Validation of a simple canopy conductance model for estimating transpiration of different citrus species under non-limiting soil water conditions

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Abstract

Improved estimates of transpiration (T) in citrus orchards are important to sustain production, especially in areas with limited water availability. Citrus trees exhibit stomatal control over T; with transpiration mainly modulated by canopy conductance (G_c) and vapour pressure deficit (VPD), suggesting that these would be important parameters in any citrus water use model. A study was therefore conducted to calibrate and validate a simple G_c model that estimates transpiration as a function of total daily radiation intercepted and VPD, together with derived parameters that represent radiation use efficiency and the response of G_c to VPD. The study was conducted in different citrus species with varying canopy sizes, grown in summer and winter rainfall regions of South Africa. The species used in the study were: 'Star Ruby' grapefruit, 'Midknight' Valencia orange, 'Valley Gold' mandarin and 'Nadorcott' mandarin. The aim of the study was to validate a G_c approach for estimating T of a wide range of citrus orchards to address the uncertainty of using a demand-limited model, such as the crop coefficient approach, in a species that is supply limited. In all the experimental orchards, T was measured with the heat ratio sap flux density method. The model was found to be more reliable for estimating monthly transpiration than for daily estimates in all orchards. On a monthly time, scale, acceptable statistical criteria were observed, with Wilmott index of agreement (D) > 0.8, mean absolute percentage error (MAPE) < 15%, root mean square error (RMSE) < 2.5 mm day^{-1} and $R^2 > 0.70$. However, discrepancies were observed on a daily time scale, particularly under conditions of low atmospheric evaporative demand. The good estimates of monthly T suggest that the model could be very useful for making strategic decisions regarding water management practices and planning. Improvement is needed for better daily estimates of T, as this will be important for tactical decisions, such as irrigation scheduling.

Keywords: fractional interception of photosynthetically active radiation, vapour pressure deficit, irrigation management

INTRODUCTION

Quantifying crop water use (transpiration (T) and soil evaporation) in citrus orchards is important for water management strategies, such as irrigation scheduling, water licensing and irrigation system planning (Jamshidi. et al., 2020). However, direct measurement of crop water use are too expensive and time consuming to be performed under all possible conditions, therefore, it is necessary to employ water use models (Taylor. et al., 2015). In most agricultural crops, the FAO-56 crop coefficient (K_c) procedure is the most widely used and convenient method for estimating water use (Pereira. et al., 2006). The FAO-56 model is an atmospheric demand-driven model and may not be the best suited model for crops such as citrus, in which transpiration may be limited by the rate of water supply to the leaves. In addition, K_c is strongly influenced by fractional canopy cover (CC), which varies considerably

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with local management practices, such as pruning and orchard age, and as a result, a range of K_c values were reported within the same species (Snyder and O'Connell, 2007).

Contrasting observations on the dynamics and magnitude of leaf resistances in citrus species were made by Taylor. et al. (2015). The authors suggested the use of a dynamic leaf resistance rather than fixed values, as previously suggested by Allen and Pereira (2009). To overcome the limitation of the K_c approach in such crops, more mechanistic models which consider canopy conductance (G_c) for estimating water use were (Orgaz. et al., 2007; Villalobos. et al., 2009). These models can be difficult to parameterise and often require input parameters that are challenging to measure. To address this, Villalobos. et al. (2013) suggested a generalised and simple transpiration model based on the concept of radiation use efficiency, as a surrogate for an assimilation model, which has been used to link leaf conductance to CO_2 assimilation. This model has been calibrated and validated in citrus species (Villalobos. et al., 2013). However, this was done in two citrus orchards with the same cultivar of similar age, growing in a winter rainfall region (i.e., Mediterranean climate).

The dynamics of G_c in citrus species and its relevance in estimating citrus transpiration are still not well established. Apart from the recognised seasonal variations of G_c due to tree size, leaf age, and climatic conditions, the possibilities that there could be another source of variation of G_c (acting on a seasonal basis) cannot be ruled out (Mills. et al., 2000). Hence, there is a need to test such models not only on different canopy sizes, but also throughout a growing season and across different climatic regions. The current study was therefore, conducted to calibrate and validate the repeatability of simple canopy conductance model of Villalobos. et al. (2013) in different citrus species of different canopy sizes, grown in both summer and winter rainfall regions. In addition, the study aimed to add knowledge on the dynamics of canopy conductance in citrus species and to provide a tool for practical irrigation management in citrus orchards.

MATERIALS AND METHODS

The study was conducted in commercial citrus orchards grown in two climatic regions, namely winter rainfall region (WRR) located at 32° 27' 15'' S, 18° 58' 03'' E; 140 m a.s.l. and summer rainfall region (SRR) located at 23°42' 0.95'' S, 30°34'58.72'' E, 480 m.a.s.l.). Measurements were conducted in twelve different orchards of varying canopy size during the 2015-2016 growing season for the WRR and in 2016-2017 for the SRR. Canopy size measurements were collected at monthly intervals throughout the growing season. These measurements included orchard leaf area index (LAI), measured using a plant canopy analyser (LAI-22000, LI-COR Inc., Lincoln, Nebraska, USA), fractional interception of photosynthetically active radiation by the canopy (*f*IPAR) which was measured using an AccuPAR LP-80 ceptometer (Decagon Devices, Pullman, WA, USA) and canopy cover (CC) determined as the fractional area shaded by the canopy at solar noon **(**Table 1**).**

Data was collected in two 'Midknight' Valencia orange orchards and one 'McLean' Valencia orange orchard of fractional canopy cover (CC of 0.83, 0.54 and 0.35) and 'Nadorcott' mandarin (CC of 0.81) in the winter rainfall region and three 'Star Ruby' grapefruit (CC of 0.83, 0.54 and 0.35), three 'Midknight' Valencia orange (CC of 0.76, 0.67 and 0.41), and 'Valley Gold' mandarin (CC of 0.42, and 0.34) in the summer rainfall region Table 1.

Trees were spaced 3 × 5 m in the winter rainfall region and 3 × 7 m in the summer rainfall region. Orchards in the winter rainfall region were drip irrigated (two drip lines per row, drippers spaced 0.8 m apart, with a delivery rate of 1.6 L h^{-1}), whilst those in the summer rainfall region were irrigated with one microsprinkler per tree (30 L h^{-1} . Trees were pruned after harvest each year to ensure adequate light penetration into the interior of the canopy.

Assessment of water stress was carried out through periodic measurements of pre-dawn water potentials using a Scholander pressure chamber (PMS Instrument Company, Albany, USA). Stress threshold values of -0.5 MPa was used (Kriedemann and Barrs, 1981). No evidence of water stress was found during measurements as the predawn values for all orchards were higher than -0.5 MPa, with an average of -0.44 MPa, and the values falling between -0.42 and -0.47 (at 95% confidence level).

Table 1. Details of the orchard's characteristics used in the study. CC = fractional canopy cover. *f*IPAR = fraction of intercepted photosynthetically active radiation. LAI = Leaf area index. All measurements represent the orchards status at the beginning of the measurements

Orchard	Planting date	Age	Soil type	CC	*f*IPAR	LAI (m^2 m^{-2})
Winter rainfall region						
'Midknight' Valencia orange	2000	15yrs.	Clay	0.83	0.74	3.08
	2008	7yrs	Clay	0.54	0.52	2.72
'Nadorcott' mandarin	2002	13 yrs.	Sandy	0.81	0.78	2.87
'McLean' Valencia orange	2010	5yrs	Sand	0.35	0.25	1.75
Summer rainfall region						
'Star Ruby' grapefruit	2006	10yrs	Clay loam	0.83	0.72	3.5
	2010	6yrs	Clay loam	0.54	0.56	3.1
	2011	5yrs	Sandy clay	0.35	0.42	2.6
'Midknight' Valencia orange	1995	21yrs	Loamy sand	0.82	0.81	3.24
	2008	8yrs	Loamy sand	0.67	0.53	2.51
	2014	2yrs	Sandy clay	0.41	0.20	1.72
'Valley Gold' mandarin	2013	3yrs	Sandy clay	0.42	0.37	3.14
	2015	1yrs	Sandy clay	0.34	0.26	1.09

Field measurements

Hourly and daily weather data were obtained from automatic weather stations installed over a dry short grass surface located close to each orchard. Reference evapotranspiration (ET_o) was calculated according to FAO-56(Allen. et al., 1998).

Transpiration was measured using sap flow measurements performed on four trees per orchard using the heat ratio method as described by Burgess. et al. (2001) and Taylor. et al. (2015) The selected trees were representative of the different size classes of trees in the orchard. Integrated volumetric sap flow of the individual trees (L day^{-1}) was converted to T (mm day^{-1}) using the ground area allocated to each tree in the orchard.

Hourly and daily fraction of intercepted photosynthetically active radiation (*f*IPAR) was measured in two trees, instrumented with sap flow equipment, in each orchard under clear sky conditions at regular intervals across each season. Measurements were taken in a grid pattern around each tree, which consisted of transect lines across the tree row which were spaced at 1 m in between transects and between the grid points. The number of measurements taken under each tree depended on the planting density of the orchard. At each hour, two reference measurements to represent full sun readings were taken in an open area next to the orchard. Hourly fIPAR was calculated from measured PAR transmittance according to Palmer (1977). The daily fraction of PAR intercepted (*f*DIPAR) was calculated by integrating the hourly measurements throughout the total measurement hours. Canopy cover was calculated according to Allen and Pereira (2009).

Modelling fractional interception of PAR by citrus orchards

The fIPAR was estimated with a parametrised model of Oyarzun. et al. (2007). The model estimates *f*IPAR of an orchard based on the fraction of the ground surface that is shaded by the orchard trees at any given time. This is obtained based on geometric relationships of the length of the shadow cast by the trees, the orchard configuration, and the canopy porosity (C_p), which was estimated from the fraction of sun-flecks within the shadow area cast by the trees on the ground and accounts for gaps within the canopy. For estimating

C_p, a plastic square grid (0.25 × 0.25 m for each square and 144 squares) was used to make a visual assessment of the patchiness of the shadow underneath the canopy, where the fraction of shade within each square was done in 10% increments.

Modelling transpiration of citrus orchards

The Daytime mean values of G_c (mm day^{-1}) were calculated by the inversion of the imposed evaporation equation from measured transpiration as follows:

$$G_c = \frac{TP_a}{VPD} \qquad (2$$

Transpiration estimates were obtained following the parametrized model of Villalobos et al. (2013). The model estimates T (mm day^{-1}) as a function of *f*IPAR of the canopy (dimensionless), daily total solar radiation (R_{sp}, J m^{-2} day^{-1}) and vapour pressure deficit (VPD, kPa) as follows:

$$T = 37.08 \times 10^{-3} \frac{(fIPAR)R_{sp}}{a + bVPD} \frac{VPD}{P_a} \qquad (3)$$

where the coefficient 37.08 x 10^{-3} was used to convert the units to mm day^{-1}; P_a is atmospheric pressure in kPa, **a (µE mol^{-1}), and b (µE mol^{-1} kPa^{-1}) are the intercept** and slope of the linear function relating (*f*IPAR*R_{sp})/G_c to VPD.

The model was calibrated and validated with different T datasets obtained from all the orchards under study. A threshold VPD value of less than 0.2 kPa was used in order to eliminate errors associated with extremely low VPD values on G_c, as suggested by. This value was selected after observing large errors in computed G_c when T and/or VPD with very low values were included in the model. In addition, data during rainy days were excluded from T estimation since sap flow is reduced in wet canopies (Villalobos. et al., 2006).

Table 2. Parameters derived from the plot of the ratio of intercepted PAR and canopy conductance versus vapour pressure deficit of citrus orchards in the winter and summer rainfall regions. The parameter D_0 is calculated as the ratio of a/b.

Orchard	Orchard age	b (µE mol^{-1} kPa^{-1})	a (µE mol^{-1})	D_0 (kPa)
		Winter rainfall region		
'Midknight' Valencia orange	15yrs	3887	205	0.06
	7yrs	3663	203	0.05
'Afourer' mandarin	13yrs	3712	207	0.05
'McLean' Valencia orange	5yrs	4302	255	0.06
		Summer rainfall region		
'Star Ruby' grapefruit	10yrs	3932	246	0.06
	6yrs	4732	260	0.05
	5yrs	4802	255	0.05
'Midknight' Valencia orange	21yrs	3632	246	0.06
	8yrs	4584	262.	0.05
	2yrs	4122	270.	0.06
'Valley Gold' mandarin	3yrs	4110	321.	0.08
	1yrs	4122	287.	0.06

RESULTS

The summary of the parameters for model calibration from the two sites is presented in Table 2. The model parameters (a and b) were fairly consistent for the different orchards with a coefficient of variation (CV %) of 8.2% and 9.3%, respectively. The parameter D_0, i.e., the ratio of a/b, which is related to the response of stomatal closure to VPD appeared to vary when compared to the two individual parameters, with a CV value of 13.2%. The slope (b) ranged between 3632to 4802 µE mol^{-1} kPa^{-1}, whilst the intercepts (a) varied between 203 and 321 µE mol^{-1} kPa^{-1}.

When an analysis of variance (two-way ANOVA) was conducted, with the two factors being the rainfall regions (WRR and SRR) and canopy size categorised according to *f*IPAR (i.e., big orchards = *f*IPAR ≥ 0.7, intermediate *f*IPAR ≥ 0.5 and small orchards *f*IPAR ≥ 0.45) , the results showed that there no significant differences in “b” values between the different canopy size ($p = 0.22$, $p > 0.005$) and across the different regions. ($p=0.36$, $p>0.005$). However, there was a significant difference with the parameter “a” between the different canopy size ($P=0.04$, $p < 0.05$), and across the different regions ($p=0.04$, $p<0.005$), although the interaction between the two factors was not significant ($p=0.45$, $p<0.005$).

From the statistical analysis, it was evident that the slope “b” was fairly conservative across the different species, but “a” varied with canopy size and region. Despite the differences in “a” across orchards, we tested the possibility of to using generic parameters for the canopy conductance model by Villalobos. et al. (2013) in different citrus orchards. This is because it is seldom possible to estimate orchard specific “a” and “b” values without detailed measurements. The average values of the calibrated model were then used to estimate daily and monthly T across different region and among the different citrus species.

Estimates by the model in the WRR and SRR is shown in Figure 1 and **Figure** 2 respectively. In general, the estimated daily T showed good agreement with the measured sap flow values during the experiment. However, there were some inconsistencies observed during the simulation period, especially in the ‘Midknight’ Valencia orchard planted in 2008 and the **‘**Nadorcott’ mandarin planted in 2002 in the WRR (Figure 1A and C). The model greatly underestimated T from April to June and slightly overestimated T in September and October 2016 in the two orchards. The errors were, in large part, a result of the underestimation of *f*IPAR during this period (data not shown). Fairly good estimates were obtained from the other two orchards (Figure 1B and D). The overall performance of the model in the winter rainfall region was acceptable; in all four orchards, as the index of agreement was greater than 0.8, MAPE values were below 20% and RMSE values were less than 1 mm day^{-1}.

The model was also able to account for seasonal variation of T throughout the measurement period in the SRR (**Figure** 2), however, under low atmospheric evaporative demands large errors in T estimates were observed. Although this issue was largely avoided by introducing a threshold VPD value (VPD < 0.2 kPa), the model occasionally underestimated T in all orchards, especially during winter when evaporative demand was low. Despite some observed discrepancies, the overall performance of the model in estimating variation of daily T in the SRR was satisfactory. Most orchards gave acceptable model evaluation indices, i.e., $D > 0.8$, MAPE < 20%, RMSE < 1 mm day^{-1} and $R^2 > 0.5$ (Figure 2). When comparing the performance of the model in the three different species, there was no clear pattern, but rather there seemed to be a carry-over effect from the inaccurate estimates of *f*IPAR from the radiation interception model.

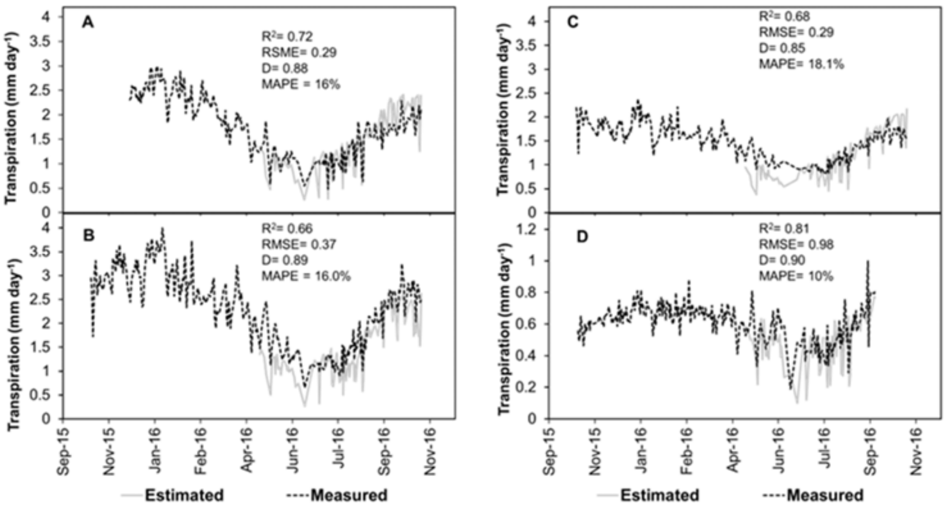

Figure 1. Comparison between daily transpiration rates measured using a sap flow technique and transpiration estimated from the model of Villalobos et al. (2013) for the different orchards in the winter rainfall region (A) 'Nadorcott' mandarin orchard, (B) 'Midknight' Valencia orange orchards, (C) Midknight' Valencia orange orchards and (D) 'McLean' Valencia orange. R^2 is the coefficient of determination, RMSE is the root mean square error, MAPE is the mean absolute error, and D is the Wilmott's index of agreement.

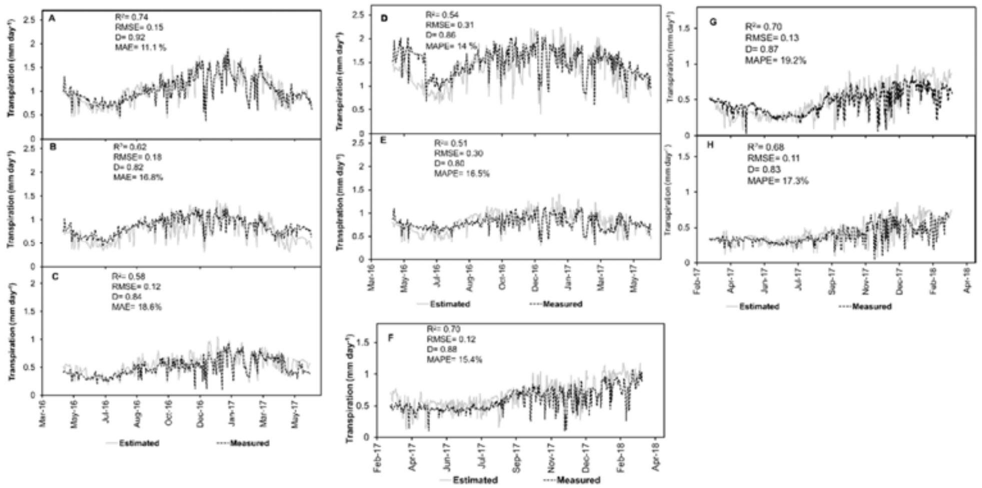

Figure 2. Comparison between daily transpiration rates measured using a sap flow technique and transpiration estimated from the model of Villalobos et al. (2013) for the 'Star Ruby' grapefruit orchards (A, B and C), the 'Midknight' Valencia orange orchards (D, E and F), and the 'Valley Gold' mandarin orchards (G and H). Measurements were collected during the 2016/2017 season in the summer rainfall region. R^2 is the coefficient of determination, RMSE is the root mean square error, MAPE is the mean absolute error, and D is the Wilmott's index of agreement.

The model performed better on a monthly time scale, as compared to a daily time scale**Error! Reference source not found.**, with MAPE < 15%, RMSE < 5 mm month^{-1}, and D > 0.9 for all but one orchard (data not shown). However, in the SRR, the intermediate 'Midknight' Valencia orange orchard had a D value of 0.84 and a MAPE value of 15%, indicating that T estimates were less accurate in this orchard when compared to the rest of the orchards in this study.

DISCUSSION

The calibrated G_c model was able to estimate both daily and monthly transpiration satisfactorily. However, discrepancies were evident in the daily estimates of T, which could be a result of several factors. Firstly, the calculation of G_c using the imposed evaporation equation assumes that leaf temperature equals air temperature, an assumption which does not always hold true when stomatal closure occurs in response to high VPD and plant biotic and abiotic stress. The high evaporative demand conditions observed in the winter rainfall region during the summer season could have resulted in leaf temperature exceeding air temperature, which would have violated this important assumption. As shown by Lu. et al. (2003) in grapevines, the computation of G_c by assuming an equilibrium between the leaf temperature and air temperature can lead to significant errors if there are marked differences between these temperatures. This could explain the discrepancies that were observed in T estimates during days of high evaporative demand, especially in the summer season in the winter rainfall region. Secondly, the model uses *f*IPAR to account for canopy cover, and whilst this variable can be estimated well using different models, any discrepancies in the measurement and/or estimation of *f*IPAR can lead to errors in the final estimation of T(Orgaz. et al., 2007). Importantly, the model successfully estimated T not only for the period of the season where it was calibrated, but throughout the season. This suggests that for the orchards in this study different periods of the year do not require different parameters, as observed by Orgaz. et al. (2007) when using the well-established Jarvis G_c model. In addition, the model parameters (a and b) were fairly conservative between orchards and given the diversity of the species and the wide range of the canopy sizes, it could be possible to use one set of parameters for all citrus under well-watered orchard conditions, which are planted in different climatic regions.

CONCLUSIONS

In this study, a simplified approach to estimate T using the model of Villalobos. et al. (2013) was evaluated in eleven orchards in both the summer and winter rainfall regions of South Africa. The results seem very promising and good daily estimates of T were obtained in all orchards. However, there were periods of under and overestimation, which could limit the use of this model for irrigation scheduling. These results demonstrate that when properly calibrated, transpiration (daily and monthly) of well-watered citrus varieties can be estimated using average parameters for the canopy conductance model by Villalobos. et al. (2013). It was also observed that the estimation of T from G_c estimates could be improved by more accurate estimates or measurements of *f*IPAR, as this parameter is important for the accuracy of T estimates.

Future work that could provide better estimates of C_p may improve estimates of *f*IPAR and when used in conjunction with the G_c model may result in more accurate estimates of daily T values. However, when monthly T estimates are required, the current calibrated model may prove to be a valuable method for estimating T in a wide range of citrus orchards grown in various climates.

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