

We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

4,800

Open access books available

122,000

International authors and editors

135M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com



Citrus Water Use

J. Teunis Vahrmeijer and Nicolette J. Taylor

Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/intechopen.79424>

Abstract

Citrus is grown in semi-arid regions or subtropical regions in large parts of the world, where rainfall is seasonal and irrigation a necessity. Water is a vitally important element in all ecosystems and as agriculture is the largest user of fresh water resources, it needs to be efficient in the use of water. This is particularly true for the citrus industry, as it has a significant irrigation requirement. Good irrigation scheduling practices rely on accurate estimates of plant water-use (transpiration) for different climatic regions, citrus varieties, tree and canopy size, and choice of rootstock. This usually requires the use of a model, where a thorough understanding of the regulation of transpiration will improve the estimation capabilities of such a model. Results from our study (Quantifying citrus water use and water stress at tree and orchard scale, Water Research Commission Project K5/2275//4) showed that transpiration (T) follows diurnal and seasonal trends and is influenced by stomatal conductance (g_s) and leaf water potentials (Ψ_l). Good correlations between T and temperature, vapour pressure deficit (VPD) and solar radiation (SR) were found, indicating the importance of the environment in supplying the energy to drive transpiration. There was also a good relationship between canopy size and T, with larger canopies having higher T.

Keywords: transpiration, vapour pressure deficit, leaf water potential, stomatal conductance

1. Introduction

Citrus is an ancient crop, with the oldest known reference to be found in Sanskrit literature (pre-800 BC), where citron and lemon are referred to as *jambhila* in the book, *White Yahir-venda*. Twenty seven varieties of mandarins are described in Chü lu (1179 AD), one of the oldest known monographs of citrus [1]. Citrus trees are perennial evergreen plants that were probably cultivated in south-east Asia for the first time [2], from where it was introduced into North

Africa and Spain. Sweet oranges were brought to Europe by Portuguese seafarers and then spread via sea mariners and settlers to the rest of the world [1].

Citrus do not grow well in humid tropical rainforests and most likely evolved in low latitude forests, as a substory species in drier monsoon regions and became widely adapted to semi-arid regions [2]. Remnants of these earlier attributes that are still evident in some of the varieties are [3]:

- i. Vegetative growth can readily assume dominance over reproductive development.
- ii. Excessive foliar development, which can be up to 25% of the fresh tree mass.
- iii. High stomatal density and low hydraulic conductivity as a result of a shallow suberized root system with only vestigial root hairs. This often results in potential transpirational losses exceeding the water uptake capacity of the root system.

Citrus orchards require irrigation, in most parts of the world, to avert lower yields and lower return on investments. With agriculture being the largest user of fresh water resources, climate change and competition for this already scarce resource from a number of end-users, emphasise the need to improve water use productivity and water use efficiencies [4] in citrus production. Reliable estimates of citrus water use are, therefore, essential to provide effective advice to both established and emerging commercial farmers on irrigation methods and scheduling.

Several reports on citrus water use exist. A prominent feature of these reports is the broad range of water use rates given, even scientific literature is full of contradicting values for water use of citrus trees. This large variation in reported values is not completely unexpected, due to the different measurement techniques used under a wide range of conditions, which includes [5–11]: different orchard characteristics and management practices, tree and canopy size, cultivars, rootstocks, climatic conditions under which the trees are grown, irrigation methods and available soil water content. At orchard level, water use is influenced by the change in citrus orchard management practices, such as the introduction of high density plantings, different pruning techniques and various micro-irrigation systems.

1.1. Citrus rootstocks and root development

Citrus has a well-defined taproot, however, its identity is often lost during the process of replanting or poor nursery practices [12]. The taproot is supplemented by lateral roots that branch and re-branch irregularly to form a dense mat in the soil surface layers. For mature citrus trees the greatest mass of fibrous roots occurs in the top 0.4 m of the soil profile, with structural roots extending to at least 1.5 m [3]. The extent of the root system is, however, dependent on soil physical properties, cultivar and rootstock [2]. Carrizo citrange and Swingle citrumelo are examples of rootstocks with few fibrous roots below 0.7 m and less lateral development [13] that are well suited for high-density, intensively managed plantings [14]. Root distribution, measured as fibrous root length density (FRLD), was determined for ‘Hamlin’ orange trees grown on Swingle citrumelo and on Carrizo citrange [15]. Results showed that Swingle citrumelo developed significantly higher FRLD in the top 0.15 m of the soil profile than trees on Carrizo citrange. Conversely, at a soil depth between 0.15 m and 0.75 m Carrizo citrange had a greater FRLD than trees on Swingle citrange [15]. FRLD distribution increase in two modes. Firstly a dense root mat developed just below the soil surface with few roots deeper than 0.5 m

at a distance of 1.5 m from the tree trunk. When these roots are well established, a second region of roots develop below 0.3 m from the soil surface (trees aged between 5 and 10 years). By the time the canopy reaches full hedgerow dimensions (trees aged between 10 and 15 years), the bimodality of the root system has fully developed [15].

One of the numerous factors influencing citrus water use include rootstocks that differ in root quantity distribution and/or efficiencies in water uptake and transport. Xylem vessel size is related to root hydraulic conductance, which affects water uptake and transport, which in turn influences the leaf transpiration rate [16]. Results from a study on the hydraulic conductivity of four rootstocks [17] showed that rough lemon and Carrizo citrange had the highest, whereas sour orange and Cleopatra mandarin had the lowest root conductivity and thus the lowest uptake and transport of water in the tree. During the last 30 years a major shift in rootstock and cultivars with better disease, drought and salinity resistance and dwarfing capabilities has taken place. For example in South Africa, 56% of the citrus trees were grafted on rough lemon and only 10% on Troyer and Carrizo citrange in 1986. In 2004 the use of rough lemon decreased to 12% and Troyer and Carrizo citrange increased to 45% [18]. This has implications for the water use of orchards, with less vigorous rootstocks having lower hydraulic conductances.

1.2. Water potentials, stomatal conductance and climate

Stomatal conductance (g_s) regulates transpiration and photosynthesis and therefore impacts directly on water use and is sensitive to environmental factors such as light, CO_2 , plant water status, vapour pressure deficit (VPD) and temperature [3]. Leaf age, canopy size and tree age were found to influence stomatal conductances. New leaves on 15 year-old citrus trees have a greater stomatal conductance than old leaves. However, this was not true for smaller trees, where the stomatal conductance for the old and new leaves was similar due to the smaller trees having rough, well ventilated canopies, with a more exposed position that tightly couples them to the atmosphere [19]. Stomata in citrus leaves require only low light levels to open fully [19]. Even shaded leaves transpire, with their transpiration (T) rates being lower than sunlit leaves due to lower temperatures and thus a lower saturated water vapour pressure [20]. Stomatal conductances were observed to decline rapidly when midday leaf water potentials (Ψ_l) went below -1.0 MPa for 30 month old Pera orange trees [21], while the closure of stomata occurred at a midday Ψ_l lower than -2.2 MPa for Washington Navels [22]. Syvertsen [23] found that stomatal closure occurs over a relative narrow range of Ψ_l 's within each age class of leaves, with stomatal closure occurring at -1.6 MPa for young leaves and for mature leaves (3–6 months old) at -3.6 MPa. Sinclair and Allen [24] also noted stable maximum rates of T regardless of environmental conditions, suggesting strong stomatal control over T.

2. Materials and methods

2.1. Description of orchards

Citrus orchards near Citrusdal ($32^{\circ}27'15.82''S$, $18^{\circ}58'44.84''E$) in the Western Cape Province (winter rainfall region) of South Africa and close to Letsitele ($23^{\circ}48'21.48''S$, $30^{\circ}28'6.62''E$) in the Limpopo Province (summer rainfall) of South Africa were used for measurements of T

and water relations. The orchards in Citrusdal were 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. In Letsitele the orchards were irrigated with one 30 L h⁻¹ microsprinkler per tree. Details are provided in the relevant sections.

2.2. Weather data

Hourly and daily weather data were obtained from the Campbell Scientific Automatic Weather Station (AWS) on the respective farms, which was installed over a short vegetated surface according to standard conditions specified in FAO 56 [25]. Irrigated orchards (2–3 m in height) were found within 10 m west, 60 m north, 30 m east and 50 m south of the AWS. The AWS was situated approximately 620 m from the 13-year old 'Midknight' Valencias and 2 km from the 5-year old 'Midknight' Valencias. For the 13 year-old 'Afourer' mandarin orchard, weather data was collected from a second Campbell Scientific AWS that was installed approximately 2 km from the orchard. Weather data for the 23 year-old 'Midknight' Valencia in the summer rainfall region (Letsitele) was obtained from QMS Laboratories™. The weather data was used to estimate the potential evapotranspiration (ET_p), using the Penman-Monteith method according to the FAO 56 procedure [25].

2.3. Root development

Profile pits were dug and soil/root samples were taken at three depths (0.2, 0.4 and 0.6 m) for a 5 year-old 'Midknight' Valencia orchard and at four depths (0.1, 0.2, 0.4 and 0.6 m) for a 13 year-old 'Bahianinha' Navel orchard. Samples were taken within the tree row close to the tree trunk, midway between the tree trunk and the canopy edge and at the canopy edge. Another set of samples were taken perpendicular to the tree row, between the tree rows close to the tree trunk, midway between the tree trunk and the canopy edge and at the canopy edge. Root samples were taken by gently tapping a metal cylinder of known volume into the soil. The edges of the metal cylinder were sharpened to facilitate the cutting of the roots. Samples were sealed in a plastic bag and transported to the laboratory. The sample was placed on a 1 mm sieve and the soil was removed by gently washing the roots under running water. The washed roots were collected and excess water was removed by placing the roots on absorbing paper. The fresh root mass of each sampling point was determined, after which the roots were then dried at 60°C and the dry mass recorded.

2.4. Water potential and stomatal conductance measurements

Leaf water potential was determined using a Scholander pressure chamber (PMS Instrument Company, Albany, USA) on three sunlit and three shaded leaves of three trees in the 'McLean' Valencia orchard (**Table 1**). Stomatal conductance was determined using an AP4 porometer (Delta-T Devices, Ltd., Cambridge, United Kingdom). Stomatal conductance was determined on three 'McLean' Valencia trees (**Table 1**), with three leaves on the east side of the tree, three leaves on the west and three shaded leaves on the inside of the canopy measured per tree. Both Ψ_l and g_s measurements were made hourly, with Ψ_l measurements starting before sunrise until sunset. Due to the occurrence of dew on the leaves early in the morning, g_s could

	'McLean' Valencia
Age (years)	5
Rootstock	Swingle/Carrizo
Tree spacing (m × m)	3.0 × 5.0
Canopy cover	0.35
Orchard - LAI (m ² m ⁻²)	3.28
Canopy dimensions:	
Height (m)	2.53
Rainfall region	Winter Citrusdal, South Africa

Table 1. Details of 'McLean' Valencia orchard used for water potential and stomatal conductance measurements.

only commence once the leaf surface was dry. The hourly values of the Ψ_l and g_s measurements were combined separately and the average for the tree was calculated.

2.5. Tree water use measurements

Tree water use was determined using the heat ratio method [26, 27] of the heat pulse velocity (HPV) technique. Four trees were selected per trial (**Table 2**) and four probe sets were installed per tree. The probe set installation depths varied according to trunk size, but were in general in the order of 10, 25, 35 and 50 mm. Each probe set consisted of a central 60 mm long and 1.8 mm thick stainless steel heater probe and two Type-T (copper-constantan) thermocouples installed 5 mm above and 5 mm below the heater probe. The probe sets were placed in the tree sapwood area via three vertically aligned and parallel holes drilled with the help

	'Midknight' Valencia		'Afourer' Mandarin	
Age (years)	17	9	23	13
Rootstock	Troyer/Carrizo	Troyer/Carrizo	Carrizo	Swingle
Tree spacing (m × m)	2.5 × 5.0	3.0 × 4.8	7.0 × 3.0	2.0 × 5.0
Canopy cover	0.83	0.54	0.74	0.81
*Orchard LAI (m ² m ⁻²)	5.63	4.51	2.54	5.65
**Canopy dimensions:				
Height (m)	4.92	3.38	4.30	5.01
Rainfall region	Winter Citrusdal	Winter Citrusdal	Summer Letsitele	Winter Citrusdal

*LAI Leaf area index is the average of 5 measurements; **Average of four selected individual trees.

Table 2. Orchard details of experimental site for tree water use trial sites in South Africa.

of a drill guide strapped to the trees. Petroleum jelly was used to ease probe insertion and maintain thermal contact between the probe and wood tissue [28]. Individual thermocouples were wired to an AM16/32B multiplexer (Campbell Scientific Inc., Logan, UT, USA). Heat pulse velocities were calculated at hourly intervals on a CR1000 logger (Campbell Scientific Inc., Logan, UT, USA). Heat pulse velocity was corrected using the wounding correction equations and a measured wound width for each orchard. The sap flux density and final sap flow volumes were calculated according to [28, 29]. The area represented by each probe was determined. The heat pulse velocity from each probe was then multiplied by the specific area represented by the probe, which yielded the volumetric sap flow per hour.

3. Results and discussions

3.1. Root distribution

The root distribution of a 6 year-old 'Midnight' Valencia tree and that of a 13 year-old 'Bahianinha' Navels are given in **Figure 1**. The soil of the 6 year-old 'Midnight' Valencias can be classified as a clay soil [30]. Field measurements and observations revealed that the

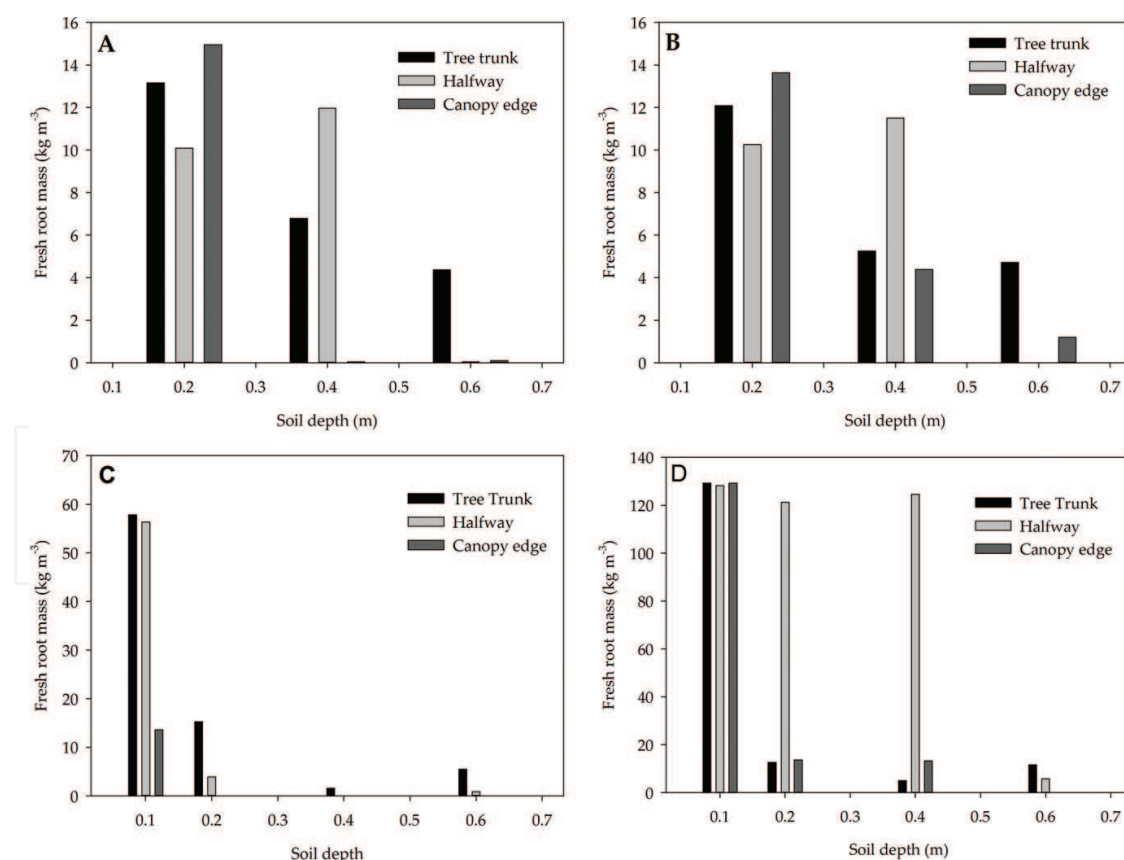


Figure 1. Root distribution (kg m^{-3}) between the rows (A) and within the row (B) in a 6 year-old 'Midnight' Valencia orchard grafted on Carrizo citrange rootstock. Root distribution (kg m^{-3}) between the rows (C) and within the row (D) in a 13 year-old 'Bahianinha' navel orchard grafted on Carrizo citrange rootstock.

roots of the 6 year-old 'Midknight' Valencias were thinner than the roots of the 13 year-old 'Bahianinha' navels. A typical bimodal distribution of the roots was also evident, with most of the roots (>60%) within the top 0.2 m of the soil surface and a less dense root mass at 0.4 m (**Figure 1A** and **B**). Ninety five percent of the roots were in the top 0.4 m. For the samples taken close to the tree trunk and at the canopy edge, the root mass decreased with soil depth within the tree row and between the tree rows. More roots were found at the 0.4 m sample depth, halfway between the tree trunk and canopy edge than at the 0.2 m sample depth (**Figure 1A** and **B**).

The soils of the 13 year-old 'Bahianinha' navel orchard consisted of coarse sand (0.5–2.0 mm) with no stones. Most of the roots (61%) were found within the top 0.1 m of the soil and more than 80% in the top 0.2 m, forming a dense mat under the drippers within the tree row. Substantially fewer roots were found within the work row. Roots were also in general thicker (2.7 mm) with larger structural roots at a depth of 0.4 m (**Figure 1C** and **D**) and substantially more than for the 6 year-old 'Midknight' Valencias (**Figure 1A** and **B**). This distribution was not unexpected, as citrus fibrous root length, in well-drained sandy soils, is a function of tree size, soil depth, distance from the trunk and rootstock [15]. The fibrous roots of young trees (canopy volume < 5 m³) develop just below the soil surface, with more than 85% of the roots within 0.5 m of the soil surface. As the canopy volume (5–15 m³) increases the fibrous roots close to the soil surface grow laterally towards the dripline of the tree, that extends to 2 m between tree rows and to a depth of 0.9 m, with a further increase in canopy volume (>15 m³) [15]. The distribution and density of roots impacts water and nutrient uptake of the trees and could influence the maximum T rate based on the rate at which water can be supplied to the leaves.

3.2. Climate as a driving force for citrus water use

It is custom to use VPD to describe evaporation from a leaf or soil surface, because it can be expected that the humidity at the leaf or soil surface is less than 1.0 and the vapour concentration is less than the saturation concentration. However, evaporating surfaces of most leaves have a humidity close to 1.0 and it can generally be assumed that the vapour concentration at the leaf surface equals the saturation vapour concentration if the air and surface temperatures are the same. For more detail on the discussion on the relation between liquid- and gas-phase of water in biological systems, the reader is referred to [31].

For this discussion of T, water potentials in a 'McLean' Valencia orchard were either calculated or measured to illustrate the direction of water flow. Thus, evaporation from a leaf (T) and soil surface is driven by a water potential gradient between the atmosphere and the leaf or soil surface. In **Figure 2** the water potential at the soil surface (-0.4 MPa), leaves (-1.68 MPa) and atmosphere (-176 MPa) was calculated for a 'McLean' Valencia orchard, in a winter rainfall region, for a summer's day (February) and a winter's day (July). Because of the steep water potential gradient between the leaves and atmosphere, citrus trees regulate the opening and closing of the stomata to prevent excessive water loss [32, 33]. An interesting observation is that although the atmospheric demand was substantially higher during summer (-176 MPa) than winter (-130 MPa) the measured Ψ 's did not differ substantially (**Figure 3**). This is

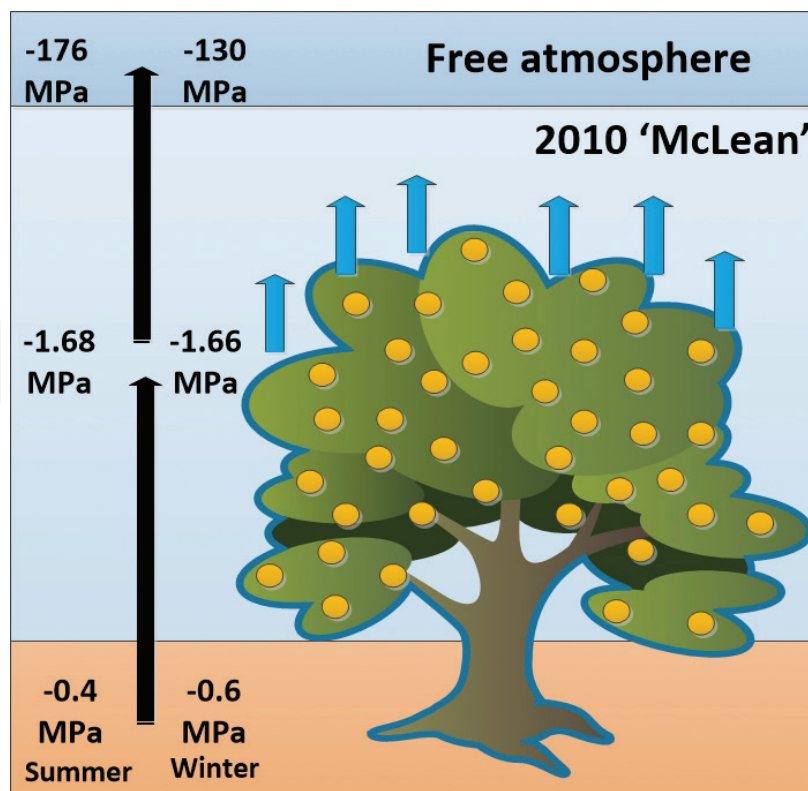


Figure 2. Measured water potentials for a 'McLean' Valencia orchard in a winter rainfall region (Citrusdal, South Africa).

probably due to strong stomatal control of T rate and therefore Ψ_l [34, 35], which is typical behaviour for an isohydric plant [36].

Leaf water potentials and g_s measured for a 'McLean' Valencia orchard are at their highest early in the morning and decreased during the day, with the Ψ_l reaching a minimum just after midday (Figure 3).

In conceptualising the inter-dependence between Ψ_l and g_s (Figure 3), at daybreak when the sun rises and the leaves are exposed to radiation from the sun, the stoma open [19, 20] and

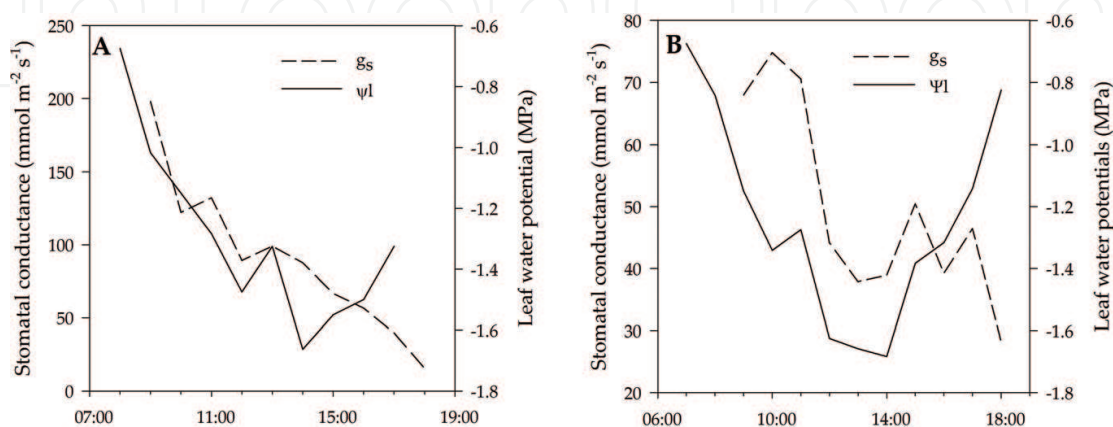


Figure 3. Measured stomatal conductance's (g_s) and leaf water potentials (Ψ_l) for a 5 year-old 'McLean' Valencia orchard during the (A) winter and (B) summer season.

water vapour moves through the stoma (stomatal conductance). As the plant loses water (T) the Ψ decreases relative to the soil, which establishes the gradient for water movement within the plant or sap flow. As water loss cannot exceed the rate of uptake, the plant must have some control over the resistance to water loss and this is achieved by regulating stomatal conductance [37]. Therefore as VPD increases during the day, stomata start to close to prevent a decline in Ψ which would cause cavitation and a loss of xylem integrity. Water continues to move into the tree, due to the water potential difference between the soil and the tree (roots, stem and leaves) causing the Ψ to increase in the afternoon. Water movement from the soil into the tree will cease when the water potential in the roots equals the soil water potential, which generally occurs in the early hours of the morning.

The important role stomata play in controlling Ψ is clearly illustrated in the differences between the winter and summer measurements in **Figure 4**. A much lower stomatal conductance in summer resulted in very similar minimum Ψ 's in summer and winter, which reflects a much bigger vapour pressure gradient out the leaf at this time due to a hotter and drier atmosphere.

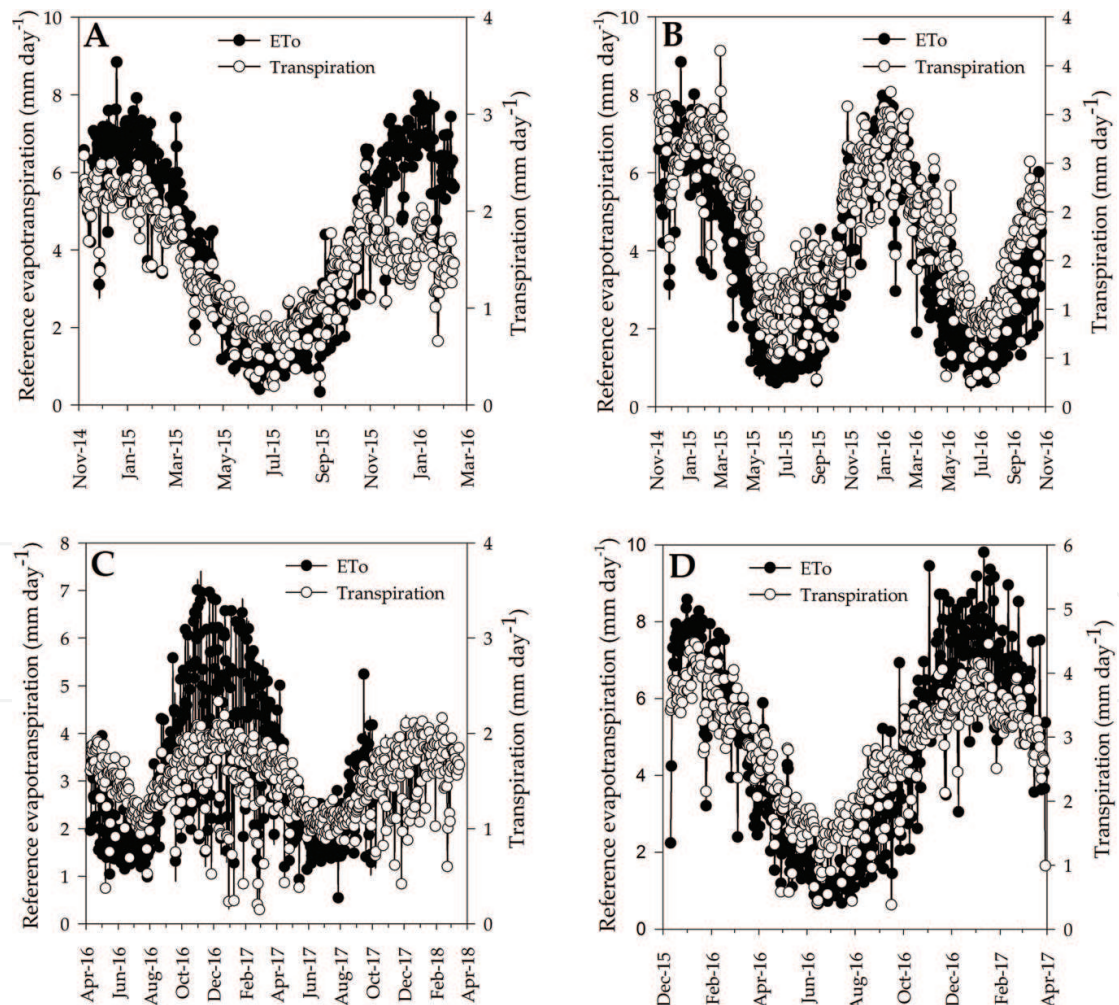


Figure 4. Daily transpiration (T) and reference evapotranspiration (ETo) for (A) a 17 year-old 'Midnight' Valencia, (B) a 9 year-old 'Midnight' Valencia in a winter rainfall region, (C) for a 23 year-old 'Midnight' Valencia in a summer rainfall region and (D) 13 year-old 'Afourer' Mandarin in a winter rainfall region.

Results from multi-seasonal T measurements (**Figure 4**), 717 days for a 17 year-old, 677 days for a 9 year-old, 707 days for a 23 year-old ‘Midnight’ Valencia orchard and 475 days for a 13 year-old ‘Afourer’ mandarin orchard, show large day-to-day variation in T. A clear seasonal trend is also evident with higher T rates recorded during the summer and lower T rates recorded during the winter season for all measuring sites. Daily T closely follows ETo, indicating that the prevailing climatic conditions influence T, as expected. Transpiration deviated from the ETo trend for the 17 year-old ‘Midnight’ Valencia (**Figure 4A**), because the orchard was heavily pruned. The pruning reduced the LAI of the measuring trees by 30% and T by 52% compared to the corresponding period of the previous season. This clearly indicates that reducing canopy volume during periods of drought can be used as a technique to reduce tree water use. For the 23 year-old ‘Midnight’ Valencia orchard (**Figure 4C**) the daily T did not follow ETo as distinctly during the mid-summer period (November 2016–March 2017) compared to the orchards in the winter rainfall region, due to a severe drought that resulted in the implementation of irrigation restrictions [38].

The daily ETo for the 17 and the 9 year-old ‘Midnight’ orchards (**Figure 4A, B**) ranged between 0.34 and 8.85 mm day⁻¹. For the 23 year-old ‘Midnight’ Valencia (**Figure 4C**) in the summer rainfall region ETo ranged between 0.54 and 7.01 mm day⁻¹, while for the 13 year-old ‘Afourer’ Mandarin in a winter rainfall region the ETo ranged between 0.66 and 9.81 mm day⁻¹ for the measurement period. A summary of the T measurements for the different orchards is given in **Table 3**. Transpiration ranged from 0.3–3.7 mm day⁻¹ in the 17 year-old (**Figure 4A**), 0.1–2.1 mm day⁻¹ in the 9 year-old (**Figure 4B**), 0.15–2.33 mm day⁻¹ in the 23 year-old ‘Midnight’ Valencia orchard (**Figure 4C**) and 0.4–4.5 mm day⁻¹ for the 13 year-old ‘Afourer’ mandarin orchard (**Figure 4D**) over the measurement period (**Table 3**). For the ‘Midnight’ orchards, the lowest daily T measurement (0.10 mm day⁻¹) was recorded in the 9 year-old ‘Midnight’ orchard, and the highest

	Transpiration				Measuring period days
	Total	Maximum	Minimum	Average	
	mm (L)	mm day ⁻¹ (L day ⁻¹)			
‘Midnight’ Valencia					
Winter—17 year-old	1295 (19417)	3.70 (54.8)	0.30 (4.0)	1.80 (27.0)	717
Winter—9 year-old	684 (10256)	2.10 (31.0)	0.10 (1.6)	1.10 (16.0)	677
Summer—23 year-old	1037 (21767)	2.30 (49.0)	0.15 (3.1)	1.46 (30.7)	707
‘Afourer’ mandarin					
Winter—13 year-old	1325 (13248)	4.5 (44.9)	0.4 (38.1)	2.8 (27.8)	475

Values in brackets indicate litres.

Table 3. ‘Midnight’ Valencia water use in a winter and summer rainfall region and ‘Afourer’ Mandarin in a winter rainfall region.

(3.70 mm day⁻¹) in the 17 year-old orchard (**Table 3**). The highest daily T (4.5 mm day⁻¹) was recorded in the 13 year-old 'Afourer' mandarin orchard. The higher T values for the 17 year-old 'Midnight' orchard can be attributed to the larger canopy of the 17 year-old 'Midnights' compared to the 9 year-old Midnight orchard as demonstrated by the LAI and canopy cover (**Table 2**). In general the average daily T reflected the canopy cover. The impact of canopy size on tree water use can be substantial, with the average daily T of the 17 year-old 'Midnight' being 39% higher than the average daily T of the 9 year-old 'Midnight' orchard (**Table 3**). However, the impact of the drought in the summer rainfall region (23 year-old 'Midnight') resulted in lower T measurements, due to the reduction in irrigation [38] and therefore the average daily T measured for this orchard was lower.

It is evident from these results that tree water use is also influenced by specie. The LAI, canopy cover and canopy dimensions of the 17 year-old 'Midnight' orchard are comparable to the

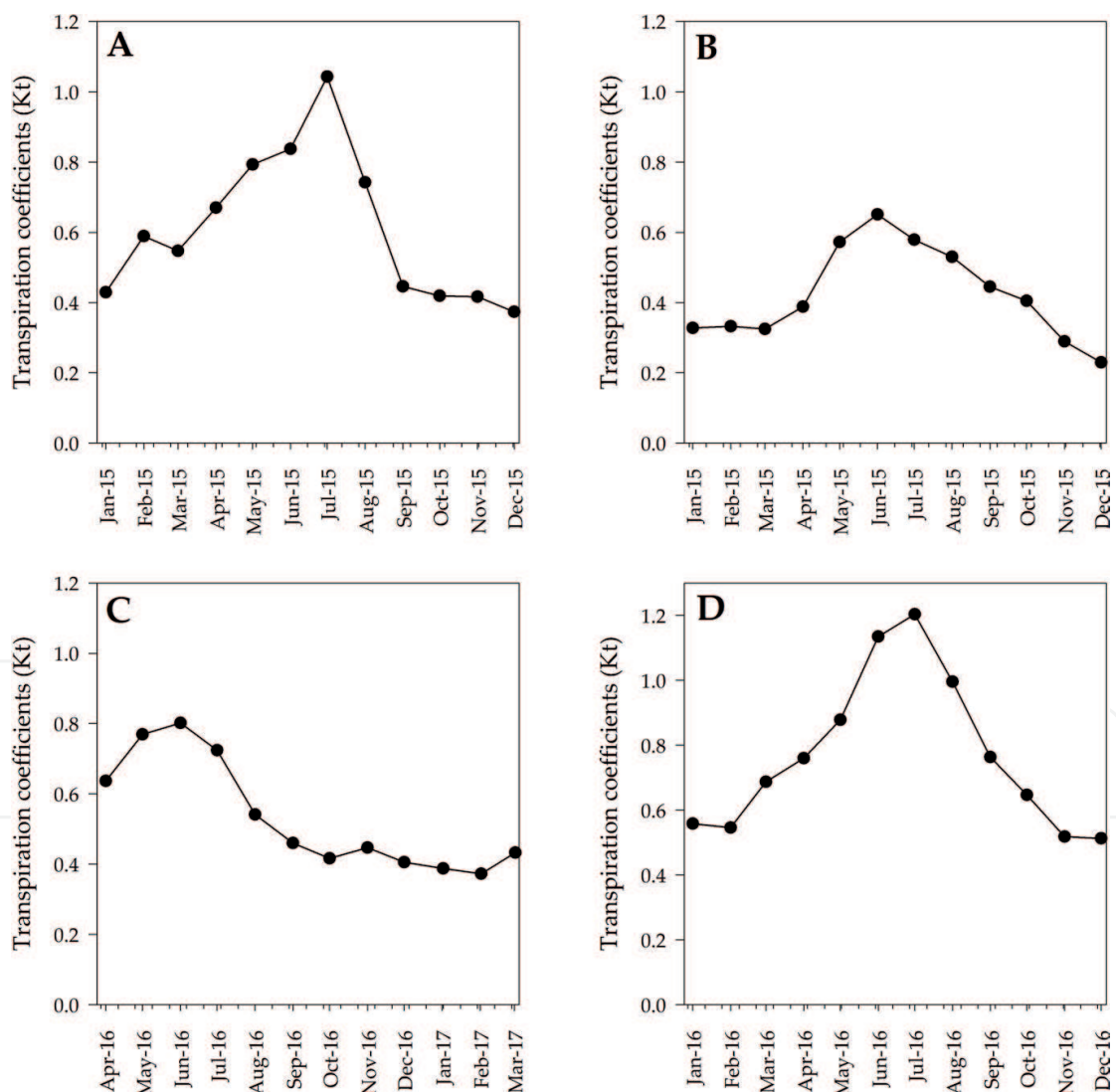


Figure 5. Transpiration coefficients for (A) a 17 year-old 'Midnight' Valencia, (B) a 9 year-old 'Midnight' Valencia in a winter rainfall region, (C) for a 23 year-old 'Midnight' Valencia in a summer rainfall region and (D) a 13 year-old 'Afourer' Mandarin in a winter rainfall region.

13 year-old 'Afourer' orchard (Table 2). But, the multi seasonal daily T average (Table 3) for the 13 year-old 'Afourer' orchard (2.8 mm day^{-1}) is 36% higher than the 17 year-old 'Midnight' orchard (1.80 mm day^{-1}). This difference in tree water use between the two citrus species may be attributed to leaf anatomical and morphological differences [3].

Monthly transpiration coefficient ($K_t = T/ET_o$) values were calculated for the different orchards for a full season (Figure 5). The K_t values varied substantially for the different 'Midnight' Valencia orchards (Figure 5A–C) and ranged from 0.37–1.04 (17 year-old 'Midnight' Valencia), 0.22–0.65 (9 year-old 'Midnight' Valencia) and from 0.37–0.80 for the 23 year-old 'Midnight' Valencia in the summer rainfall region. For the 'Afourer' mandarin orchard, the monthly K_t values ranged from 0.49–1.2 (Figure 5D). Average monthly K_t values showed a similar trend between all orchards, with the maximum values calculated for the winter and the lowest for the summer seasons. The proportional relationship between water use to canopy size was also evident, with the 17 year-old 'Midnight' Valencia and 'Afourer' mandarin orchard (Figure 5A, D) having the largest canopy cover (Table 2) and generally the highest K_t values for the same month. The orchard with the lowest canopy cover (9 year-old 'Midnight' Valencia) also have the smallest K_t values (Figure 5D) when compared for the same month.

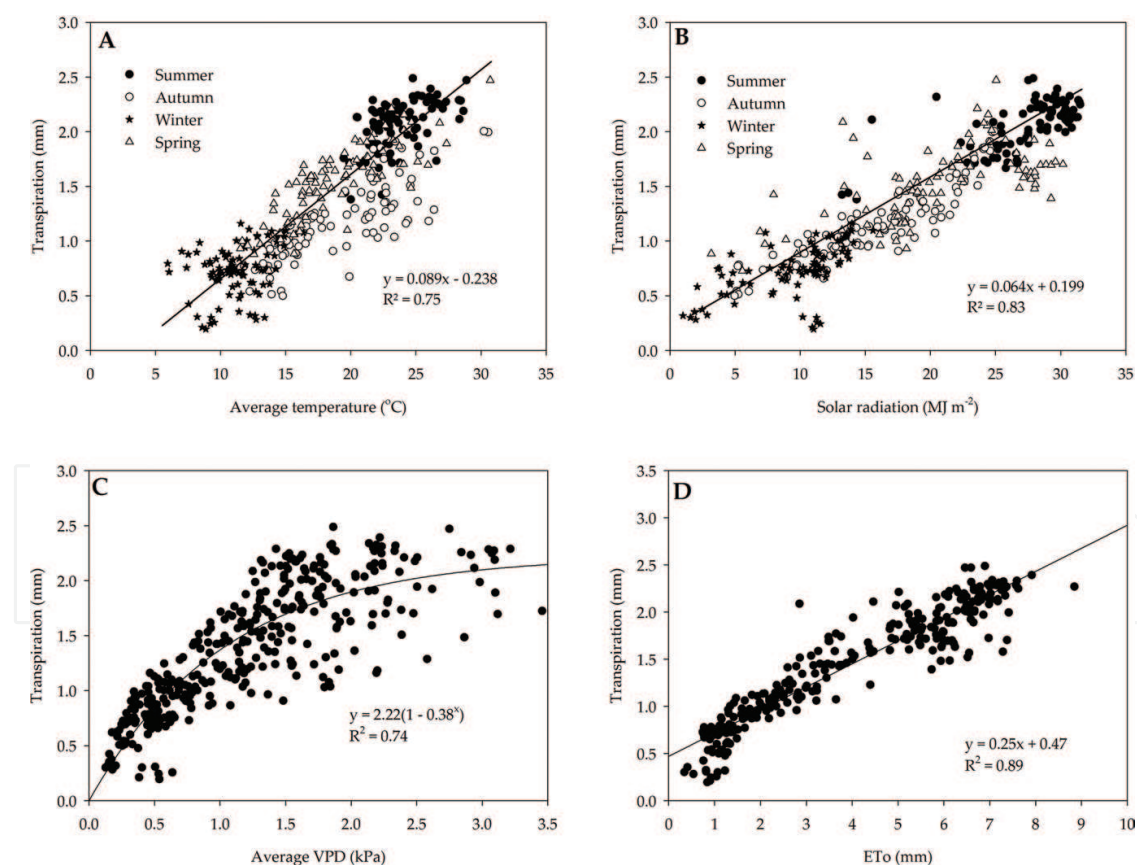


Figure 6. Relationship between transpiration (mm) and (A) average temperature ($^{\circ}\text{C}$), (B) solar radiation (MJ m^{-2}), (C) average vapour pressure deficit (VPD, kPa) and (D) reference evapotranspiration (ET_o , mm) for the 9 year-old 'Midnight' Valencia in a winter rainfall region.

A typical response of citrus to average daily temperature, solar radiation, average daily VPD and ETo is given in **Figure 6**. The response of transpiration to increases in temperature (**Figure 6A**), solar radiation (**Figure 6B**) and ETo (**Figure 6D**) was linear in the 9 year-old 'Midknight' Valencia orchard, with a clear seasonal trend is evident. The lower daily average temperatures and solar radiation in winter that corresponds with the lower T values are grouped together at the bottom of the graph and the higher daily average temperatures and solar radiation in summer that corresponds with higher T values are grouped at the top of the graph. The T in the transition seasons (autumn and spring), which represents a wider range of daily average temperatures and solar radiation, fills the region between the winter and summer values. From the relationship between VPD and T it seems if the upper limit of T was influenced by VPD. Thus, in the mornings, when VPD is still low, a linear relation between solar radiation and T exist, however, as the day progresses the VPD increases and becomes the limiting factor for T, which overrides the influence of radiation. Transpiration seems to reach a maximum once VPD had exceeded 3.0 kPa.

4. Conclusion

Results from the research showed that transpiration (T) followed diurnal and seasonal trends and was influenced by stomatal conductance (g_s) and leaf water potentials (Ψ_l). Good correlations between T and temperature, vapour pressure deficit (VPD) and solar radiation (SR) were found, indicating the importance of the environment in supplying the energy to drive transpiration. A good relationship between canopy size and T, with larger canopies having higher T was evident and should be taken into account with the planning of irrigation infrastructures (convey to field and on-field delivery) and irrigation scheduling. Especially the cumulative effect over a season must be considered when planting new orchards. Provision in the allocation of water should be made for when newly planted orchards with smaller canopies, which use substantially less water, develop mature canopies.

Acknowledgements

Results reported in this chapter are from a 5-year research project entitled "Quantifying citrus water use and water stress at tree and orchard scale" (Project K5/2275//4) that was initiated, managed and funded by the Water Research Commission (WRC) and co-funded by Citrus Research International.

Conflict of interest

Both authors have no conflict of interest in conducting this research.

Author details

J. Teunis Vahrmeijer* and Nicolette J. Taylor

*Address all correspondence to: jtv@villacrop.co.za

Department of Plant and Soil Sciences, University of Pretoria, Pretoria, South Africa

References

- [1] Scora RW. On the history and origin of citrus. *Bulletin of the Torrey Botanical Club*. 1975;**102**:369-375. DOI: 10.2307/2484763
- [2] Carr MKV. The water relations and irrigation requirements of citrus (*Citrus* spp.): A review. *Experimental Agriculture*. 2012;**48**:347-377. DOI: 10.1017/S0014479712000038
- [3] Kriedemann PE, Barrs HD. Citrus orchards. In: Kozlowski T, editor. *Water Deficits and Plant Growth*. New York: Academic Press; 1981. pp. 325-417. DOI: 10.1016/b978-0-12-424156-5.50011-1
- [4] Perry C. Efficient irrigation; inefficient communication; flawed recommendations. *Irrigation and Drainage*. 2007;**56**:367-378. DOI: 10.1002/ird.423
- [5] Hoffman GJ, Oster JD, Alves WJ. Evapotranspiration of mature orange trees under drip irrigation in an arid climate. *Transactions of the American Society of Agricultural Engineers*. 1982;**25**:992-996. DOI: 10.13031/2013.33653
- [6] Smajstria AG, Harrison DS, Tai C, Clapp D. Water budget of crown flood irrigated citrus [Florida]. In: *Proceedings of the Annual Meeting Florida State Horticultural Society*; 1982. pp. 11-14
- [7] Du Plessis HM. Evapotranspiration of citrus as affected by soil water deficit and soil salinity. *Irrigation Science*. 1985;**6**:51-61. DOI: 10.1007/bf00272475
- [8] Castel JR. Water use of developing citrus canopies in Valencia, Spain. In: *Proceeding International Society Citriculture, IX Congress*; 3-7 December. Orlando, Florida: ISC; 2000. pp. 223-226
- [9] Consoli S, O'Connell N, Snyder R. Estimation of evapotranspiration of different-sized navel-orange tree orchards using energy balance. *Journal of Irrigation and Drainage Engineering*. 2006;**132**:2-8. DOI: 10.1061/(asce)0733-9437(2006)132:1(2)
- [10] Villalobos FJ, Testi L, Moreno-Perez MF. Evaporation and canopy conductance of citrus orchards. *Agricultural Water Management*. 2009;**96**:565-573. DOI: 10.1016/j.agwat.2008.09.016
- [11] Fares A, Dogan A, Abbas F, Parsons LR, Obreza TA, Morgan KT. Water balance components in a mature citrus orchard. *Soil Science Society of America Journal*. 2008;**72**: 578-585. DOI: 10.2136/sssaj2007.0167

- [12] Spiegel-Roy P, Goldschmidt EE. *Biology of Citrus*. Cambridge: Cambridge University Press; 1996. DOI: 10.1017/CBO9780511600548
- [13] Castle WS, Krezdorn AH. Effect of citrus rootstocks on root distribution and leaf mineral content of 'Orlando' tangelo trees. *Journal. American Society for Horticultural Science*. 1975;**100**:1-4
- [14] Castle, WS. Citrus root systems: Their structure, function, growth, and relationship to tree performance. In: *Proceedings of the International Society of Citriculture*; 15-23 August. Sydney: University of Sydney; 1978. pp. 62-69
- [15] Morgan KT, Obreza TA, Scholberg JMS. Orange tree fibrous root length distribution in space and time. *Journal American Society of Horticultural Science*. 2007;**132**:262-269
- [16] Rodríguez-Gamir J, Intrigliolo DS, Primo-Millo E, Forner-Giner MA. Relationships between xylem anatomy, root hydraulic conductivity, leaf/root ratio and transpiration in citrus trees on different rootstocks. *Physiologia Plantarum*. 2010;**139**:159-169. DOI: 10.1016/j.scienta.2010.06.015
- [17] Syvertsen JP. Hydraulic conductivity of four commercial citrus rootstocks. *Journal of the American Society for Horticultural Science*. 1981;**106**:378-381
- [18] CGA. *Citrus statistics*. Cape Town: Citrus Growers Association; 2012
- [19] Mills TM, Morgan KT, Parsons LR. Canopy position and leaf age affect stomatal response and water use of citrus. *Journal of Crop Production*. 2000;**2**:163-179. DOI: 10.1300/j144v02n02_06
- [20] Moreshet S, Cohen Y, Green GC, Fuc M. The partitioning of hydraulic conductances within mature orange trees. *Journal of Experimental Botany*. 1990;**41**:833-839. DOI: 10.1093/jxb/41.7.833
- [21] Gomes MMA, Lagôa AMMA, Medina CL, Machado EC, Machado MA. Interactions between leaf water potential, stomatal conductance and abscisic acid content of orange trees submitted to drought stress. *Brazilian Journal of Plant Physiology*. 2004;**16**:155-161. DOI: 10.1590/s1677-04202004000300005
- [22] Cohen S, Cohen Y. Field studies of leaf conductance response to environmental variables in citrus. *Journal of Applied Ecology*. 1983;**20**:561-570. DOI: 10.2307/2403526
- [23] Syvertsen JP. Minimum leaf water potential and stomatal closure in citrus leaves of different ages. *Annals of Botany*. 1982;**49**:827-834. DOI: 10.1093/oxfordjournals.aob.a086309
- [24] Sinclair TR, Allen LH. Carbon dioxide and water vapour exchange of leaves on field-grown citrus trees. *Journal of Experimental Botany*. 1982;**33**:1166-1175. DOI: 10.1093/jxb/33.6.1166
- [25] Allen RG, Pereira LS, Raes D, Smith M. *Crop evapotranspiration - Guidelines for computing crop water requirements*. Rome: Food and Agriculture Organization of the United Nations; 1998

- [26] Burgess SO, Adams MA, Turner NC, Beverly CR, Ong CK, Khan AAH, Bleby TM. An improved heat pulse method to measure low and reverse rates of sap flow in woody plants. *Tree Physiology*. 2001;**21**:589-598. DOI: 10.1093/treephys/21.9.589
- [27] Bleby TM, Burgess SO, Adams MA. A validation, comparison and error analysis of two heat-pulse methods for measuring sap flow in *Eucalyptus marginata* saplings. *Functional Plant Biology*. 2004;**31**:654-658. DOI: 10.1071/fp04013
- [28] Barrett D, Hatton T, Ash J, Ball M. Evaluation of the heat pulse velocity technique for measurement of sap flow in rainforest and eucalypt forest species of South-Eastern Australia. *Plant, Cell and Environment*. 1995;**18**:463-469. DOI: 10.1111/j.1365-3040.1995.tb00381.x
- [29] Marshall DC. Measurement of sap flow in conifers by heat transport. *Plant Physiology*. 1958;**33**:385-396. DOI: 10.1104/pp.33.6.385
- [30] Soil Classification Working Group. Soil classification. In: A Taxonomic System for South Africa. Vol. 2. Pretoria: Department of Agricultural Development; 1991
- [31] Campbell GS, Norman JM. An Introduction to Environmental Biophysics. Vol. 2. New York: Springer; 1998
- [32] Camacho-B SE. Some aspect of the stomatal behavior of citrus. In: Proceedings of the International Society of Citriculture; 1-8 May. Orlando, Florida: ISC; 1977. pp. 66-69
- [33] Steppe K, Dzikiti S, Lemeur R, Milford JR. Stomatal oscillations in orange trees under natural climatic conditions. *Annals of Botany*. 2006;**97**:831-835. DOI: 10.1093/aob/mcl031
- [34] Mantell A. Water use efficiency of citrus: Room for improvement. In: Proceedings of the International Society of Citriculture; 1-8 May. Orlando, Florida: ISC; 1977. pp. 74-79
- [35] Hoare ER, Barrs HD. Water relation and photosynthesis among horticultural species as affected by simulated water stress. In: Proceedings of the 19th International Horticultural Congress; 11 September. Warsaw, Poland: International Society for Horticultural Science; 1974. pp. 321-334
- [36] Tardieu F, Simonneau T. Variability among species of stomatal control under fluctuating soil water status and evaporative demand: Modelling isohydric and anisohydric behaviours. *Journal of Experimental Botany*. 1998;**49**:419-432. DOI: 10.1093/jexbot/49.suppl_1.419
- [37] Campbell GS, Turner NC. Plant-soil-water relationships. In: Hoffman GJ, Howell TA, Solomon KH, editors. Management of Farm Irrigation Systems. St Joseph, MI: The American Society of Agricultural Engineering; 1990. pp. 15-29
- [38] WRC. Limpopo Water Restrictions. 2016. Available from: <http://www.droughtsa.org.za/limpopo-water-restrictions.html>