters given for citrus (K_t Allen and Pereira), using estimates of monthly average r_l values from transpiration data (K_t monthly avg. r_l) 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-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*)
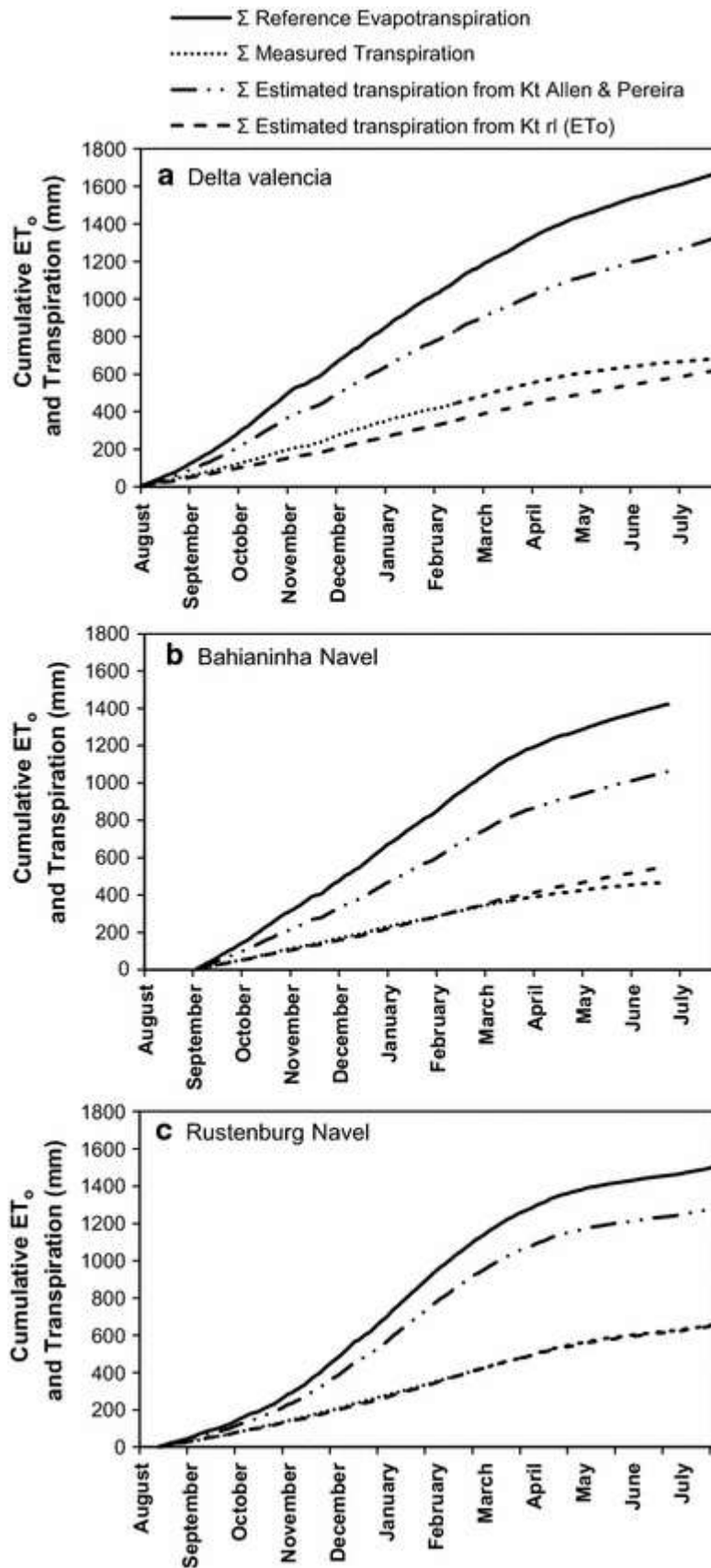
Fig. 6 : Cumulative ET $_o$, measured transpiration and transpiration estimated from the derived transpiration coefficients in a the „Delta" Valencia orchard from 1 August 2008 to 31 July 2009, b the „Bahianinha" Navel orchard from 3 September 2009 to 30 June 2010 and c the „Rustenburg Navel orchard from 13 August 2010 to 12 August 2011

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. It is suggested that a more appropriate value for r_l can be estimated for the determination of F_r by inverting Eq. 5, after solving for F_r by inverting Eq. 4, using known values of $K_{t\ full}$ (Allen and Pereira 2009). Monthly $K_{t\ full}$ values for this study were obtained by scaling measured monthly K_t values with the density coefficient (K_d, Eq. 3), and were used to calculate a mean monthly r_l. Although these values may only be useful for re-use in Eq. 5, it is clear that mean monthly estimated r_l (Fig. 7) is not constant throughout the season and varies with leaf age and climatic conditions, as found by van Bavel et al. (1967). As a result of the greater degree of stomatal control of transpiration in citrus, which is more evident at high VPDs (Sinclair and Allen 1982), leaf resistance in all three orchards increased in the summer months, which results in a disproportionate increase in ET$_o$ relative to transpiration and therefore a lowering of the appropriate crop coefficient.
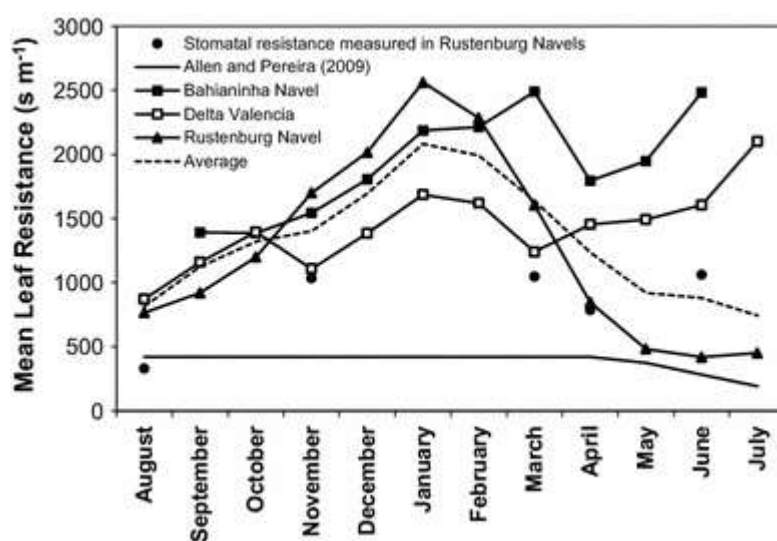

Fig. 7 : Monthly mean leaf resistances from the three citrus orchards calculated using the procedure outlined in Allen and Pereira (*2009*), compared with the value suggested by Allen and Pereira (*2009*) for citrus and daily stomatal resistance measured in the „Rustenburg" Navel orchard in Citrusdal

As the calculated monthly average r_l values were derived directly from measured K_t values (K_t measured), it is not surprising that they provided very good estimates of K_t (K_t monthly avg. r_l) for the three orchards (Fig. 5 a, b and c), with the two plots sitting perfectly on top of one another. This indicates that a change in leaf resistance in a citrus orchard over the season needs to be taken into account. Unlike Allen and Pereira (2009) suggested, resistance in the study orchards did not decline at the end of the season, and in Groblersdal, r_l increased at this point. Whilst it is acknowledged that these r_l values contain artifacts of the $K_{t\ full}$ estimates, weather data error and the constructs of Eq. 4 and Eq. 5 and should only be used with confidence for the estimation of F_r (Allen and Pereira 2009), a comparison of these resistance values (ranging from 419 to 2694 s m^{-1}) with published measured data indicates that leaf and canopy resistances higher than 420 s m^{-1} are routinely found in citrus. In the summer rainless months in Israel daily leaf resistances in Shamouti orange varied from 500 to 2000 s m^{-1} (Cohen and Cohen 1983) and in winter in Zimbabwe, resistances in young Navel orange trees varied from 200 to 8280 s m^{-1} (Dzikiti et al. 2007). Pérez-Pérez et al. (2008) also reported stomatal resistances ranging between 295 and 830 s m^{-1} in oranges throughout the fruit growth period in Southern Spain. However, average daily stomatal resistance, measured in the various citrus orchards in Citrusdal, was between 300 and 1000 s m^{-1} (Fig. 7), which was considerably lower than the r_l values of between 530 and 2694 s m^{-1} for this period, but generally the trend was very similar. The r_l values in Fig. 7 thus seem to be a little higher than actual r_l could be expected to be in a citrus orchard, and may therefore be slightly biased by the procedure outlined by Allen and Pereira (2009), indicating that measured leaf resistances could potentially underestimate crop coefficients when used in Eq. 5. This requires further investigation, especially during the hot summer months, but it is clear that r_l values higher than 420 s m^{-1} are routinely found in citrus and seasonal variation must be taken into account.

Whilst calculating mean r_l values resulted in the accurate estimation of K_t values in the three orchards, 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. In order to make this approach more transferrable, the parameterization of r_l was attempted for the Citrusdal site with climatic data in the 2010/11 season, to determine if there was a reproducible

relationship between r_l and a routinely measured weather variable, such as relative humidity, VPD or ET_o. The most reproducible empirical relationship on a monthly basis was found between ET_o (mm day^{-1}) and mean estimated r_l (s m^{-1}) (Fig. 8),
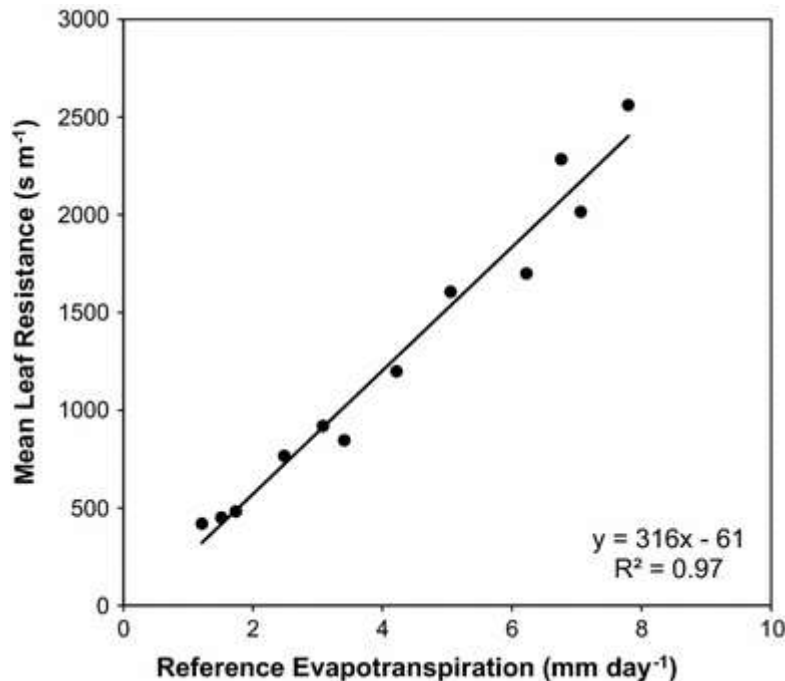

Fig. 8 : Relationship between mean leaf resistance and reference evapotranspiration (ET $_o$) for the „Rustenburg" Navel orchard in the 2010/2011 season

where r_l = 316 ET_o - 61 described the relationship with an excellent coefficient of determination (R^2) of 0.97. When comparing seasonal estimates of transpiration based on estimated K_t values (K_t r_l (ET_o)) (Figs 5 a, b and c) from this relationship, transpiration was underestimated by 0.1% in the 2010/11 season and by 11% in the 2011/12 season in the „Rustenburg" Navels, and underestimated by 9% in the „Delta" Valencia orchard and overestimated by 18% in the „Bahianinha" Navel orchard (Fig. 6 and Fig. 9). The performance of the model, as determined by statistical parameters, was good for the two seasons in the orchards in Citrusdal, as the MAE was less than 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. However, considering the empirical nature of the relationship between r_l and ET_o this exceeded expectations and provided reasonable estimates on a seasonal basis. In the „Delta" Valencia and „Bahianinha" orchards, transpiration was underestimated at the beginning of the season and overestimated at the end of the
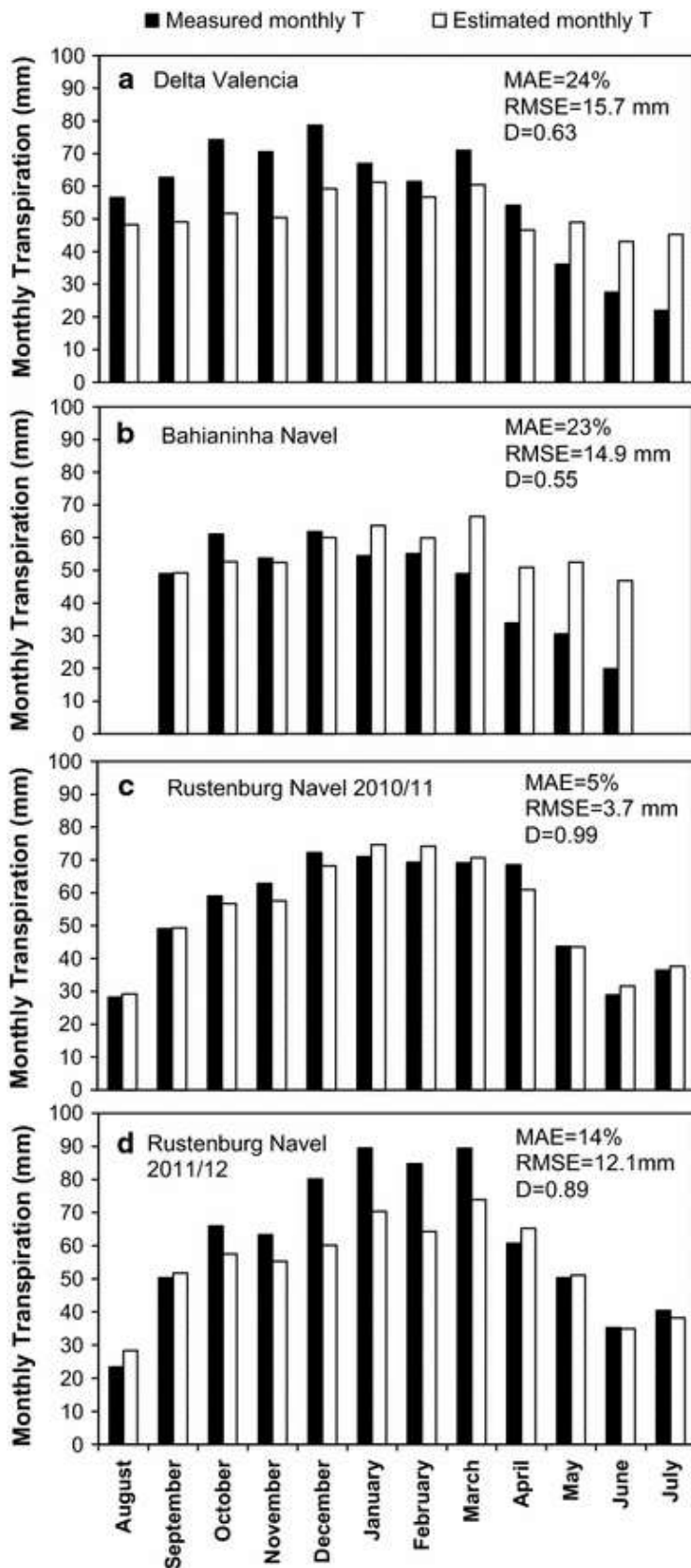
Fig. 9 : Comparison between monthly measured and estimated transpiration using K_t values derived from mean leaf resistance, estimated from the relationship between reference evapotranspiration and mean leaf resistance, for the a „Delta" Valencia orchard, b „Bahianinha" Navel orchard, c „Rustenburg" Navel orchard in the 2010/2011 season and d „Rustenburg" Navel orchard in the 2011/2012 season. MAE is mean absolute error, RMSE is root of the mean square error and D is the index of agreement of Willmott (*1982*)

season (Fig. 9a). 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, (Fig. 9b). In the „Rustenburg" Navel orchard, in the 2010/11 season, good estimates of water use were obtained throughout the season (Fig. 9c). However, in the subsequent 2011/12 season, water use was underestimated during the peak water use period from October to March (Fig. 9d), but model performance was still satisfactory (MAE=14% and D=0.89).

The use of a simple empirical relationship between ET_o and r_l, together with the procedure outlined by Allen and Pereira (2009), provided good seasonal transpiration estimates in the study orchards, implying that this method could be used for irrigation planning purposes and water licensing. 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 radiant flux energy, ambient CO_2 concentration, leaf to air 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 link 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

Alternatively, a combination of a crop coefficient approach, together with the concept of a maximum transpiration rate (Sinclair and Allen 1982) needs to be considered, where it is recognised that the tree is only able to supply a certain maximum amount of water to the atmosphere, irrespective of the atmospheric demand. This is mainly attributed to high internal resistances to water movement in citrus (Cohen and Cohen 1983; Syvertsen and Graham 1985; Rodríguez-Gamir et al. 2010). If using such a model it will be important to be able to determine what this maximum transpiration rate would be for a certain sized canopy, which in itself is not a trivial matter and may also be influenced by sink source relationships and by rootstock choice. Ultimately, 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. In order to obtain accurate water use estimates for citrus using crop coefficients, the crop coefficient often needs to be decreased during the hottest time of the year when VPD increases. This can be done by using a dynamic estimate of leaf resistance which gives reasonable estimates of water use for much of the season. However, more mechanistic models which are able to capture the control of transpiration through canopy conductance in citrus varieties, and other crops displaying similar stomatal control, such as olive and macadamia, should be considered for improved water management.

Acknowledgements

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