Measurement and modelling of water use by high yielding apple orchards and orchards of different age groups in the winter rainfall areas of South Africa

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Abstract

Apple production for the export market is in South Africa entirely dependent on irrigation. In recent years, high performing orchards yielding up to 120 t of fruit ha^{-1} are becoming common in a country where the average yield is between 60 and 80 t ha^{-1}. This raises important questions regarding the sustainability of the exceptionally high yields given the limited availability of water for irrigation. Moreover, there is also no accurate quantitative information published on water use by apple orchards of different age groups and this compromises efficient irrigation scheduling. The aim of this study was to quantify water use by high yielding apple orchards and orchards of different age groups. Data were collected in four commercial orchards, two planted to non-bearing 'Cripps' Pink' and 'Golden Delicious' apples and another two high-yielding full-bearing orchards of these cultivars. Transpiration in the full-bearing orchards was measured using the heat pulse velocity sap flow method. Granier probes were used on the young non-bearing trees. Orchard evapotranspiration (ET) was measured using eddy covariance systems during selected periods. Ancillary data which included the orchard microclimate, stomatal resistance, soil water content and soil evaporation were also collected. The full-bearing 'Golden Delicious' orchard (22-year-old) had the highest seasonal transpiration of 785 mm, followed by the full-bearing 'Cripps' Pink' (9-year-old) which transpired 587 mm. The non-bearing 'Cripps' Pink' (3-year-old) transpired 272 mm compared to 198 mm for the non-bearing 'Golden Delicious' (2-year-old). The data were used to validate a dual source ET model based on the Shuttleworth-Wallace method. Transpiration of full-bearing orchards was accurately predicted by the model with the RMSE of 0.55 mm d^{-1} for 'Cripps' Pink' and 0.70 mm d^{-1} for the 'Golden Delicious' orchards. Improvements to the substrate evaporation sub-model are required to account for various orchard floor management practices.

Keywords: evapotranspiration, *Malus*, sap flow, Shuttleworth-Wallace model, soil evaporation

INTRODUCTION

South Africa is currently the 7th biggest exporter of apples in the world and the main southern hemisphere competitor is Chile, which is third in terms of export. In South Africa, the bulk of the apples are grown in the Western Cape Province which is located in the south-western part of the country, and experiences Mediterranean (winter rainfall) climatic conditions. This region is projected to experience severe water shortages in future due to the rapidly increasing population, increasing industrial activities and climate change (Midgley and Lötze, 2011).

An important information gap currently exists regarding the water requirements of high yielding (≥100 t ha^{-1}) apple orchards which have become the norm in this region in

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recent years. There is also no published local information on how water use varies with orchard growth stages from planting until full-bearing. Several studies have quantified water use by apple orchards (Braun et al., 2000; Volschenk et al., 2003;Dragoni et al., 2005; Gush and Taylor, 2014). Since it is impossible to measure the water use of every orchard, appropriate models are required to extrapolate the measured information to other orchards. This study therefore seeks: 1) to quantify water use by high yielding full-bearing and non-bearing apple orchards, and; 2) to use the data in a model that can potentially be used to predict water use in other apple growing areas. This research is part of a bigger project entitled "Quantifying water use by high performing apple orchards in the winter rainfall areas of South Africa" – project no WRC K5/2398 (Water Research Commission, 2015).

Given the heterogeneous nature of orchards comprising trees in rows and wide open spaces between the rows, the Shuttleworth and Wallace (1985) model has previously been applied to orchards (Ortega-Farias et al., 2012; Ortega-Farias and López-Olivari, 2012). According to this model, evapotranspiration (ET, in W m^{-2}) is calculated as the algebraic sum of transpiration from the trees (T, in W m^{-2}) and evaporation from the orchard floor, hereafter called substrate evaporation (E_s, in W m^{-2}) such that:

$$ET = T + E_s \tag{1}$$

where

$$T = C_c \frac{\Delta A + \left\{ \dfrac{\rho c_p D - \Delta r_a^{\,c} A_s}{r_a^{\,a} + r_a^{\,c}} \right\}}{\Delta + \gamma \left\{ 1 + r_s^{\,c} / (r_a^{\,a} + r_a^{\,c}) \right\}} \tag{2}$$

$$E_s = C_s \frac{\Delta A + \dfrac{\left\{ \rho c_p D - \Delta r_a^{\,s} (A - A_s) \right\}}{r_a^{\,a} + r_a^{\,s}}}{\Delta + \gamma \left\{ 1 + r_s^{\,s} / (r_a^{\,a} + r_a^{\,c}) \right\}} \tag{3}$$

where C_c is a dimensionless canopy resistance coefficient; C_s is the substrate resistance coefficient, also dimensionless; Δ is the slope if the saturation vapour pressure-temperature curve (kPa K^{-1}), c_p is the specific heat at constant pressure (J kg^{-1} K^{-1}), ρ is the density of air (kg m^{-3}); D is the vapour pressure deficit of the air at the reference height (kPa), r_a^a (in s m^{-1}) is the aerodynamic resistance between canopy source height and reference level, r_a^c (in s m^{-1}) is the boundary layer resistance of the canopy, r_s^c (s m^{-1}) is the canopy resistance, r_s^s (s m^{-1}) is the surface resistance of the substrate, r_a^s (s m^{-1}) is the aerodynamic resistance between the substrate and the canopy source height and γ is the psychrometric constant (kPa K^{-1}). A is the available energy (W m^{-2}) absorbed by the orchard calculated as the difference between the net radiation and the soil heat flux, and A_s (W m^{-2}) is the available energy at the orchard floor calculated from A using Beer's law.

MATERIALS AND METHODS

Four orchards were selected in the Koue Bokkeveld region of the Western Cape Province during the 2014-2015 growing season (September-June). Two of the orchards were full-bearing 'Golden Delicious' (22 years old, 1667 spha, 11.1 ha) and 'Cripps' Pink' (9 years old, 1667 spha, 6.0 ha) blocks, on the M793 rootstock. According to yield history since 2010/11, the 'Golden Delicious' orchard consistently produced more than 100 t of fruit ha^{-1}, while the yield of the 'Cripps' Pink' orchard had gradually increased and exceeded 100 t ha^{-1} in the last two seasons (2012-2014).

The other two orchards comprised a non-bearing 2-year-old 'Golden Delicious' block (1667 spha, 3.2 ha) and a 3-year-old 'RosyGlo' (a 'Cripps' Pink' variant) block (2285 spha, 6.0 ha). The non-bearing ‘Golden Delicious’ trees were grafted on the M793 rootstock, whilst the ‘RosyGlo’ trees were grafted onto the MM109 rootstock. All the orchards were planted on deep sandy soils. All the orchards were micro-sprinkler irrigated and management of the orchards followed the current growers’ practice.

Transpiration in each of the full-bearing orchards was measured from mid-September 2014 until the end of June 2015 on five trees of different stem sizes using the heat ratio method of the heat pulse velocity (HPV) sap flow technique (Burgess et al., 2001). Four sets of heater probes and T-type thermocouple pairs were inserted into the sap wood of the stems at depths ranging from 10 to 50 mm depending on stem size to account for the radial variation in the sap velocity. The HPV data were corrected for wounding, moisture fraction and wood density at the end of the experiment. The size of the conducting sapwood area was determined by injecting methylene blue dye into the stems after harvest to determine the extent of the active xylem vessels. Transpiration by the smaller trees in the non-bearing orchards was measured using Granier probes (TDP 10: Dynmax Inc., Houston, USA) (Granier, 1987). Three trees were instrumented per orchard and the average sap velocity was determined in the range 0 to 10 mm of the stems. The sensors were installed at a height between 50 and 75 cm from the ground to eliminate errors due to the cold sap especially in the morning. A double layer of aluminium bubble wrap was wrapped around the probes to minimize the effects of exogenous heating on the sap temperature signals.

Additional data collected included the orchard microclimate, which was measured using an automatic weather station that recorded the weather variables at hourly and daily intervals. Penman-Monteith reference evapotranspiration was calculated according to Allen et al. (1998). Tree leaf area index (LAI) was measured at regular intervals using a plant canopy analyser (Model LAI 2000: Licor, Lincoln, USA) while the soil water content in each of the ‘Golden Delicious orchards’ was measured using 30 soil moisture probes (Model CS616, Campbell Scientific, Logan, UT, USA). In addition, the midday stem water potential (ψ_{stem}) was measured on November 25, 2014, January 15, 2015 and February 18, 2015 using a Scholander-type pressure chamber to check the level of water stress in the orchards. Orchard ET was measured at selected seasonal intervals using the open path eddy covariance system. Evaporation from the orchard floor (substrate evaporation) was measured at hourly intervals from sunrise to sunset on selected days which coincided with the eddy covariance campaigns. These data were collected using 8 microlysimeters installed around a single tree with different sun-shade and wet-dry exposures. The microlysimeter data was used to estimate the substrate resistance (r_s^s in Equation 3). Values of r_s^s that reasonably matched the microlysimeter data were ~100 s m^{-1} for the full-bearing, and ~500 s m^{-1} for the non-bearing orchards.

Stomatal resistance (r_{st}) was also measured in continuous cycles on selected days in each orchard from sunrise to sunset on tagged leaves using a porometer (Model AP4: Delta-T, Co, UK). These data were used to model the canopy resistance (r_s^c) following a Jarvis-type approach in which:

$$r_{st} = \frac{r_{st\min}}{f(VPD).f(Rs)} \tag{4}$$

$$r_s^c = \frac{r_{st}}{LAI} \tag{5}$$

where f(VPD) and f(Rs) are the vapour pressure deficit (VPD) and solar radiation (Rs) stress factors with values between 0 and 1 and r_{stmin} was the measured minimum stomatal resistance which was set at 155 s m^{-1} for all orchards.

RESULTS AND DISCUSSION

The seasonal total reference evapotranspiration (ET_0) was 1256 mm from September 2014 to June 2015 (Figure 1a). The measured transpiration totals were 785 mm for the full-bearing 'Golden Delicious', 587 mm for the full-bearing 'Cripps' Pink', 272 mm for the non-bearing 'Cripps' Pink' and 198 mm for the non-bearing 'Golden Delicious' (Figure 1b, c).

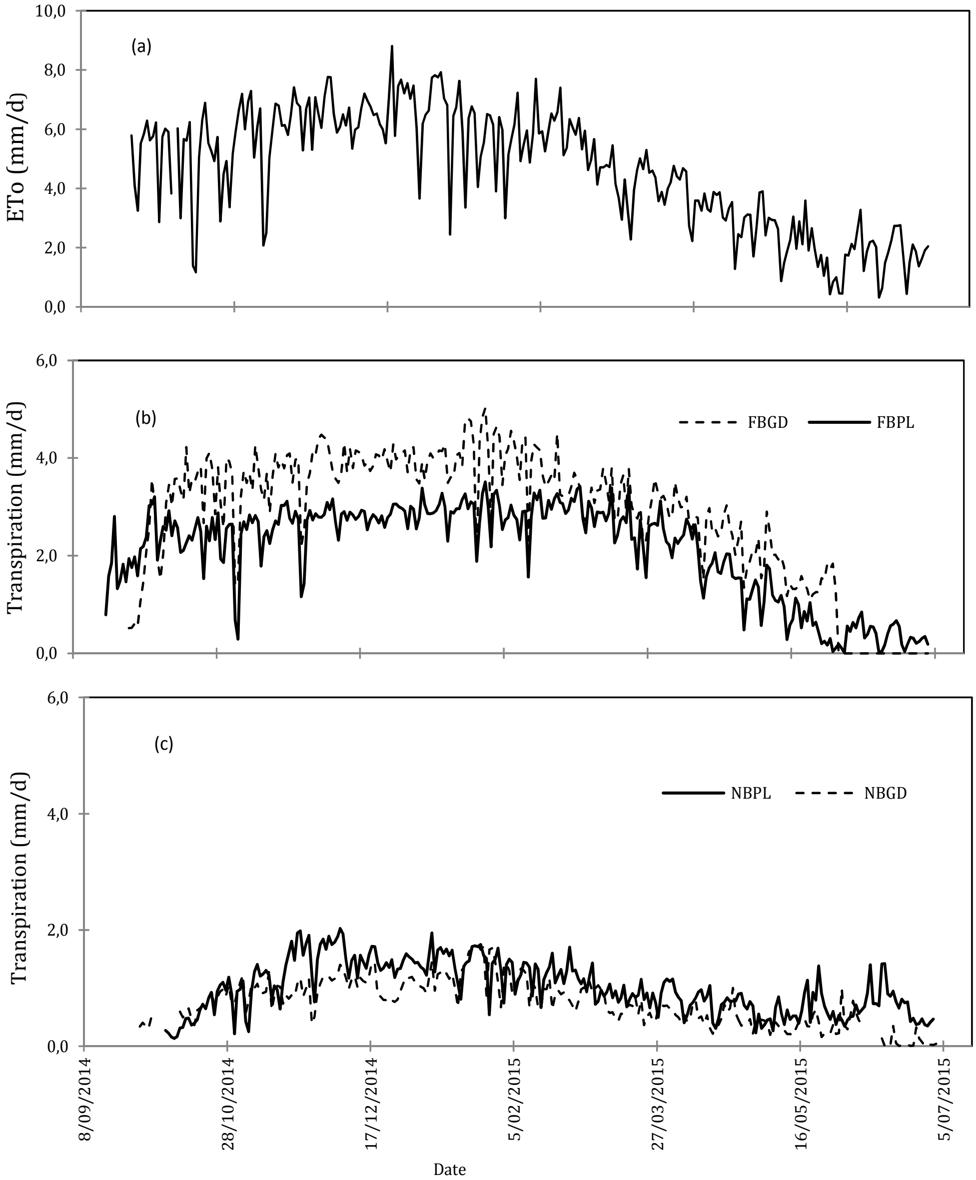

Figure 1. Seasonal variation in; a) reference evapotranspiration (ET_0) and transpiration by: b) full-bearing 'Golden Delicious' (FBGD) and 'Cripps' Pink' (FBPL), and: c) non-bearing 'Golden Delicious' (NBGD) and 'Cripps' Pink' (NBPL) apple orchards.

None of the orchards were under stress in November 2014 (ψ_{stem} >-1.0 MPa). Severe stress (ψ_{stem} <-2.2 MPa) was detected in the non-bearing 'Cripps' Pink' orchard in January 2015. The transpiration data from mid-December 2014 to mid-January 2015 were subsequently corrected for stress using a basal crop coefficient derived under non-stress conditions. Mild stress (ψ_{stem} >-1.46 MPa) was detected in the full-bearing 'Golden Delicious' orchard in February 2015 although the soil water content measurements (data not shown) suggest that the full-bearing 'Golden Delicious' orchard may have been under-irrigated. The peak LAI of the trees measured in January 2015 were 3.6 and 2.7 for the full-bearing 'Golden Delicious' and 'Cripps' Pink' trees, respectively, and 1.05 and 0.7 for the non-bearing 'Golden Delicious' and 'Cripps' Pink' trees. The average yield of the full-bearing orchards was slightly lower than in previous years being 98 and 84 t ha^{-1} for the ‘Golden Delicious’ and ‘Cripps’ Pink’ orchards.

A previous study in a low yielding 13-year-old ‘Cripps’ Pink’ orchard in the same production area producing on average 60 t ha^{-1} with a peak LAI of 3.1 transpired 683 mm per season (Gush and Taylor, 2014) which is higher than that measured in the high yielding ‘Cripps’ Pink’. The current data however, do not show a clear correlation between yields and transpiration levels. Rather, it is evident though that trees that had higher leaf area indexes tended to have higher transpiration rates. No significant decline in transpiration was observed in both cultivars after harvest. Other studies that have investigated crop load-water use relationships e.g., Steduto et al. (2012) showed an immediate drop in transpiration rates following the de-fruiting of apple trees compared with trees that kept their fruit. However, the LAI of the de-fruited trees subsequently increased at a faster rate compared with that of trees with fruit such that no significant differences in water use were observed between the fruited and de-fruited treatments at the end of the season.

The partitioning of the measured ET into the transpiration (beneficial water use) and substrate evaporation (non-beneficial water use) for a full-bearing ‘Golden Delicious’ orchard is shown in Figure 2 for a typical clear day on February 18, 2015. Evaporation from the orchard floor accounted for approximately 20% of the measured ET and this contribution increased to close to 50% in a non-bearing ‘Golden Delicious’ orchard.

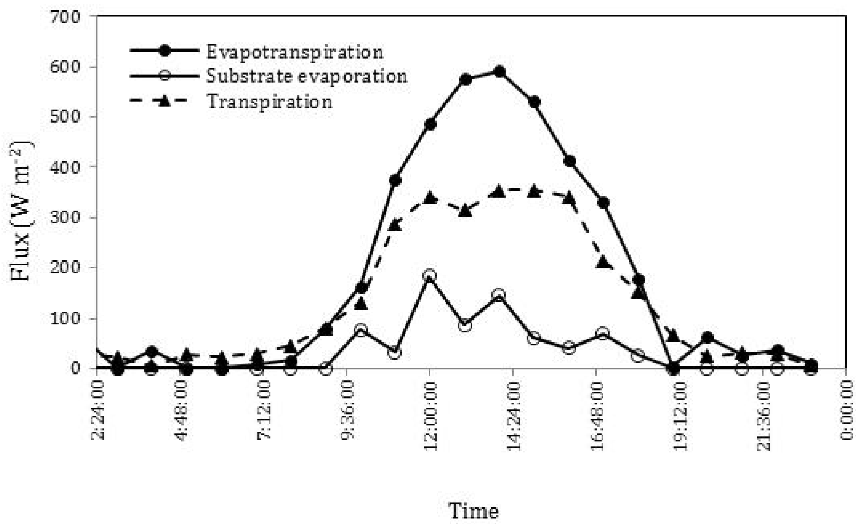

Figure 2. Partitioning of evapotranspiration (closed circles) into transpiration (closed triangles) and substrate evaporation (open circles) in a high yielding full-bearing ‘Golden Delicious’ apple orchard.

The seasonal variation in observed ET components and those predicted by the Shuttleworth-Wallace model are shown in Figure 3 for the full-bearing (a) and pre-bearing (b) ‘Golden Delicious’ orchards. As expected, substrate evaporation was a substantial proportion of the total ET at the beginning of the season when the trees had no leaves. Transpiration by the full-bearing orchards was fairly well predicted by the model (Table 1) with a root mean square error (RMSE) between 0.50 and 0.70 mm d^{-1}. The model significantly underestimated transpiration in non-bearing orchards (Table 1) and the reasons for this are unclear. A different parameterization of the canopy resistance sub-model may be required for the non-bearing orchards given that the light interception patterns are different from those of full-bearing orchards. Although the seasonal dynamics of ET in all the orchards were as expected, the accuracy of the absolute values was variable and more work is required particularly to improve the substrate evaporation simulations.

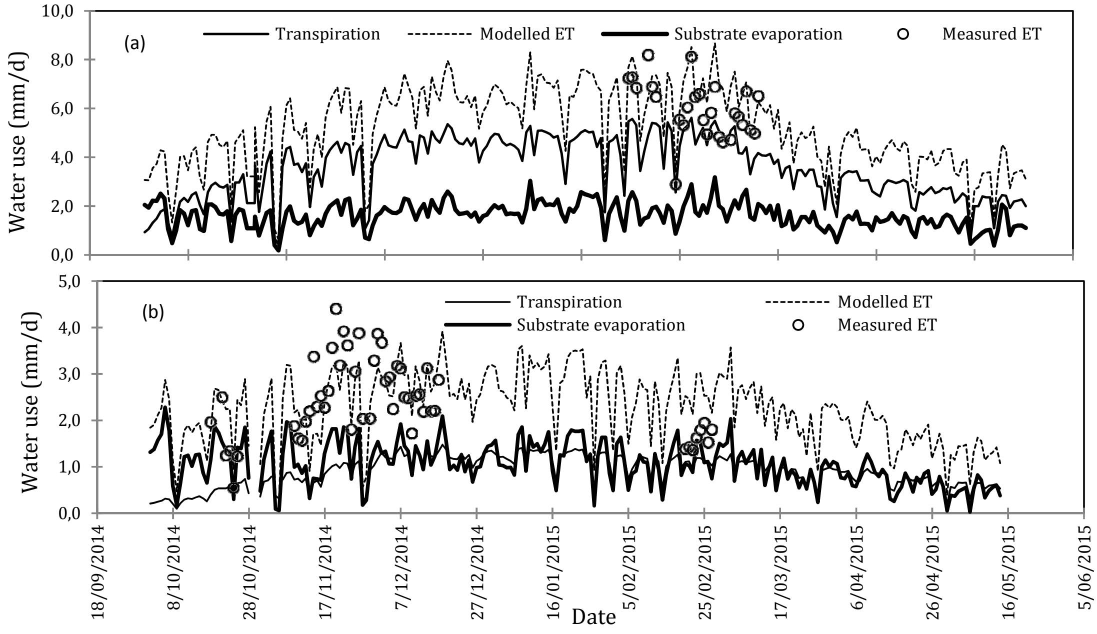

Figure 3. Partitioning of evapotranspiration modelled with the Shuttleworth-Wallace model in: a) full-bearing, and; b) non-bearing 'Golden Delicious' apple orchards. Open circles depict the measured evapotranspiration.

Table 1. Comparison of the measured and modelled transpiration (T) and evapotranspiration (ET) for apple orchards of different age groups.

Cultivar	Variable	Slope	Int.	R^2	RMSE	MAE	N
FBGD	T	1.10	0.15	0.51	0.70	0.58	225
	ET	0.76	2.34	0.48	1.34	1.09	21
FBPL	T	0.94	0.47	0.77	0.55	0.46	193
	ET	0.49	1.80	0.66	0.58	0.48	11
NBGD	T	0.64	0.38	0.54	0.25	0.22	210
	ET	0.50	2.57	0.29	2.97	1.48	51

CONCLUSIONS

This study shows that the total seasonal transpiration in orchards of different age groups was strongly related to the canopy size of the trees, depicted by the LAI. Trees with higher LAI used more water and vice versa although the high plant density in the non-bearing 'Cripps' Pink' or 'RosyGlo' orchard may have contributed to the higher transpiration totals due to the higher stand sap wood area. Based on observations from this study and from literature, it appears that both high yields and large canopy sizes are equally likely to lead to high rates of water use. Further research is clearly required to fully understand the crop load-water use relationships in apple orchards. Fairly accurate simulations of transpiration were obtained in the full-bearing apple orchards with the Shuttleworth and Wallace model. However, further model improvements are needed to predict the transpiration of non-bearing orchards and to estimate evaporation from the orchard floor which involves complex mixtures of cover crops, bare ground and mulches.

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Literature cited

Allen, R.G., Pereira, L.S., Raes, D., and Smith, M. (1998). Crop evapotranspiration. FAO Irrigation and Drainage Paper 56 (Rome, Italy: Food and Agriculture Organization (FAO)).

Braun, P., Maurer, B., and Heinemann, G. (2000). Scaling transpiration in apple orchards-meteorological versus plant based physiological measurements. Acta Hortic. *537*, 45–51 http://dx.doi.org/10.17660/ActaHortic.2000.537.2.

Burgess, S.S.O., Adams, M.A., Turner, N.C., Beverly, C.R., Ong, C.K., Khan, A.A.H., and Bleby, T.M. (2001). An improved heat pulse method to measure low and reverse rates of sap flow in woody plants. Tree Physiol. *21* (*9*), 589–598 http://dx.doi.org/10.1093/treephys/21.9.589. PubMed

Dragoni, D., Lakso, A.N., and Piccioni, R.M. (2005). Transpiration of apple trees in a humid climate using heat pulse sap flow gauges calibrated with whole-canopy gas exchange chambers. Agric. For. Meteorol. *130* (*1-2*), 85–94 http://dx.doi.org/10.1016/j.agrformet.2005.02.003.

Granier, A. (1987). Evaluation of transpiration in a Douglas-fir stand by means of sap flow measurements. Tree Physiol. *3* (*4*), 309–320 http://dx.doi.org/10.1093/treephys/3.4.309. PubMed

Gush, M.B., and Taylor, N.J. (2014). The water use of selected fruit tree orchards (Volume 2): Technical report on measurements and modelling. WRC report no 1770/2/14 (Pretoria, South Africa: Water Research Commission).

Midgley, S.J.E., and Lötze, E. (2011). Climate change in the western cape of South Africa: trends, projections and implications for chill unit accumulation. Acta Hortic. *903*, 1127–1134 http://dx.doi.org/10.17660/ActaHortic.2011.903.157.

Ortega-Farias, S., and López-Olivari, R. (2012). Validation of a two-layer model to estimate latent heat flux and evapotranspiration in a drip irrigated olive orchard. Amer. Soc. Agric. Biol. Eng. *55*, 1169–1178.

Ortega-Farias, S., López-Olivari, R., Poblete-Echeverria, C., and Zuñiga, M. (2012). Evaluation of a two-layer model and sap flow to estimate olive transpitration. Acta Hortic. *951*, 147–152 http://dx.doi.org/10.17660/ActaHortic.2012.951.17.

Shuttleworth, J.W., and Wallace, J.S. (1985). Evaporation from sparse crops-an energy combination theory. Quart. I. R. Met. SOC. *111* (*469*), 839–855 http://dx.doi.org/10.1002/qj.49711146910.

Steduto, P., Hsiao, T.C., Fereres, E., and Raes, D. (2012). Crop yield response to water. FAO Irrigation and Drainage paper 66 (Italy: Food and Agricultural Organization).

Volschenk, T., de Villiers, J.F., and Beukes, O. (2003). The selection and calibration of a model for irrigation scheduling of deciduous fruit orchards. Report no WRC 892 (Pretoria, South Africa: Water Research Commission).

Water Research Commission. (2015). WRC knowledge review 2014/15. (in press). www.wrc.org.za.