VOLUME 2

# QUANTIFYING CITRUS WATER USE AND WATER STRESS AT ORCHARD LEVEL

## Measurement and Modelling of Seasonal Citrus Water Use for Different Growth Stages and Canopy Sizes

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WATER RESEARCH COMMISSION

TT 772/2/18

# Quantifying Citrus Water Use and Water Stress at Orchard Level

## Measurement and Modelling of Seasonal Citrus Water Use for Different Growth Stages and Canopy Sizes

## (Volume 2)

Report to the
**WATER RESEARCH COMMISSION and**
**DEPARTMENT OF AGRICULTURE FORESTRY AND FISHERIES**

by

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in collaboration with

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This report forms part of a series of two reports. The other report is *Validation and Calibration of Sap Flux Density Measurements in Citrus - Volume 1.* **(WRC Report No TT 772/1/18)**



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## EXECUTIVE SUMMARY

### BACKGROUND

This study presents information on the validation and calibration of sap flux density (SFD) techniques that were used to measure citrus water use (Volume 1). The most appropriate sap SFD technique, to quantify transpiration in *Citrus sinensis*, was identified and then used to gather information on citrus water use (Volume 2). A unique set of data on citrus water use was compiled and comprises of the following:

i. Hourly measurements of transpiration.
ii. Multi seasonal. The largest dataset consists of water use measurements, of a single orchard, for 718 days.
iii. Water use information on three different sized (small, medium and mature) canopies.
iv. Information on water use for the following species: *Citrus sinensis, Citrus paradisi* and *Citrus reticulata*.
v. Results on citrus water use from both the winter rainfall (Citrusdal area) and summer (Letsitele area) regions of South Africa.
vi. Relationships between selected plant physiological measurements, such as stomatal conductances, leaf and stem water potentials, and transpiration.
vii. Impact of water stress on yield and fruit quality.

### RATIONALE

The citrus industry is the largest exporter of fresh produce, in South Africa, in terms of volume and one of the highest for earning of foreign exchange with more than 100 million 15 kg cartons exported annually. The 70 917 hectare citrus industry, which depends on irrigation, provides more than 125 000 jobs that support more than 750 000 people. Citrus is a perennial crop that requires a constant supply of water in order not to limit yields and returns on investment. Due to climate change, established production areas are likely to become drier, which will place increasing pressure on water resources and irrigation management to maintain productivity. A previous WRC research project (K5/1770//4) used a sap flow technique to quantify water use of mature citrus, deciduous fruit and nut tree cultivars under best management practices. Findings from this project indicate results that were contrary to expectations, specifically for citrus. In addition an external international review recommended more in depth research to first validate measuring techniques; and secondly to quantify water use over all growth stages for different cultivars. The more detailed research should investigate water use over seasonal growth stages, from planting to mature canopy size and water stress in relation to fruit yield and quality.

In order to provide effective advice to both established and emerging commercial farmers on irrigation methods and scheduling, accurate knowledge is required on water use. The emerging commercial farmers, who comprise approximately 300 of the 2 700 citrus growers and are supported by the industry through bursaries, mentoring and extension, are especially in need of this information. All citrus fruit producers are faced with a major challenge in maintaining high yields per hectare and fruit quality, whilst simultaneously achieving viable returns and ensuring sustainability. Given the increase in competition for water between irrigation agriculture, secondary industry and domestic water use, more knowledge is required on citrus water use for growers to remain competitive and justify future production.

**AIMS AND OBJECTIVES**

The aims and objectives for this WRC project are given below. The results from this study are published in two volumes. The first volume addresses the validation and calibration of the sap flux density techniques (Objective 1) that were used to measure and model the water use of different sized citrus trees in the summer and winter rainfall region of South Africa (Objective 2). Results from the infield water use measurements and modelling, and from the study on the impact of water stress on yield and fruit quality (Objective 3) are presented in Volume 2.

**General**

To analyse the water use, yield, fruit size and quality of a selected Valencia, navel, grapefruit and/or soft citrus cultivar for different canopy architectures in summer and/or winter rainfall regions; including a detailed analysis of water stress in relation to yield and quality for a selected cultivar at a single location.

**Specific**

1. To validate citrus water use by comparing different sap flux density techniques with an appropriate technique such as lysimetry, cut stem and/or eddy covariance.

2. To measure and model citrus water use and water use efficiency according to seasonal growth stages from planting to mature canopy size.

3. To determine the influence of water stress on fruit set, fruit yield, and pre- and post-harvest fruit quality for a selected cultivar and single location.

## METHODOLOGY

Infield tree water use ($T_{sap}$) was measured in the Western Cape and Limpopo Provinces that represent two different rainfall regions of South Africa. Both Citrusdal and Letsitele are considered to be influenced by the local steppe climate and is classified as BSh by Köppen and Geiger. The average annual temperature for Citrusdal is 18.4°C and for Letsitele 21.7°C. Citrusdal is situated in the Western Cape in the winter rainfall region of South Africa and has an annual rainfall of approximately 315 mm. Letsitele is located in the Limpopo Province, which is a summer rainfall region in the north eastern part of South Africa, and has an annual rainfall of approximately 646 mm.

$T_{sap}$ measurements, using the heat ratio (HR) technique, were upscaled to orchard level to gain insights on the influence of climate, canopy size, and specie and cultivar on citrus water use. Ancillary measurements were also done to facilitate our understanding of the factors and processes that drive transpiration (T). These measurements included stomatal conductance ($g_s$), photosynthesis, interception of photosynthetically active radiation (PAR) and stem ($\Psi_{stem}$) and leaf ($\Psi_{leaf}$) water potentials. The first phase of sap flow measurements, with the HR method, started early in August 2013 in four orchards on the farm Patrysberg (32°27’15’’ S and 18°58’03’’ E). Two Valencia and two navel orchards, with different size canopies, were instrumented. Constant power heat balance gauges, for $T_{sap}$ measurements, were also installed in a small ‘Cambria’ navel orchard for short periods of time during the 2013 and 2014 seasons. The second phase of measurements, in the winter rainfall region, involved removing equipment from navel orchards and installing the equipment in soft citrus orchards. As a result two ‘Afourer’ mandarin (Nadorcott) orchards were instrumented on the farm Brakfontein (32°30’27.63” S and 18°59’49.13” E) in August 2015. The campaign to measure water use in citrus in the summer rainfall region commenced in 2015 on various farms, owned by Mahela Boerdery, in Letsitele. A total of 8 orchards were instrumented with the sap flow equipment (HR method). Three different size orchards of each species were instrumented, except in the case of the ‘Valley Gold’ mandarins, where a suitable mature orchard could not be located on the farm.

In Citrusdal hourly and daily weather data were obtained from Campbell Scientific automatic weather stations (AWS) on Patrysberg (32°27’2.57” S and 18°58’6.23” E) and from October 2015 on Brakfontein (32°29’30.46” S and 18°59’48.79” E). These AWS were installed according to the standard conditions specified in FAO-56. Weather data was obtained from two AWS in the summer rainfall region that were operated and maintained by QMS Laboratories. The Constantia (23°40’54.96’’ S and 30°35’27.19’’ E) and Letsitele junction (23°52’08.07’’ S and 30°22”50.10’’ E) AWS were surrounded by irrigated orchards and buildings. Whilst the irrigated orchards would have conditioned the boundary layer, the height of the orchards may have impacted wind speed, which may have resulted in an underestimation of $ET_o$.

The root distribution of selected orchards was determined by digging profile pits and taking soil/root samples at a maximum of four depths between 0.2 and 0.6 m. Samples were taken perpendicular with the tree row and between the tree rows at three positions: close to the tree trunk, midway between the tree trunk and the canopy edge and at the canopy edge.

Tree height, width (across the tree row) and breadth (within the tree row) of each orchard were routinely measured every 6 to 12 weeks. Canopies were approximately ellipsoidal, therefore canopy volume was calculated using the formula for an ellipsoid. Leaf area index (LAI) of individual trees and the orchard as a whole was determined using an LI-2200 Plant Canopy Analyser (Li-Cor Biosciences, Lincoln, Nebraska, USA) under diffuse light conditions. For determining individual tree LAIs, measurements were made at the four cardinal points under each tree, with clear sky readings taken in the open next to the orchard. For determining orchard LAIs, measurements under the canopy were made across the work row from the trunk of one tree to the trunk of the tree in the next row. Once again, clear sky readings were taken in the open next to the orchard.

Fractional interception of PAR was determined with a Decagon AccuPAR LP-80 ceptometer (Decagon Devices, Pullman, WA, USA) in a grid pattern, around a representative tree, in each orchard. The grid consisted of transect lines across the tree row with 1 m in-between transects and with 1 m between the grid points. The number of measurements in each orchard depended on the planting density of the orchard. Measurements were conducted throughout the course of the day, on the hour, every hour under clear sky conditions. Full sun readings were taken in an open area next to the orchard. Five calibrated tube solarimeters (Delta-T) were used to continuously measure solar radiation ($R_n$) received at the orchard floor for all the study orchards for short periods of time. The solarimeters were positioned in the work row on both the east and west sides of the tree row, with the 5$^{th}$ solarimeter placed directly under the canopy in the tree row.

Leaf and stem water potentials were measured hourly, using a Scholander pressure chamber (PMS Instrument Company, Albany, USA), from before sunrise to sunset on selected days. Three sunlit leaves and three shaded leaves were measured on the four trees instrumented with sap flow equipment. Stem water potential was also measured hourly by selecting leaves in the inside of the canopy. These leaves were then enveloped in aluminium foil and enclosed in plastic bags for at least 30 min prior to measurement. Predawn leaf water potentials ($\psi_{pd}$) were measured during all measurement campaigns.

Stomatal conductance measurements were performed using a SC-1 leaf porometer (Decagon Device Inc, Pullman, WA, USA) at the beginning of the project and an AP4 porometer (Delta-T Devices Ltd, Cambridge, United Kingdom) towards the end of the project. Three leaves on the east of the tree, three on the west and three shaded leaves were measured on the four trees instrumented with sap flow equipment. Measurements were performed from sunrise to sunset at hourly intervals on healthy mature leaves. On days with early morning dew on the leaves, $g_s$ measurements only commenced once the leaf surface was dry. Hydraulic conductance (k) was estimated according to Cohen and Naor (2002), where k was separated into the pathways; a) from the soil to the stem ($k_{soil\text{-}stem}$) and b) from the stem to the leaves ($k_{stem\text{-}leaf}$).

Detail on the methodology and theory of SFD measurements is detailed in Volume 1 (Validation and calibration of sap flux density measurements in citrus) of the report. Infield calibration and validation of the HR method was conducted in the winter rainfall region of South Africa. The trial site consisted of a 4.1 ha, 9-year-old commercial orchard of 'Washington' navels (*Citrus sinensis*), grafted on 'Carrizo' citrange rootstock that was planted in 2006. An open path eddy covariance (EC) system was used for the measurement of orchard ET for the calibration period (3-18 March 2015). Measurements were performed by the Council for Scientific and Industrial Research (CSIR), Natural Resources and Environment unit based in Stellenbosch. Soil evaporation ($E_s$) was measured daily from 9-14 March 2015 using cylindrical microlysimeters. A set of twelve microlysimeters were installed taking into account the dry and wet areas on the orchard floor and movement of shade throughout the day within the orchard. Transpiration ($T_{res}$) for the orchard was then taken as the residual between ET and $E_s$.

Sap flow measurements, to determine $T_{sap}$, were conducted in trees in the proximity of the EC tower. Four trees were instrumented with the HR method equipment to quantify and compare T measurements. One of the major challenges faced infield, was the onset of gumming which hastened the rate of corrosion of the heater probes soon after the trees were instrumented. This problem was solved by inserting brass collars (2.5 mm in diameter) in the tree to accommodate the heater probes, thus reducing the occurrence of corrosion. At the end of the experiment sections of the tree trunk, where probes were inserted, were removed from the four HR method measurement trees. The exposed, fresh face was shaved smooth using a chisel, after which the wound width was clearly identified by its darker colour. Wound width at its widest point was measured for each tree using a digital Vernier calliper and an average wound for the orchard was determined, which was then used for the calculation of the SFD. Sapwood depth was determined through staining the conducting tissue with safranin O dye.

**RESULTS AND DISCUSSION**

Results from this research showed that in all the orchards measured, both winter and summer rainfall regions, T followed clear diurnal and seasonal trends. Large day-to-day variations were evident, where T varied from less than 1 mm $day^{-1}$ to more than 4 mm $day^{-1}$. The highest daily T (4.5 mm $day^{-1}$) was measured in the 2002 'Afourer' mandarin orchard (Table 8.1). Annual orchard water use also showed significant variation, with an annual water use varying from 136 mm for the 2015 'Valley Gold' mandarin orchard to 953 mm for the 2002 'Afourer' mandarin orchard. The large variation in daily T measured was driven by environmental conditions and differences in canopy size between orchards. Good correlations between daily T and daily temperature, VPD, $R_s$ and $ET_o$ were found, especially for the winter rainfall region, demonstrating the importance of the environment in supplying the energy to drive T. However, the response of T to $ET_o$ and VPD was not always linear. After an initial strong positive response, T tended towards a plateau value as $ET_o$ and VPD increased passed a certain threshold value. However, despite this response, $ET_o$ still explained a large proportion of the variation in T and therefore $K_t$ values may still be appropriate for estimating the T of orchards from $ET_o$ estimations.

In an attempt to explain the plateau response of T to $ET_o$ and VPD, a number of ecophysiological measurements were performed. Stomata were found to close in 'Midknight' Valencia orchards in both the summer and winter rainfall regions as VPD exceeded approximately 1 kPa. Environmental conditions also significantly influenced the diurnal course of $\Psi_{leaf}$, with $\Psi_{leaf}$ reaching lower values on hot and dry days, as opposed to cooler and more humid days. However, despite hot and dry conditions, values lower than -2.5 MPa were seldom recorded, which again supports some form of physiological control over leaf water status. The reason for this tight physiological control seems to be linked to lower hydraulic conductance in the soil to stem pathway, rather than in the stem to leaf pathway. This agrees with the findings of Kriedemann and Barrs (1981), Sinclair and Allen (1982) and Van Bavel et al. (1967) who suggested that citrus trees have high root resistances.

It was also evident that canopy size was a major determinant of T rates, with larger canopies having higher T both on a daily and annual basis (Table 1 and 2). The drastic increase in water use from planting to maturity should be taken into account when planning irrigation infrastructure (convey to field and on-field delivery) and scheduling irrigation. Whilst newly planted orchards have fairly low water requirements, within 5-6 years this requirement can double and even triple. The cumulative effect over a season must also be considered when planting new orchards, as the initial increase in the size of small trees can be quite dramatic. 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.

**Table 1 Summary of the tree water use of the orchards in the winter rainfall region**

| | 2000 'Midknight' Valencia | | 2008 'Midknight' Valencia | | 2010 'McLean' Valencia | | 1990 'Bahianinha' navels | | 2006 'Washington' navels | | 2002 'Afourer' mandarin | | 2013 'Afourer' mandarin | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Transpiration** | **mm** | **L** | **mm** | **L** | **mm** | **L** | **mm** | **L** | **mm** | **L** | **mm** | **L** | **mm** | **L** |
| **Total** | 1 601 | 20 014 | 1 064 | 15 959 | 436 | 6 537 | 117 | 1 895 | 2001 | 3 009 | 1 325 | 13 248 | 150 | 2 057 |
| **Maximum per day** | 4.0 | 49.9 | 2.8 | 42.0 | 1.3 | 19.4 | 1.7 | 27.9 | 1.2 | 17.3 | 4.5 | 44.9 | 2.5 | 33.8 |
| **Minimum per day** | 0.3 | 4.2 | 0.2 | 3.4 | 0.1 | 0.7 | 0.3 | 5.3 | 0.1 | 0.9 | 0.4 | 3.8 | 0.2 | 2.8 |
| **Average per day** | 2.2 | 27.9 | 1.5 | 22.2 | 0.7 | 11.1 | 1.1 | 17.4 | 0.7 | 10.7 | 2.8 | 27.8 | 1.1 | 15.7 |
| **Annual water use** | 812 | 10 152 | 539 | 8 078 | 251 | 3 765 | 477* | 7 730* | 264* | 3 962* | 953 | 9 533 | 392* | 5 386* |
| **Canopy cover** | 0.83 | | 0.54 | | 0.35 | | 0.58 | | 0.48 | | 0.81 | | 0.19 | |
| **WUE (kg m$^{-3}$)** | - | | 4.7 | | 3.9 | | 8.4* | | 14.4* | | 7.9 | | 5.4* | |
| **Measurement period (days)** | 718 | | 718 | | 588 | | 109 | | 280 | | 476 | | 131 | |

*Estimated value.

**Table 2 Summary of the tree water use of the orchards in the summer rainfall region**

| | 2006 'Star Ruby' grapefruit | | 2010 'Star Ruby' grapefruit | | 2011 'Star Ruby' grapefruit | | 1995 'Midknight' Valencia | | 2008 'Midknight' Valencia | | 2014 'Midknight' Valencia | | 2013 'Valley Gold' mandarin | | 2015 'Valley Gold' mandarin | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Transpiration** | **mm** | **L** | **mm** | **L** | **mm** | **L** | **mm** | **L** | **mm** | **L** | **mm** | **L** | **mm** | **L** | **mm** | **L** |
| **Total** | 576 | 12 096 | 446 | 9 372 | 328 | 6 885 | 1 109 | 23 291 | 547 | 11 497 | 213 | 4 472 | 185 | 3 881 | 154 | 3 233 |
| **Maximum per day** | 1.9 | 39.7 | 1.3 | 26.6 | 1.1 | 23.2 | 2.5 | 51.6 | 1.2 | 24.5 | 1.1 | 22.7 | 0.8 | 17.6 | 0.8 | 15.9 |
| **Minimum per day** | 0.1 | 2.3 | 0.3 | 6.9 | 0.1 | 1.1 | 0.2 | 3.3 | 0.1 | 1.3 | 0.1 | 2.1 | 0.03 | 0.6 | 0.02 | 0.5 |
| **Average per day** | 1.0 | 20.8 | 0.8 | 17.1 | 0.5 | 10.8 | 1.6 | 32.9 | 0.8 | 16.2 | 0.6 | 12.3 | 0.5 | 9.7 | 0.4 | 8.1 |
| **Annual water use** | 387 | 8 135 | 314 | 6 599 | 180 | 3 789 | 560 | 11 751 | 275 | 5 776 | 213 | 4 472 | 167 | 3 506 | 139 | 2 917 |
| **Canopy cover** | 0.71 | | 0.59 | | 0.41 | | 0.74 | | 0.51 | | 0.27 | | 0.42 | | 0.34 | |
| **WUE (kg m$^{-3}$)** | 14.9 | | 19.0 | | 15.4 | | 11.4 | | 13.5 | | 9.6 | | 5.3 | | 2.9 | |
| **Measurement period (days)** | 581 | | 547 | | 636 | | 707 | | 707 | | 363 | | 402 | | 401 | |

Importantly, water use in citrus orchards does not only consist of T, but also from $E_s$. Whilst extensive measurement and modelling of $E_s$ was not completed in this study, window periods of ET measurements allowed the assessment of the partitioning of ET between T and $E_s$. Understanding the partitioning of ET is important as substantial water savings can potentially be made by reducing the non-beneficial consumptive water use or $E_s$. This will be of particular importance during periods of drought or when a grower wishes to expand production with his existing water allocation. The fraction of ET partitioned to T was significantly higher in Citrusdal, which is considerably hotter and drier compared to Letsitele. In Citrusdal this value varied between 65% for the 'Washington' navel orchard to 91% in the 'Afourer' Mandarin orchard. However, in Letsitele this value varied from 19% in the 2013 'Valley Gold' mandarin orchard to 45% in the 2006 'Star Ruby' grapefruit orchard. This is most likely a result of the sandier soils and drip irrigation in the Citrusdal orchard, as opposed to the microsprinkler irrigation and more clay soils in Letsitele. A more comprehensive understanding of the dynamics of $E_s$ in orchards will be important to consider in future in order to improve the WUE of a wide range of orchards. It will also assist growers in making better use of a limited resource.

Whilst T values are very useful to understand how much water was required by the orchards of varying sizes during the course of this study, these values are not always easily transferable to different orchards and different regions. This is due to the dependency of T on environmental conditions and canopy size, as demonstrated in this study. One way to try and account for varying environmental conditions is to normalise for local weather conditions using reference evapotranspiration, commonly calculated as $ET_o$. Transpiration crop coefficients ($K_t$) were, therefore, derived from this process and used to make the T data determined in this study more applicable to a wider range of regions in South Africa. Transpiration crop coefficients were also regressed against a number of descriptors of canopy size (volume, LAI and fractional interception of PAR) to determine if a single relationship exist between $K_t$ and canopy size, for different citrus species and if this relationship is consistent between rainfall regions. In order to do this, a semi-empirical model that calculates bulk $g_c$ as a function of tree intercepted radiation and VPD was calibrated and validated and used to estimate Kt from *f*IPAR. Results from the model as well as fortnightly and monthly $K_t$ values are being reported.

The impact of water stress on the yield and quality of 'Delta' Valencias was more evident in the pre-harvest than the postharvest assessments. Water stress during phase I (fruit set, cell division) and phase II (cell enlargement) of fruit development had the largest impact, with a 32% reduction in yield. No significant decrease in yield was observed when the water was withhold during phase III (fruit maturity) of fruit development. Excessive fruit drop was also observed during phase I and II of fruit development that resulted in less, but larger fruit on the trees.

Water stress treatments at fruit set (phase I), fruit enlargement (phase II) and fruit maturity (phase III) did not significantly influence colour development, percentage fruit juice, acid percentage and total soluble solids. As a result, the impact of water stress on yield and post-harvest fruit quality during phase III of fruit growth will be less than if water stress occurs during phase I or phase II of fruit growth. Water stress during phase I or phase II of fruit growth will most likely result in a yield penalty, although larger fruit may develop due to less fruit on the tree. Water stress during these stages may also have a limited impact on the post-harvest quality of the fruit.

## CAPACITY BUILDING

A number of students benefitted from this research project and used the data generated throughout the project to obtain post graduate qualifications. Three students received their MSc degrees and two their honours degrees. Information on and results from the project were communicated to the grower community through a series of information sessions held at the CRI Research Symposium, farmer's days, study group meetings and workshops. Results from this research project were also presented at local and international conferences and published in conference proceedings and as a chapter in a book named Citrus. The detail of the capacity building activities are listed below.

### MSc

i. Ms M Sam. 2016. Calibration of sap flow techniques in citrus using the stem perfusion method. University of Pretoria.
ii. Mr M Banda. 2017. Validating sap flux density measurement methods in *Citrus sinensis*. University of Pretoria.
iii. N Shongwe. 2018. Measuring and modelling canopy size of *Citrus sinensis* in relation to water use. University of Pretoria. In press.

### Honours projects

i. Ms A Bresler. 2016. Environmental control of transpiration of different Citrus spp. University of Pretoria.
ii. Mr N Neethling. 2016. Seasonal variation in water relations and transpiration of Valencia oranges in summer and winter rainfall regions. University of Pretoria.

**Information dissemination and study groups**

i. A special session titled "Water use of citrus orchards" was held at the 8th Citrus Research Symposium on 19 August 2014. This symposium is held every two years and is the main event, with more than 500 delegates, for the exchange of knowledge and experience between researchers, industry and farmers in South Africa
ii. A farmer's day for upcoming citrus farmers was arranged by Mr Andrew Mbedzi and held in conjunction with the CRI at the farm of Mr Chauke, close to Thohoyandou in the Limpopo Province, on 6 August 2015. The meeting was attended by 48 delegates that consisted of emerging citrus farmers, the Chief of the local area, and officials from the local municipality and Agriculture Research Council
iii. Mr MC Pretorius, an extension officer of the Citrus Research International (CRI) arranged an information day in conjunction with the CRI and Letsitele Constantia Study Group in the Letsitele region on 5 April 2016. The meeting was attended by approximately 40 commercial citrus farmers. Information on the project was well received, especially in the light of the current drought

**Study group meetings**

i. Citrusdal Study Group, Patrysberg. Citrus Water Use and Irrigation Scheduling, JT Vahrmeijer. 7 February 2017
ii. Benede-Oranje River Study Group. Field visits to Mosplaas Sitrus, Loveren & Renosterkop. Presentation at Lake Grapa. Citrus Water Use and Irrigation Scheduling, JT Vahrmeijer. 9 February 2017

**Workshops**

i. CRI production workshops held at Swadini, Loskop Dam, Nelspruit, Jeffreys Bay and Citrusdal, JT Vahrmeijer during September 2015
ii. Drought management, Allée Bleue, Simondium. Citrus Water Use and Management, JT Vahrmeijer. 27 October 2017

**Popular articles**

i. Water research in citrus. JT Vahrmeijer, TG Grout and NJ Taylor. South African Fruit Journal. June 2015, p 88-90
ii. Irrigation scheduling made easy. JT Vahrmeijer, and NJ Taylor. AgriCulture, April 2017

**Conference presentations**

i. Are sap flow measurements useful for determining water use of fruit orchards, when absolute values are important? Taylor NJ, Ibraimo NA, Annandale JG, Everson CS, Gush MB, Vahrmeijer JT. 9th International Workshop on Sap Flow Ghent, Belgium. June 2013

ii. Calibrating sap flow systems: is it really necessary? Taylor NJ, Vahrmeijer JT, Everson CS, Sam MC, Teklemichael B, Gilfillan RG, Annandale JG. South African Society of Crop Production/Soil Science Society of South Africa/Southern African Society of Horticultural Sciences Combined Congress, Grahamstown, January 2014

iii. Are citrus trees thirsty? Vahrmeijer JT, Annandale JG, Everson CS and Taylor NJ. 8th Citrus Research Symposium, Champagne Sports Resort, Drakensberg 17-20 August 2014

iv. Are all citrus trees created equal? Taylor NJ, Annandale JG, Everson CS and Vahrmeijer JT. 8th Citrus Research Symposium, Champagne Sports Resort, Drakensberg 17-20 August 2014

v. Validating sap flux density measurement methods in potted *Citrus sinensis*. Banda M, Vahrmeijer JT and Taylor NJ. South African Society of Crop Production/Soil Science Society of South Africa/Southern African Society of Horticultural Sciences Combined Congress, George, January 2015

vi. Calibration of sap flow techniques using the stem perfusion method. Sam MC, Taylor NJ and Vahrmeijer JT. South African Society of Crop Production/Soil Science Society of South Africa/Southern African Society of Horticultural Sciences Combined Congress, George, January 2015

vii. Validating sap flux density measurement methods in potted *Citrus sinensis.* Banda M, Vahrmeijer JT and Taylor NJ. South African Society of Crop Production/Soil Science Society of South Africa/Southern African Society of Horticultural Sciences Combined Congress, George, January 2015

viii. Modelling water use of subtropical fruit the crops: the challenges. Taylor NJ, Annandale JG, Vahrmeijer JT, Ibraimo NA, Mahohoma W, Gush MB, Allen RG. X International Symposium on Modelling in Fruit Research and Orchard Management, June 2-June 5, 2015. Agropolis international, Avenue Agropolis. Montpellier, France

ix. Testing the heat ratio method for sap flow estimates in *Citrus sinensis*. Vahrmeijer JT, Taylor NJ, Everson CS and Banda M. X International Symposium on Modelling in Fruit Research and Orchard Management, June 2-June 5, 2015. Agropolis international, Avenue Agropolis. Montpellier, France

x. Validating sap flux density measurement methods in potted *Citrus sinensis.* Banda M, Taylor NJ, Everson CS and Vahrmeijer JT. South African Society of Crop Production/Soil

Science Society of South Africa/Southern African Society of Horticultural Sciences Combined Congress, Bloemfontein, 18-21 January 2016

xi. Modelling transpiration of citrus orchards. Taylor NJ, Vahrmeijer JT, van der Merwe S, Ibraimo NA, and Annandale JG. South African Society of Crop Production/Soil Science Society of South Africa/Southern African Society of Horticultural Sciences Combined Congress, Bloemfontein, 18-21 January 2016

xii. Can crop coefficients be used to schedule irrigation in citrus? Taylor NJ, Mahohoma W, Vahrmeijer JT, Gush MB, Allen RG and Annandale RG. 9th Citrus Research Symposium held at Champagne Sports Resort, Drakensberg on 21-25 August 2016

xiii. Citrus water use in a winter rainfall region. Vahrmeijer JT, Taylor NJ, Banda M and Sam CM. 9th Citrus Research Symposium, Champagne Sports Resort, Drakensberg, 21-25 August 2016

xiv. Validating sap flux density measurement methods in potted Citrus sinensis. Banda M, Taylor NJ and Vahrmeijer JT. 9th Citrus Research Symposium, Champagne Sports Resort, Drakensberg, 21-25 August 2016

xv. Validating sap flux density measurement methods in potted *Citrus sinensis.* Banda M, Taylor NJ, Everson CS and Vahrmeijer JT. International Citrus Conference, Foz do Iguaçu, Brazil, 18-23 September 2016

xvi. Citrus water use in a Mediterranean climate. Vahrmeijer JT, Taylor NJ, Banda M, Sam M and Everson CS. International Citrus Conference, Foz do Iguaçu, Brazil, 18-23 September 2016

**Conference proceedings**

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**RECOMMENDATIONS FOR FUTURE RESEARCH**

When using the stem perfusion method it is suggested that a better way is found to achieve different flow rates, as these sudden changes in flow are registered by the gravimetric readings but are not necessarily taken into account by the SFD techniques. Future also focus on improved practical infield measurements and assessment of the wound widths.research should

In this study a technique to measure tree water use was validated and rigorously tested. Emphases was not put on soil water content measurements and how they influence transpiration, because one of the assumptions was that the field experiments were conducted in well-watered and managed citrus orchards. However, drought conditions occurred, which had had an influence on tree water use. Thus, more detailed soil water measurements should be included in any following tree water use studies. Sap flow techniques can give detailed insights in tree water use and changes in tree water use due to external factors, such as changes in canopy size and irrigation management. Therefore, in the light of the recent droughts, future research should focus on quantifying tree water use when water saving practices are implemented, such as the reduction in canopy size, change of irrigation practices and systems and the use of mulches. The research should take into account the impact of reduce tree water use on yield, fruit quality and the time it takes to recover to previous yield levels under optimal conditions.

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| AWS | Automated Weather Station |
| CRM | Coefficient of Residual Mass |
| $C_p$ | Canopy Porosity |
| D | Willmott Index of Agreement |
| E | Evaporation |
| EC | Eddy Covariance |
| ET | Evapotranspiration |
| $ET_o$ | Reference Evapotranspiration from a short grass reference surface |
| $ET_r$ | Reference Evapotranspiration from a tall grass reference surface |
| $E_s$ | Evaporation from Soil Surface |
| fc | Fractional Canopy Cover |
| FLW | Flush Leaf Wood |
| FRLD | Fibrous Root Length Density |
| G | Soil Heat Flux |
| $g_c$ | Canopy Conductance |
| $g_s$ | Stomatal Conductance |
| HFD | Heat Field Deformation |
| HPV | Heat Pulse Velocity |
| HR | Heat Ratio |
| $K_c$ | Crop Coefficient |
| $K_t$ | Transpiration Crop Coefficient |
| LAI | Leaf Area Index |
| MAE | Mean Absolute Error |
| MBE | Mean Bias Error |
| PAR | Photosynthetically Active Radiation |
| RH | Relative Humidity |
| RMSE | Root of the Mean Square Error |
| $R_n$ | Net Radiation |
| $R_s$ | Solar Radiation |
| SFD | Sap Flux Density ($cm^3\ cm^{-2}\ h^{-1}$) |
| T | Transpiration |
| TA | Titratable Acids |
| $T_a$ | Air Temperature |
| $T_{res}$ | ET - $E_s$ |

| | |
|---|---|
| $T_{sap}$ | Transpiration determined with the sap flow technique |
| TSS | Total Soluble Solids |
| $V_h$ | HPV (cm $h^{-1}$) |
| VSF | Volumetric Sap Flow (L $h^{-1}$) |
| VPD | Vapour Pressure Deficit |
| WUE | Water Use Efficiency |
| $\psi_{leaf}$ | Leaf Water Potential |
| $\psi_{pd}$ | Predawn Leaf Water Potential |
| $\psi_{stem}$ | Stem Water Potential |
| $\rho_s$ | Density of Water (g $cm^{-3}$) |
| $\rho_b$ | Sapwood Density |

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# 1 INTRODUCTION

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, emphasises the need to improve water use efficiencies (WUE) and water use productivity (Perry, 2007) in citrus production. Reliable estimates of evapotranspiration (ET) are, therefore, fundamental to determining water management practices, designing irrigation systems, scheduling irrigation and calculating crop yield in some instances (Kool et al., 2014). In systems with full canopy cover, such as many annual field crops, ET is often assumed to be similar to transpiration (T). However, in sparsely vegetated crops, such as orchards, evaporation from the soil surface ($E_s$) may constitute a large fraction of ET due to substantial areas of exposed soil between tree rows. This component will also vary depending on area and frequency of soil surface wetting. As a result estimates of ET are not a good indication of the productive use of water in these systems, making separate assessment of $E_s$ and T necessary. Villalobos et al. (2013) also stressed the importance of determining T, as this is related to tree assimilation and productivity and it allows accurate partitioning of ET between T and $E_s$. Several reports exist on T measurements in citrus, which reflect the wide range of orchard characteristics that includes, tree size, cultivars and rootstocks available, climatic conditions under which the trees are grown, and irrigation methods. However, limited information on citrus water use that reflects the different canopy sizes, species and rainfall regions exist in South Africa.

Modelling efforts can be separated into two broad categories. Firstly, complex, mechanistic models and secondly, the relatively simpler empirical models. Complex detailed models are generally more explanatory and more accurately transferred to different situations, but they usually require a number of inputs that may not be practical or easy to obtain in field situations. Simple crop models, on the other hand, are usually more empirical, based on robust relationships between plant behaviour and key environmental variables, but only tend to apply within their calibration range. This means that they do not always apply outside of the area in which the relationships were developed. However, due to their limited input requirements they are often more easily adopted by farmers. 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 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 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, where variation is attributed to variety, rootstock, tree spacing, canopy height, ground cover, tillage, leaf area index (LAI), method of estimating reference evapotranspiration ($ET_o$), microclimate, irrigation method and frequency and method of measuring crop ET (Naor et al., 2008, Snyder and O'Connell, 2007). As much of the variation in $K_c$ values is also attributed to $E_s$, as a result of different irrigation systems and rainfall patterns (Villalobos et al., 2009), the measurement of T should allow improved estimates of transpiration 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.

The aim and objectives for this WRC project are given below with the results published in two volumes. The first volume deals with validating and calibration of the sap flux density (SFD) techniques (Objective 1) that were used to measure and model the water use of different sized citrus trees in the summer and winter rainfall region of South Africa (Objective 2). Results from the infield water use and modelling and from the study on the impact of water stress on yield and fruit quality (Objective 3) are covered in volume 2.

**General aim**

To analyse the water use, yield, fruit size and quality of a selected Valencia, navel, grapefruit and/or soft citrus cultivar for different canopy architectures in summer and/or winter rainfall regions; including a detailed analysis of water stress in relation to yield and quality for a selected cultivar at a single location.

**Specific aims**

1. To validate citrus water use by comparing different sap flux density techniques with an appropriate technique such as lysimetry, cut stem and/or eddy covariance.

2. To measure and model citrus water use and water use efficiency according to seasonal growth stages from planting to mature canopy size.

3. To determine the influence of water stress on fruit set, fruit yield, and pre- and post-harvest fruit quality for a selected cultivar and single location.

# 2 LITERATURE REVIEW ON CITRUS WATER USE AND WATER USE EFFICIENCY

## 2.1 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 (Scora, 1975). Citrus trees are perennial evergreen plants that were probably cultivated in south-east Asia for the first time (Carr, 2012), 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 (Scora, 1975).

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 (Carr, 2012). Remnants of these earlier attributes that are still evident in some of the varieties are (Kriedemann and Barrs, 1981):

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.

## 2.2 Water use

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: 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 (Hoffman et al., 1982; Du Plessis, 1985; Castel, 2000; Consoli et al., 2006; Fares et al., 2008; Villalobos et al., 2009). 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.

### 2.2.1 Planting density

Fibrous root density is influenced by tree spacing, with a higher root density for trees planted at higher tree densities (Castle, 1978; Whitney et al., 1991). Crane (1984) found for 12-year-old bearing orange trees that the increase in planting density from 215 to 716 trees $ha^{-1}$ did not significantly alter the rate of soil water depletion. Whitney et al. (1991) also observed no significant difference in soil water use for Hamilin on Milan rootstock sweet oranges (Valencia), that were planted between 889 trees $ha^{-1}$ (2.5 x 4.5m spacing) and 370 trees $ha^{-1}$ (4.5 x 6 m spacing). However, soil water use was greater for the in-row orientation than between-rows orientation, with the highest water use and root density underneath the tree canopy dripline. Soil depth was also correlated with soil water use with the highest soil water use measured between 0.3 and 0.6 m below the soil surface, after which it decreases with depth. Castle (1978) found that in high density plantings the root systems of adjacent trees overlap and lose their individual identity and therefore soil can be treated as a root bearing volume over a unit of land in the same way as fruit-bearing foliage is considered.

### 2.2.2 Rootstock

Citrus has a well-defined taproot, however, its identity is often lost during the process of replanting or poor nursery practices (Spiegel-Roy and Goldschmidt, 1996). 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 (Kriedemann and Barrs, 1981). The extent of the root system is, however, dependent on soil physical properties, cultivar and rootstock (Carr, 2012). Carizzo citrange and Swingle citrumelo are examples of rootstocks with few fibrous roots below 0.7 m and less lateral development (Castle and Krezdorn, 1975) that are well suited for high-density, intensively managed plantings (Castle, 1978). Root distribution, measured as fibrous root length density (FRLD), was determined for 'Hamlin' orange trees grown on Swingle citrumelo and on Carizzo citrange (Morgan et al., 2007). Results showed that Swingle citrumelo developed significantly higher FRLD in the top 0.15 m of the soil profile than trees on Carizzo citrange. Conversely, at a soil depth between 0.15 m and 0.75 m, Carizzo citrange had a greater FRLD than trees on Swingle citrange (Morgan et al., 2007). 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 5-10 years). By the time the canopy reaches full hedgerow dimensions (trees aged between 10-15 years), the bimodality of the root system has fully developed (Morgan et al., 2007).

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 T rate (Rodríguez-Gamir et al., 2010). Results from a study on the hydraulic conductivity of four rootstocks (Syvertsen, 1981) 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 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% (CGA, 2012). This has implications for the water use of orchards, as less vigorous rootstocks have lower hydraulic conductances.

### 2.2.3 Stomatal responses

Stomata regulate T 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 (Kriedemann and Barrs, 1981). Leaf age, canopy size and tree age were found to influence stomatal conductance ($g_s$). New leaves on 15-year-old citrus trees have a higher $g_s$ than old leaves. However, this was not true for smaller trees, where the $g_s$ 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 (Mills et al., 2000). Stomata on citrus leaves require only low light levels to open fully (Mills et al., 2000). Even shaded leaves transpire, with their T rates being lower than sunlit leaves due to lower temperatures and thus a lower saturated water vapour pressure (Moreshet et al., 1990). Stomatal conductance was observed to decline rapidly when midday leaf water potentials ($\Psi_{leaf}$) fell below -1.0 MPa for 30 month old Pera orange trees (Gomes et al., 2004), whilst stomatal closure occurred at a midday $\Psi_{leaf}$ lower than -2.2 MPa for 'Washington' navels (Cohen and Cohen, 1983; Cohen et al., 1983). Syvertsen (1982) found that stomatal closure occurs over a relative narrow range of $\Psi_{leaf}$'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 (1982) also noted stable maximum rates of T regardless of environmental conditions, suggesting strong stomatal control over T.

### 2.2.4 Hydraulic conductance

The use of Ohm's law as an analogue to water transport as a whole dates back to Gradmann (1928) and Van den Honert (1948) with the primary assumption that the steady-state flux of water through the soil-plant-atmosphere continuum is proportional to the water potential gradient and inversely proportional to flow resistances. Cowan (1965) showed that this model is an over-simplification of the system and that water transport in the soil-plant-atmosphere is a complex series-parallel network that is disconnected at some points, for example, the liquid-vapour boundaries in the leaves and near the soil surface.

Under steady state conditions the hydraulic conductance, due to a water potential difference between the roots (high water potential) and transpiring leaf ($\Psi_{leaf}$) is described by the relationship between transpiration rate (F) and the potential difference between the root ($\Psi_{root}$) and leaf ($\Psi_{leaf}$) (Moreshet *et al.,* 1990):

$$F = K_T(\Psi_{root} - \Psi_{leaf}) \qquad (1)$$

Where $K_T$ is the bulk hydraulic conductance of the plant.

For citrus under field conditions (transient state) the capacitance component of the roots and trunk is very small and can be neglected (Cohen and Cohen, 1983; Moreshet et al., 1990), while the bulk driving force for water movement through the plant consists of the potential of all the transpiring leaves (sun lit and shade) within the canopy of the tree (Moreshet et al., 1990). The total tree conductance is the combined conductances in series and parallel representing the water movement from the root through the trunk into the multi-stem canopy. Three major components can be distinguished: the conducting cells of the transpiring leaves, the axial conductances in the xylem of the roots, stems and branches and the radial conductance of the roots (Moreshet et al., 1990).

Soil temperature plays an important role in the hydraulic conductivity of citrus roots. Syvertsen (1981) reported that the hydraulic conductivity of four rootstocks (rough lemon, sour orange, Carrizo citrange and Cleapatra mandarin) increased linearly with root temperature between 15 and 30°C. On the other hand, as the temperature decreased the hydraulic root resistance increased for rough lemon due to the membrane system that acts as a barrier to radial water flow, probably due to changes in the permeability of the root cell membranes or to increased suberin deposition in the cell walls of the cortical cells (Ramos and Kaufmann, 1979). Castle (1978) also found the citrus root resistance to be four times as high as leaf resistance and although water stress increased hydraulic root resistance, as observed for rough lemon after several drying cycles, it is assumed that the resistance of water flow through roots is the principal hydraulic resistance within the plant (Ramos and Kaufmann, 1979; Kriedemann and Barrs, 1981).

## 2.3 Citrus crop coefficients

Crop coefficients describe the relationship between ET of a crop and the evapotranspiration from a reference surface ($ET_o$), which is often a clipped, cool season and well-watered grass. This simple empirical relationship has been used extensively to determine water use of crops and schedule irrigation (Doorenbos and Kassam, 1979; Allen et al., 2004). Besides this more practical application of $K_c$ values, Allen et al. (2011) suggest that by calculating $K_c$, water use or ET can be normalised for climate, which allows for comparisons of rates of ET from different time periods and different regions. The impact of relative surface roughness, leaf area and albedo on water use can then be assessed by comparing $K_c$ values for these different time periods and regions, which can aid in explaining temporal and spatial differences in ET measurements.

A comparison of published $K_c$ values for citrus (Table 2.1) reveals a very wide range of values, which can be attributed to variety, rootstock, tree spacing, canopy height, ground cover, tillage, LAI, method of estimating $ET_o$, microclimate, irrigation method and frequency and method of measuring crop ET (Snyder and O'Connell, 2007; Naor et al., 2008). Values range from 0.26 in winter in Brazil (Marin and Angelocci, 2011) to 1.28 in autumn in South Africa (Green and Moreshet, 1979). Even within seasons, values are seen to vary considerably, e.g. from 0.32 to 1.05 in summer. When comparing monthly $K_c$ values for a number of studies (Figure 2.1), over an entire season, it is evident that for the majority of the reports the $K_c$ stays fairly constant over the entire season. This is perhaps not surprising as it is an evergreen crop and the same exaggerated change in canopy size is not observed, as is the case with deciduous fruit tree species, indicating that there will be a constant relationship between ET of the crop and $ET_o$ and water use will be mainly governed by climatic conditions. However, some studies note a decrease in the $K_c$ value in the hot summer months, when $ET_o$ increases and the canopy has increased in size as a result of both the spring and summer flushes. This suggests that water use of citrus is not solely driven by atmospheric demand and supports the conclusion that citrus has greater stomatal control of transpiration than most other crops (Kriedemann and Barrs, 1981; Sinclair and Allen, 1982). The calculation of $K_c$ values and the comparison with published data can therefore give valuable information on the control of water use in crops, with specific reference to how management of the orchard can impact water use. This is important as management practices have changed considerably, with the advent of high density plantings and micro-irrigation systems.

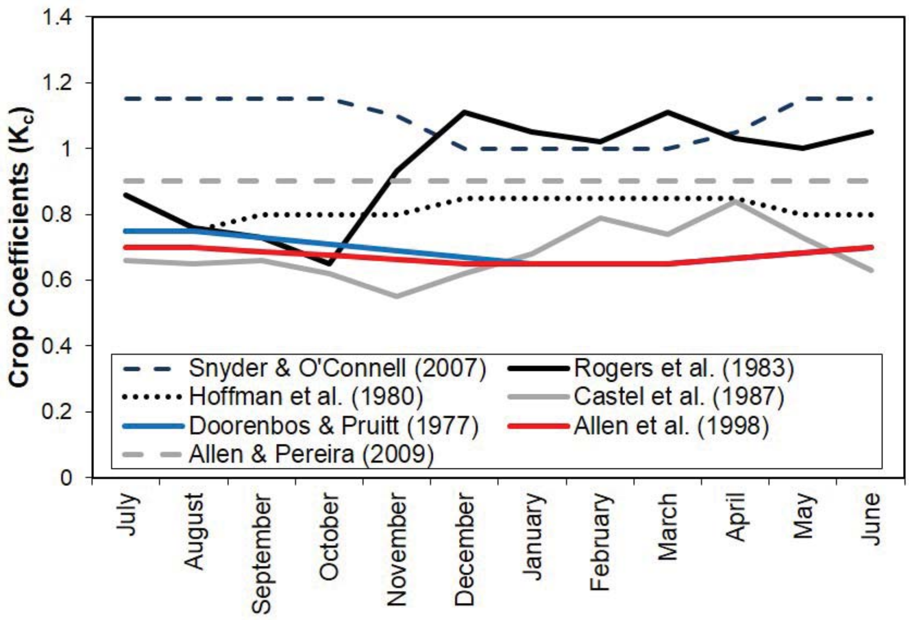


**Figure 2.1 Published seasonal crop coefficients for citrus**

## 2.4 Water use efficiency

Water use efficiency is a generic term, which can be broadly defined as the ratio of productivity (output) to the amount of water applied or consumed (input). This definition may be specified depending upon the purpose and the selected parameters of output (yield or product) and input (water used/applied) (Tanner and Sinclair, 1983; Douglass and Poulton, 2000). In this study, tree-level WUE is defined as harvestable biomass (kg) per volume of water ($m^3$) used (Wallace, 2000).

### 2.4.1 Water application

Irrigation types and frequency and extent of soil wetting (reduced application or flooding) affect WUE of citrus (Hutton and Loveys, 2011). Compared to other irrigation systems, drip irrigation improves WUE by reducing water losses (Bielorai, 1982) through reduced soil wetting to which the majority of the roots are confined. On the other hand, in order to meet citrus water requirements, frequent water applications may be required when using drip irrigation, which could lead to higher drainage losses (Bielorai, 1973; Middleton et al., 1979).

Bielorai (1982) found that reducing water application of grapefruits to 80% of full irrigation resulted in higher WUE under drip and sprinkler systems (Table 2.2), with only marginal effects on fruit quality. This was due to a greater decrease in water use than number and sizes of fruits. García-Tejero et al. (2010) also found that deficit irrigation in mature orange trees resulted in a bigger reduction in water use (up to 24%) than yield (10-12%) compared to full irrigation. As a result, WUE (ratio of yield to water applied) increased.

**Table 2.1 Seasonal crop coefficients ($K_c$) determined in citrus orchards across the growing regions of the world**

| Reference | Region | $ET_o$ | | | | $K_c$ | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Summer* | Autumn | Winter | Spring | Summer | Autumn | Winter | Spring |
| Marin and Angelocci (2011) | Brazil | 4.4 | - | 2.7 | - | 0.7 | - | 0.26 | - |
| Villalobos et al. (2009) | Spain | - | 4.99 | - | 5.88 | - | 0.44 | - | 0.43 |
| Snyder and O'Connell (2007) | USA | 6.27 | 3.03 | 1.10 | 4.13 | 1.00 | 1.07 | 1.15 | 1.13 |
| Alves Jr et al. (2007) | Brazil | 4.33 | 3.49 | 2.90 | 4.33 | 1.05 | 0.93 | 0.53 | 0.69 |
| García Petillo and Castel (2007) | Uruguay | 4.99 | 1.77 | 1.45 | 4.06 | 0.64 | 0.77 | 0.84 | 0.83 |
| Romero et al. (2006) | Spain | - | - | - | - | 0.7 | 0.7 | 0.9 | 0.7 |
| Rana et al. (2005) | Italy | - | - | - | - | 1.04 | 0.77 | 0.81 | 1.16 |
| Castel (1997) | Spain | 4.69 | 2.75 | 1.66 | 3.68 | 0.32 | 0.49 | 0.36 | 0.24 |
| Castel et al. (1987) | Spain | 4.93 | 2.57 | 1.53 | 3.43 | 0.70 | 0.77 | 0.65 | 0.61 |
| Rogers et al. (1983) | USA | 4.1 | 3.13 | 2.37 | 4.37 | 1.04 | 1.01 | 0.93 | 0.81 |
| Hoffman et al. (1982) | USA | 7.7 | 4.1 | 2.27 | 5.27 | 0.85 | 0.83 | 0.77 | 0.80 |
| Green and Moreshet (1979) | South Africa | 6.86 | 3.15 | 2.62 | 4.59 | 0.80 | 1.28 | 0.79 | 0.62 |
| van Bavel (1966) | USA | 7.91 | 3.77 | 2.25 | 6.30 | 0.62 | 0.72 | 0.48 | 0.48 |

*Seasons were determined according to the equinoxes and solstices, with each season comprising 3 months. A hyphen indicates unavailable data

**Table 2.2 Effects of irrigation on grapefruit water use efficiency (WUE) (Bielorai, 1982)**

| Irrigation treatment and wetted soil surface area (%) | Irrigation intervals | % of seasonal water application | WUE (kg fruit $m^{-3}$) |
|---|---|---|---|
| Drip, single lateral, 30% | 3 days | 80% (632 mm) | 13.8 |
| | 3 days | 100% (803 mm) | 12.3 |
| | 7 days | 100% | 11.5 |
| Drip, double lateral, 40% | 3 days | 80% | 14.3 |
| | 3 days | 100% | 12.6 |
| | 7 days | 100% | 13.3 |
| Sprinkler, 70% | 14 days | 80% | 13.2 |
| | 14 days | 100% | 11.8 |
| | 21 days | 100% | 12.2 |

Increasing soil dryness did not increase WUE of sour orange and sweet lime (Bielorai and Mendel, 1969), while Kamota et al. (1974) found a gradual increase in WUE in 'Satsuma' mandarin as soil water supplies declined. Under limited water supply and high evaporative demand, citrus trees, tend to make physiological adaptations to survive, and this can be manipulated using the partial root zone drying method, which is a method of irrigating one side of tree roots at a time (Dry *et al.,* 1998). Hutton and Loveys (2011) used this method on mature navel oranges in order to ensure continuous water supply to a portion of the roots while minimising non-beneficial water losses and triggering partial closure of stomata. As a result, WUE, total soluble solids (TSS) percentage and juice acid percentage increased, while fruit size and juice content slightly decreased.

### 2.4.2 Genotypes

Genotypes affect WUE of the citrus trees (Rodríguez-Gamir et al., 2010). Higher WUE values were observed in 'Eremolemo' than in 'Lisbon' lemon due to lower mesophyll resistance (higher photosynthetic rates) in the former (Kriedemann and Barrs, 1981). Effects of flooding (Table 2.3 and Figure 2.2) and water stress (Table 2.4) on citrus WUE were also functions of genotype (Arbona et al., 2009).

**Table 2.3 Effects of flooding on leaf water use efficiency (WUE) of three citrus genotypes (Arbona et al., 2009)**

| Genotype | Treatment | WUE ($\mu mol\ CO_2\ \mu mol\ H_2O^{-1}$) | |
|---|---|---|---|
| | | Flooding | Recovery |
| Citrumelo CPB 4475 | Control | 5.30 ± 0.26a | 4.04 ± 0.13b |
| | Flooding | 6.41 ± 0.28b | 3.57 ± 0.22a |
| Carrizo citrange | Control | 4.55 ± 0.25a | 4.21 ± 0.20a |
| | Flooding | 4.25 ± 0.15a | 4.45 ± 0.23a |
| Cleopatra mandarin | Control | 3.52 ± 0.15a | 6.54 ± 0.47b |
| | Flooding | 3.76 ± 0.36a | 4.06 ± 0.28a |

García-Sánchez et al. (2007) found that $CO_2$ assimilation by leaves of Cleopatra mandarin was higher and water loss lower than that of Carrizo citrange, leading to higher leaf WUE of the former.

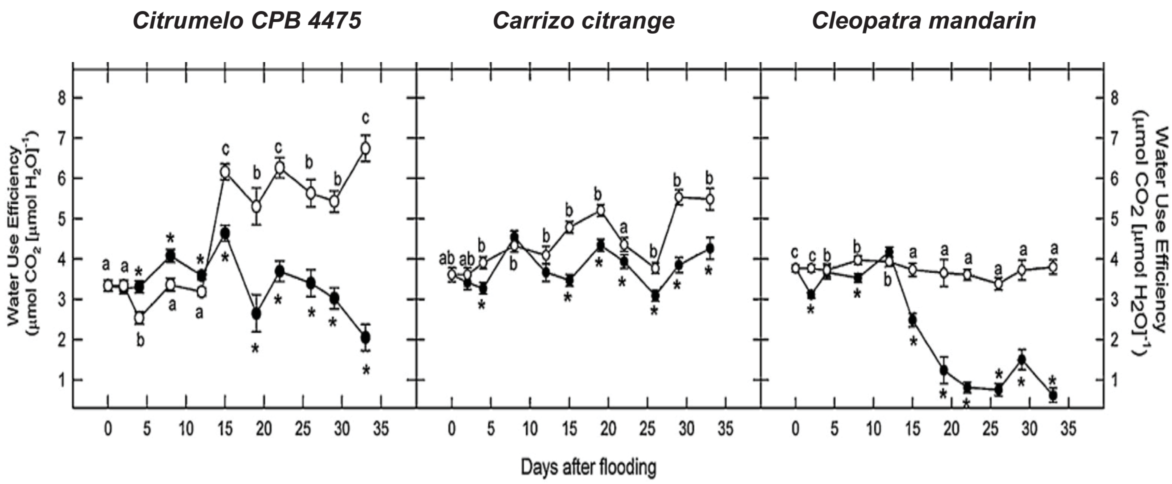


**Figure 2.2 Water use efficiencies of well-watered (control) seedlings (○) and flooded seedlings (•) of three citrus genotypes (Arbona et al., 2009)**

**Table 2.4 Leaf water use efficiencies (WUE) of two genotypes and their hybrid as affected by stress due to the absence of irrigation (Different letters in WUE column indicate significant differences) (Rodríguez-Gamir et al., 2010)**

| **Genotype** | **WUE ($\mu mol\ CO_2\ mmol\ H_2O^{-1}$)** | |
|---|---|---|
| | **Well watered (Control)** | **Stress (no. of drought stress days)** |
| *Poncirus trifoliate* | 4.68 | 0.57b (11) |
| Cleopatra mandarin | 5.35 | 5.40a (11) |
| Forner-Alcaide | 4.43 | 4.33a (11) |

### 2.4.3 Rootstocks

Rootstocks affect WUE of the citrus trees (Rodríguez-Gamir et al., 2010) by affecting plant water relations and stress tolerances (Syvertsen and Levy, 2005), which include tolerances to flooding (Syvertsen and Smith Jr, 1983; Li et al., 2006) and drought (Castle et al., 1993) as shown in Table 2.5 and Table 2.6. Syvertsen et al. (1997), however, found that rootstock had no effect on leaf-level WUE of 'Redblush' grapefruit (*Citrus paradisi* Macf.) (Table 2.7). Comparing ‘Cleopatra’ mandarin and Carrizo citrange rootstocks, leaf WUE of the former was higher that the latter (García-Sánchez and Syvertsen, 2006) and remained higher under reasonable soil salinity (García-Sánchez et al., 2002).

**Table 2.5 Leaf water use efficiencies (WUE) as affected by interaction of citrus rootstock with flooding and drought stress (García-Sánchez et al., 2007)**

| **Genotype** | **Treatment** | **WUE ($\mu mol\ CO_2\ mmol\ H_2O^{-1}$)** |
|---|---|---|
| Carrizo citrange | Control | 1.52c |
| | Drought stress | 0.46f |
| | Flooding | 0.77e |
| Cleopatra mandarin | Control | 2.43a |
| | Drought stress | 1.07d |
| | Flooding | 1.96b |

**Table 2.6 Leaf water use efficiencies (WUE) of Valencia orange scion on the rootstock of the *Poncirus trifoliate* (Pt) Cleopatra mandarin (Cm) and Forner-Alcaide (FA) genotypes as affected by stress due to the absence of irrigation (Different letters in WUE column indicate significant differences) (Rodríguez-Gamir et al., 2010)**

| Genotype | WUE ($\mu$mol $CO_2$ mmol $H_2O^{-1}$) | |
|---|---|---|
| | Well-watered (Control) | Stress (no. of drought stress days) |
| Valencia orange scions on Pt | 4.57 | 1.58c (20) |
| Valencia orange scions on Cm | 3.68 | 3.03b (20) |
| Valencia orange scions on FA | 4.68 | 4.62a (20) |

**Table 2.7 Effects of rootstock on 'Redblush' grapefruit leaf nitrogen (leaf N) and water use efficiency (Syvertsen et al., 1997)**

| Genotype | Leaf N ($\mu$mol $m^{-2}$) | WUE ($\mu$mol $CO_2$ mmol $H_2O^{-1}$) |
|---|---|---|
| Grapefruit scions on Volkamer lemon | 230.6* (19.6) | 3.57 (0.29)$^{NS}$ |
| Grapefruit scions on Sour orange | 289.3 (24.4) | 4.19 (0.35) |

*significant rootstock effect at $P < 0.05$

## 2.5 The influence of water stress on yield and quality of fruit during different phenological phases

Water stress can be defined as a state when plant water potential reaches a critical level where physiological plant processes cannot proceed normally. It occurs when the soil cannot continuously provide water to the roots or when the T demand from the atmosphere exceeds the tree supply (Levitt, 1980). This results in a decrease in $g_s$, plant water potential, stem diameter and sap flow rates (Kriedemann and Barrs, 1981; Ginestar and Castel, 1996; Steppe et al., 2010) that ultimately lead to an increase in leaf temperature (Ballester et al., 2013). Water stress has a negative effect on the yield and growth of a crop and the severity depends on the intensity, duration and phenological stage of the citrus tree (Abadi Ghadim and Pannell, 1999; García-Tejero et al., 2010).

### 2.5.1 Leaf water potential

Predawn $\Psi_{leaf}$ gives an indication of the severity of water stress in plants (Ortuno et al., 2006; García-Tejero et al., 2010; Dzikiti et al., 2011). Measurements of $\Psi_{leaf}$ are taken at predawn, when the $\Psi_{leaf}$ is in equilibrium with the water potential of the xylem, or at midday when water stress conditions are most pronounced. Predawn $\Psi_{leaf}$ reflects the soil water potential since the water potential gradient between the soil and the plant will be close to zero (Rodríguez-Gamir et al., 2010). The xylem water potential acts as a signal transmitting agent (Steppe et al., 2006) so that when the $\Psi_{stem}$ decreases below a critical point, the stomata close, as the plant cannot provide the amount of water to the leaf needed to match atmospheric demand (Dzikiti et al., 2007). This phenomenon is known as a supply limited response from the citrus tree and is a mechanism to conserve water within the plant, which is required during long periods of limited water supply. Kriedemann and Barrs (1981) suggest that $\Psi_{pd}$ greater than -0.50 MPa impact citrus tree growth, whilst Ribeiro and Machado (2007) found $\Psi_{pd}$ of -0.20 MPa in sweet orange in Brazil. García-Tejero et al. (2011) suggested limits for midday $\Psi_{stem}$ to aid with the scheduling of deficit irrigation in southern Spain. At $\Psi_{stem}$ > -0.8 MPa the trees are well irrigated, but as $\Psi_{stem}$ falls below stress is experienced, with moderate stress at -1.0 MPa, medium stress at -1.2 MPa and severe stress at -1.4 MPa.

### 2.5.2 Flowering and fruit set

Flowering and fruit set are known to be very sensitive to water stress (Ginestar and Castel, 1996; Pérez-Pérez et al., 2010; Hutton and Loveys, 2011) and one of the responses to water stress during flower induction is the production of excessive numbers of flowers (Doorenbos and Kassam, 1979). This is a survival mechanism, that may lead to alternate bearing, which will impact negatively on yield and quality (Doorenbos and Kassam, 1979). More leafless inflorescences will also be present (Southwick and Davenport, 1986) resulting in lower fruit set and yield compared to well-watered trees (Ginestar and Castel, 1996). Water stress during this period also results in more off-season flowering during the upcoming flushes (González-Altozano and Castel, 2000) and indirectly influences root development. During the “on-year”, i.e. a large crop load, in an alternate bearing cycle, root growth is absent presumably due to the depletion of carbohydrates lost by the harvested fruits (Smith, 1976).

### 2.5.3 The influence of water stress during fruit set (phase I)

Water stress during early fruit development (phase I) reduces the number of fruit set, which ultimately reduces the number of fruits reaching maturity. Although there is a physiological process known as the December fruit drop (in the southern hemisphere), water stress during this stage will result in an increase in fruit drop (Ertsen and van der Spek, 2009). Water stress early on in fruit development (phase 1) also influences fruit quality, such as an increase in the peel:pulp ratio, and a reduction in the rate of fruit growth (Pérez-Pérez et al., 2010). Therefore, the mean crop load based on mass and number of fruits per square meter canopy decreases (Treeby et al., 2007).

García-Tejero et al. (2010) found that water stress in the previous year had an effect on fruit yield in the current year. This could be due to irregular vegetative growth. Vegetative growth of citrus trees is also influenced by the amount of water available during a specific phase. If water stress occurs early in the season then the canopy development and stem growth are restricted in young citrus trees and the summer and autumn vegetative flushes are delayed (Kriedemann and Barrs, 1981; Shalhevet and Levy, 1990).

### 2.5.4 The influence of water stress on fruit size and development (phase II)

It is well-documented that water stress during phase II results in a decrease in size, number and fresh mass of the fruit (Ginestar and Castel, 1996; Treeby et al., 2007; Hutton and Loveys, 2011) and can also trigger flowering upon re-watering when the tree is subjected to water stress. This off-season flowering produces fruits of low yield and poor quality (González-Altozano and Castel, 2000).

The period after December fruit drop (Southern hemisphere) is known to be the least sensitive to water shortages (Cohen and Goell, 1988). Fruit quality can be managed by reducing water during this phase. Additional sugar in the fruit is not the result of dehydration but rather accumulates due to an osmoregulatory response during Phase II of fruit growth (Yakushiji et al., 1998). This response, however, can be managed by the timing, duration and level of water stress (Castel and Buj, 1990; Huang et al., 2000). Results from field trials done in Israel indicated that when water stress was induced (Phase II), grapefruit continued to accumulate dry matter without increasing the fruit volume. Upon re-watering these water-stressed fruits expanded faster than fruits on regularly watered trees. They concluded that the fruit expanded according to the quantity of dry matter accumulated (Cohen and Goell, 1988). In another study, Huang et al. (2000) found that fruit ripening processes are enhanced by water stress conditions due to a decline in fruit water potential, because of the water loss from the transpiring leaves surrounding the fruit. This resulted in an increase in the TSS and titratable acidity (TA) due to a decrease in osmotic potential. Cell wall loosening also occurred, which resulted in a further decrease in fruit water potential (Ginestar and Castel, 1996).

### 2.5.5 The influence of water stress fruit quality (phase III)

Water stress during phase III resulted in an increase in the TSS, TA and a decrease of juice percentage without influencing the maturity index (TSS/TA ratio), thereby allowing some control over the harvesting date (Ginestar and Castel, 1996; Pérez-Pérez et al., 2010). Evidence of a decrease in final fruit size at harvest was observed (García-Tejero et al., 2010), while Treeby et al. (2007) found a decrease in rind thickness with a lower incidence of albedo breakdown when water stress was induced during phase III.

# 3 MATERIAL AND METHODS – FIELD MEASUREMENTS

## 3.1 Introduction

Infield tree transpiration ($T_{sap}$) was measured in the Western Cape and Limpopo Provinces that represents two different rainfall regions of South Africa. $T_{sap}$ measurements were upscaled to orchard level to gain insights into the influence of climate, canopy size, and specie and cultivar on citrus water use. Ancillary measurements were also done to facilitate our understanding of the factors and processes that drive T. These measurements included $g_s$, photosynthesis, interception of photosynthetically active radiation (PAR) and $\Psi_{stem}$ and $\Psi_{leaf}$.

Both Citrusdal and Letsitele are considered to be influenced by the local steppe climate and are classified as BSh by Köppen and Geiger. The average annual temperature for Citrusdal is 18.4°C and for Letsitele 21.7°C. Citrusdal is situated in the Western Cape in the winter rainfall region of South Africa and has an annual rainfall of approximately 315 mm. Letsitele is located in the Limpopo Province, which is a summer rainfall region in the north eastern part of South Africa, and has an annual rainfall of approximately 646 mm.

## 3.2 Plant material and experimental sites

The aim of the project was to measure water use of orchards from planting to mature canopy size. Canopy cover was used to differentiate between different size canopies and is defined as the proportion of the area allocated to a tree that is shaded at solar noon. Mature canopies were defined as those orchards in which a hedgerow had formed and where canopy cover exceeded 0.7. Intermediate-sized orchards were orchards in which a hedgerow had not formed and canopy cover varied between 0.4 and 0.6, while newly planted orchards were defined as those orchards in which canopy cover was less than 0.4.

### 3.2.1 Winter rainfall region

The first phase of sap flow measurements, using the heat ratio (HR) method, measurements started early August 2013 in four orchards on the farm Patrysberg (32° 27' 15'' S and 18° 58' 03'' E), just outside Citrusdal. Two Valencia and two navel orchards with different sized canopies were instrumented (Figure 3.1). Heat balance collars, for $T_{sap}$ measurements, were also installed in a small Cambria navel orchard for short periods of time during the 2013 and 2014 seasons. These, collars could not be left on stems for long periods of time, as the constant heat caused damage to the stems. Reinstallation in three of the four orchards took place in both March and April 2014, due to excessive gum production by the trees and subsequent failure of the sap flow systems. Monitoring in a mature navel orchard was moved in November 2014 from the 23-year-old 'Bahianinha' navel orchard to a 22-year-old 'Newhall' navel orchard and from a 13-year-old ‘Bahianinha’ orchard to an 8-year-old ‘Washington’ navel orchard. Equipment was moved to the ‘Newhall’ orchard as the soils had a lower stone content for better soil water content measurements, whilst the smaller ’Bahianinha’ orchard was removed by the grower due to poor yields. Unfortunately very poor data was collected in the ‘Newhall’ navel orchard despite numerous attempts to improve the data. As a result this data has been excluded from the final report.

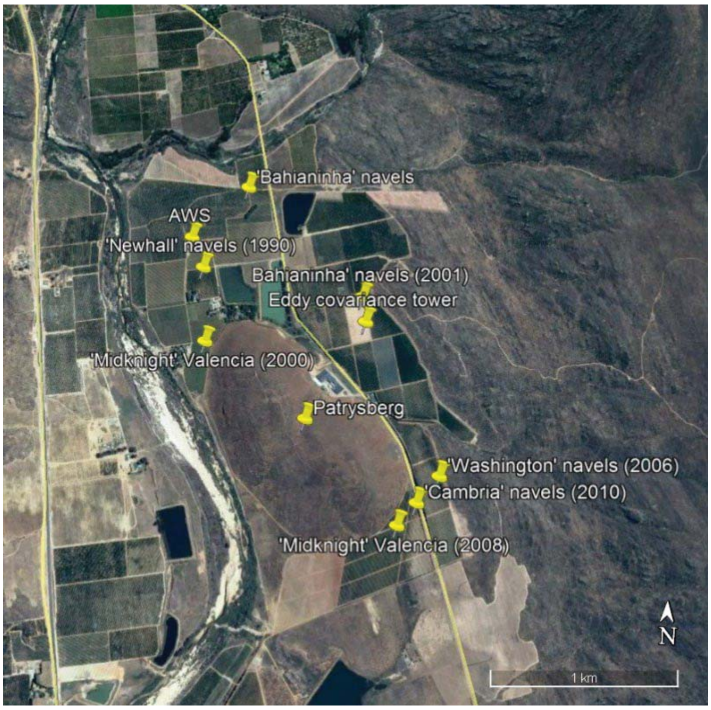


**Figure 3.1 Selection of orchards for water use measurements in the winter rainfall region of South Africa**

The second phase of measurements, in the winter rainfall region, involved removing equipment from navel orchards and installing the equipment in soft citrus orchards. As a result, two ‘Afourer’ mandarin (Nadorcott) orchards were installed in August 2015 on the farm Brakfontein (32$^o$30’27.63” S and 18$^o$59’49.13” E, Figure 3.2). More detail on all the orchards used in the study is given below.


**Figure 3.2 Selection of soft citrus orchards for water use measurements in the winter rainfall region of South Africa**

#### 3.2.1.1 Root distribution

The root distribution of selected orchards was determined by digging profile pits and taking soil/root samples by gently tapping a metal cylinder of known volume, perpendicular into the wall of the profile pit at certain depths. The edges of the metal cylinder were sharpened to facilitate the cutting of the roots. In general soil samples were taken at three depths (0.2, 0.4 and 0.6 m). For the 'Bahianinha' navel orchard, planted in 2001, samples were taken at four depths (0.1, 0.2, 0.4 and 0.6 m) and for the 'Midknight' Valencia orchard, planted in 2000, samples were taken only at two depths (0.2 and 0.4 m) within the tree row. Samples were taken within the tree row close to the A) tree trunk, B) midway between the tree trunk and the canopy edge and at the C) canopy edge (Figure 3.3). Another set of samples were taken perpendicular to the tree row, between the tree rows close to D) tree trunk, E) midway between the tree trunk and the canopy edge and at the F) canopy edge. Except for the 2000 'Midknight' Valencia and the 1990 'Bahianinha' navel, where samples within the row were taken only at two positions, B and C.

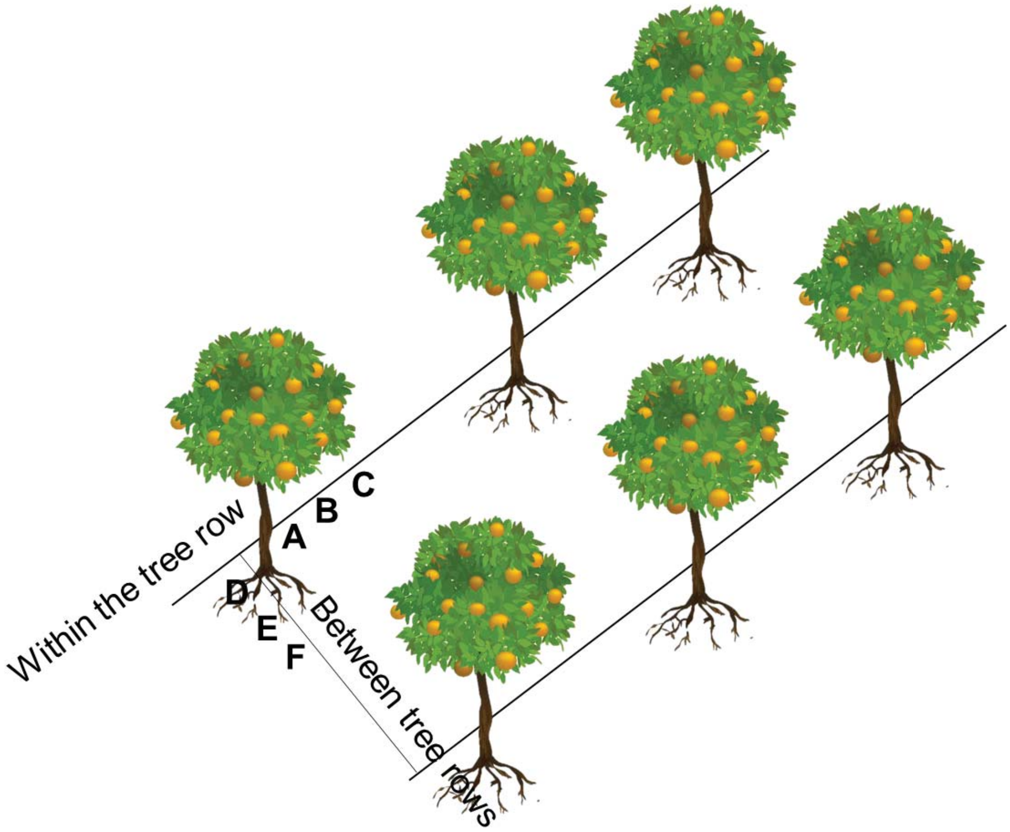


**Figure 3.3 Schematic illustration of root sampling positions in the citrus orchards in Citrusdal**

### 3.2.1.2 Orchard characteristics of the Valencias

Three Valencia orchards were instrumented during the course of the study: 1) 'Midknight' Valencia planted in 2000 (14 years at the start of measurements), 2) 'Midknight' Valencia planted in 2008 (6 years at the start of measurements) and 3) 'McLean' Valencia planted in 2010 (5 years at the start of the study) (Figure 3.4). These represented a mature, full bearing orchard, an intermediate-sized orchard and an orchard that had just started to bear fruit.

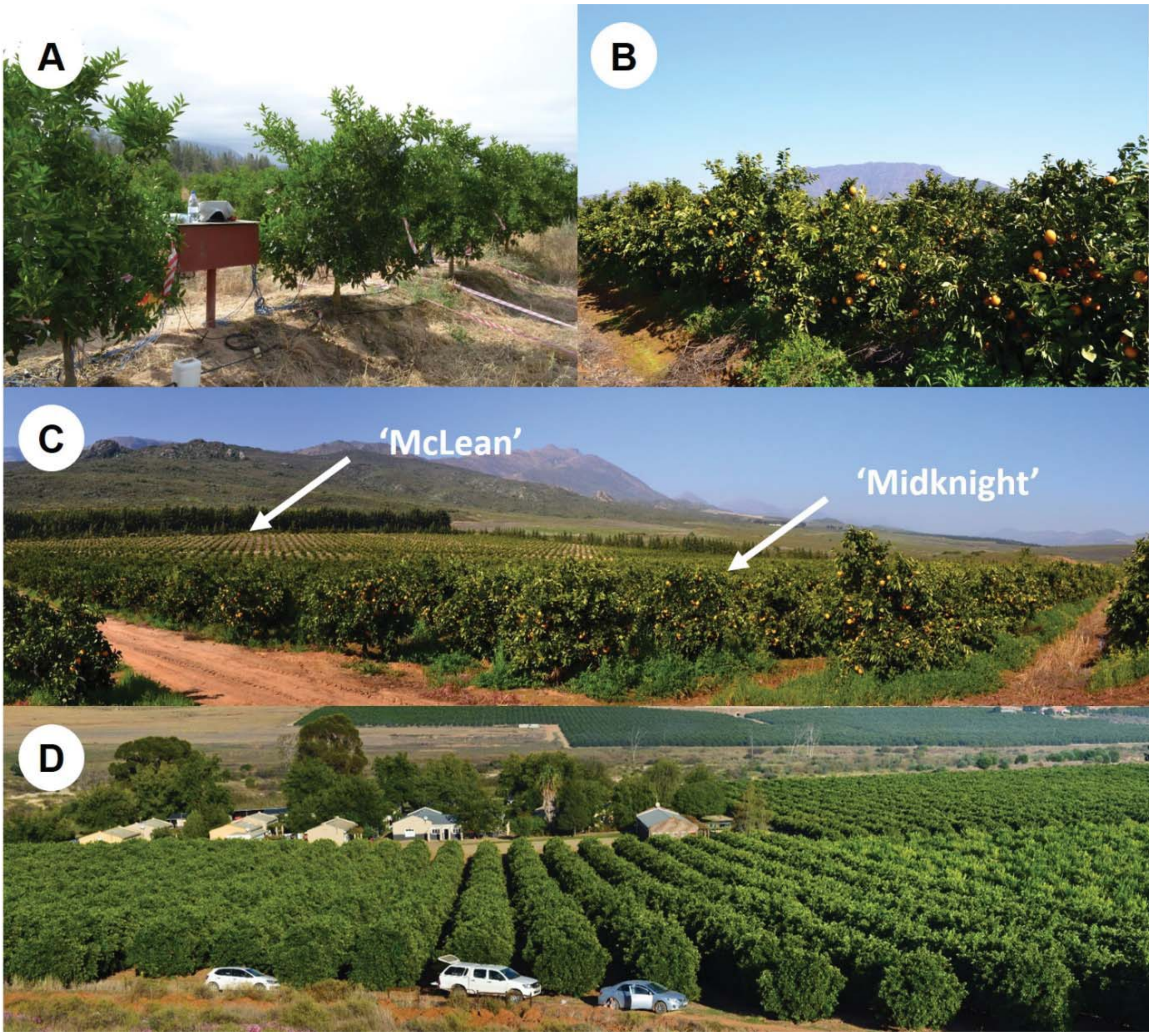


**Figure 3.4 The Valencia orchards planted on Patrysberg. A) 'McLean' Valencia orchard planted in 2010 (5 years old). B) 'Midknight' Valencia orchard planted in 2008 (6 years old). C) view of both the 'McLean and 'Midknight' Valencia orchards and D) the 'Midknight' Valencia orchard planted in 2000 (14 years old)**

Details of the Valencia orchards planted on the farm Patrysberg farm in the winter rainfall region are given in Table 3.1. The LAI and canopy dimensions are the average of the four measured trees and the yield data represents the orchard average. Yield was determined by harvesting the orchard separately and the mass of the fruit was determined according to standard pack house protocols. The average LAI, of the four measured trees, for the 2000 and 2008 'Midknight' Valencia were 3.46 $m^2\ m^{-2}$ (canopy cover 0.83) and 4.46 $m^2\ m^{-2}$ (canopy cover 0.54) respectively, while for the 'McLean' Valencia the average LAI was 3.19 $m^2\ m^{-2}$ (canopy cover 0.35) at the end of the study (Table 3.1).

**Table 3.1 Orchard details for 'Midknight' Valencias planted in 2000 and 2008 and 'McLean' Valencia planted in 2010 in the winter rainfall region of South Africa**

| **Cultivar** | **'Midknight' Valencia** | | **'McLean' Valencia** |
|---|---|---|---|
| **Measurement period:**<br>**Start**<br>**End** | 07-Nov-2014<br>24-Oct-2016 | 07-Nov-2014<br>14-Sep-2016 | 31-Oct-2015<br>09-Jun-2017 |
| **Age** | 14 years old (planted 2000) | 6 years old (planted 2008) | 5 years old (planted 2010) |
| **Rootstock** | Troyer/Carizzo | | Swingle/Carrizo |
| **Orchard size** | 3.3 ha | 3.4 ha | 2.3 ha |
| **GPS co-ordinates** | 32°27'22.49" S, 18°58'10.76" E | 32°27'55.31" S, 18°58'54.77" E | 32°27'53.95" S, 18°58'58.41" E |
| **Tree spacing** | 2.5 m x 5 m (12.5 $m^2$) planted on ridges (40 cm high) | 3 m x 5 m (15 $m^2$), planted on ridges (70 cm high) | 3 m x 5 m (15 $m^2$) planted on ridges (50 cm high) |
| **Row orientation** | East-West | North-South | |
| **Irrigation** | Drip irrigation, 2 drip lines per tree row. Drippers were spaced 0.8 m apart and had a delivery rate of 1.6 L $hr^{-1}$ = 6.3 drippers per tree | Drip irrigation, 2 drip lines per tree row. Drippers were spaced 0.8 m apart and had a delivery rate of1.6 L $hr^{-1}$ = 7.5 drippers per tree | |
| **Canopy dimension – average of 4 individual trees *(STDev)** | Height – 4.92 m (0.15)<br>Width – 2.68 m (0.50)<br>Breadth – 4.17 m (0.42) | Height – 3.38 m (0.26)<br>Width – 3.08 m (0.19)<br>Breadth – 2.59 m (0.25) | Height – 2.53 m (0.15)<br>Width – 2.40 m (0.18)<br>Breadth – 2.18 m (0.23) |
| **Canopy cover** | 0.83 | 0.54 | 0.35 |
| **Leaf area index**<br>**– orchard ($\bar{x}$ = 5 measurements)**<br>**– average of 4 individual tree *(STDev)** | 2.72 $m^2$ $m^{-2}$ (1.13)<br>3.46 $m^2$ $m^{-2}$ (1.4) | 3.08 $m^2$ $m^{-2}$ (0.48)<br>4.46 $m^2$ $m^{-2}$ (0.72) | 1.75 $m^2$ $m^{-2}$ (0.21)<br>3.19 $m^2$ $m^{-2}$ (0.46) |
| **Experimental trees** | 4 | 4 | 4 |
| **Trunk circumferences** | 1 – 48.7 cm<br>2 – 50.9 cm<br>3 – 47.0 cm<br>4 – 48.5 cm | 1 – 34.0 cm<br>2 – 33.8 cm<br>3 – 45.4 cm<br>4 – 29.1 cm | 1 – 20.8 cm<br>2 – 20.4 cm<br>3 – 17.2 cm<br>4 – 21.2 cm |
| **Yield (orchard)** | 0 t $ha^{-1}$ due to severe pruning | 25.5 t $ha^{-1}$ | 9.8 t $ha^{-1}$ |
| **Water use efficiency** | - | 4.7 kg $m^{-3}$ | 3.9 kg $m^{-3}$ |
| **Soil texture** | Clay | Clay | Sand |

*Standard deviation is in brackets

#### 3.2.1.3 Orchard characteristics of the navels

Over the course of the study three navel orchards were instrumented: 1) ‘Bahianinha’ navel planted in 1990 (23 years at the start of measurements), 2) ‘Washington’ navel planted in 2006 (8 years at the start of measurements) and 3) ‘Cambria’ navel planted in 2010 (4 years at the start of measurements) (Figure 3.5).

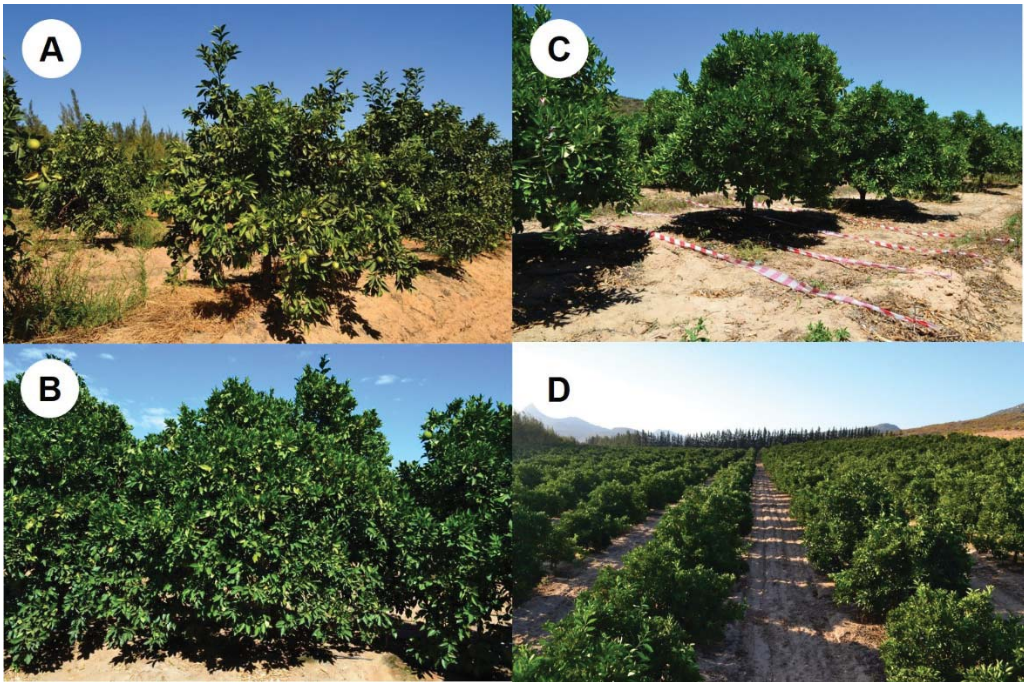


**Figure 3.5 Navel orchards at Patrysberg, A) 'Cambria' navel orchard planted in 2010 (4 years old). B) 'Bahianinha' navel orchard planted in 1990 (23 years old). C) ‘Washington’ navel orchard planted in 2006 (8 years old) and D) aerial view of the ‘Washington’ navel orchard**

Details of the navel orchards planted on Patrysberg farm in the winter rainfall region are given in Table 3.2. The LAI and canopy dimensions are the average of the four measured trees and the yield data represents the orchard average. The average LAI, of the four measured trees, for the 1990 ‘Bahianinha’ navels was 4.74 $m^2 m^{-2}$, for 2006 ‘Washington’ 3.27 $m^2 m^{-2}$ and for ‘Cambria’ navels 2.84 $m^2 m^{-2}$ (Table 3.2).

**Table 3.2 Orchard details for 'Bahianinha', 'Washington' and 'Cambria' navels planted in 1990, 2006 and 2010 respectively, in the winter rainfall region of South Africa**

| Cultivar | 'Bahianinha' navels | 'Washington' navels | 'Cambria' navels |
|---|---|---|---|
| Measurement period:<br>Start<br>End | <br>05-Oct-2013<br>12-Apr-2014 | <br>07-Nov-2014<br>14-Aug-2015 | <br>23-Mar-2014<br>02-May-2015 |
| Age | 23 years old (planted 1990) | 8 years old (planted 2006) | 4 years old (planted 2010) |
| Rootstock | Troyer/Carizzo | | |
| Orchard size | 3 ha | 4.1 ha | 2.1 ha |
| GPS co-ordinates | 32°26'52.40" S, 18°58'17.88" E | 32°27'43.31" S, 18°59'1.46" E | 32°27'51.14" S, 18°58'58.42" E |
| Tree spacing | 3 m x 5.4 m ($16.2\ m^2$) planted on ridges | 3 m x 5 m ($15\ m^2$) | 3 x 5.5 m ($16.5\ m^2$) planted on ridges |
| Row orientation | North-South | | |
| Irrigation | Drip irrigation, 2 drip lines per tree row. Drippers were spaced 0.8 m apart and had a delivery rate of 1.6 L $hr^{-1}$ = 7.5 drippers per tree | | |
| Canopy dimension – average of 4 individual trees *(STDev) | Height – 3.2 m (0.28)<br>Width – 2.9 m (0.32)<br>Breadth – 2.6 m (0.31) | Height – 2.57 m (0.18)<br>Width – 2.80 m (0.22)<br>Breadth – 2.6 m (0.16) | Height – 2.3 m (0.21)<br>Width – 2.1 m (0.24)<br>Breadth – 2.2 m (0.26) |
| Canopy cover | 0.58 | 0.48 | 0.28 |
| Leaf area index*<br>– orchard ($\bar{x}$ = 5 measurements)<br>– average of 4 individual tree *(STDev) | $1.4\ m^2\ m^{-2}$ (0.4)<br><br>$4.74\ m^2\ m^{-2}$ (0.32) | $1.71\ m^2\ m^{-2}$ (0.36)<br><br>$3.27\ m^2\ m^{-2}$ (0.14) | $3.17\ m^2\ m^{-2}$ (0.81)<br><br>$2.84\ m^2\ m^{-2}$ (0.38) |
| Experimental trees | 4 | 4 | 6 |
| Trunk circumferences | 1 – 48.0 cm<br>2 – 40.0 cm<br>3 – 35.5 cm<br>4 – 37.0 cm | 1 – 25.8 cm<br>2 – 29.5 cm<br>3 – 26.2 cm<br>4 – 27.8 cm | 1 – 21.3 cm<br>2 – 19.2 cm<br>3 – 20.1 cm<br>4 – 24.8 cm<br>5 – 21.0 cm<br>6 – 22.3 cm |
| Yield (orchard) | 40 t $ha^{-1}$ | 38 t $ha^{-1}$ | 40 t $ha^{-1}$ |
| Water use efficiency | 8.4 kg $m^{-3}$ ** | 14.4 kg $m^{-3}$ ** | - (insufficient T data) |
| Soil texture | Sandy clay loam | Sand | Sandy loam |

*Standard deviation is in brackets
**Estimated value

### 3.2.1.4 Orchard characteristics of the 'Afourer' mandarins

Over the course of the study two soft citrus orchards were instrumented: an 'Afourer' mandarin planted in 2002 and an 'Afourer' mandarin planted in 2013 (Figure 3.6). These represented a mature and newly planted orchard. No intermediate-sized mandarin orchard was instrumented in Citrusdal as we could not find a suitable orchard on any of the farms with whom we worked regularly. Details of the mandarin orchards planted on Brakfontein farm in the winter rainfall region are given in Table 3.3.


**Figure 3.6 Soft citrus orchards at the farm Brakfontein. A) 'Afourer' mandarin orchard planted in 2002 (13 years old) and B) 'Afourer' mandarin orchard planted in 2013 (3 years old)**

The LAI and canopy dimensions are the average of the four measured trees and the yield data represents the orchard average. Yield was determined by harvesting the four trees and weighing the fruit separately. The average of the four trees were then used to calculate the yield per hectare. The average LAI, of the four measured trees, for the 2002 and 2013 'Afourer' mandarins were 2.78 $m^2 m^{-2}$ (canopy cover 0.81) and 2.87 $m^2 m^{-2}$ (canopy cover 0.19) respectively at the end of the trial.

**Table 3.3 Orchard details for 'Afourer' mandarins planted in 2002 and 2013 in the winter rainfall region of South Africa**

| **Cultivar** | **'Afourer' mandarin** | |
|---|---|---|
| **Measurement period:**<br>**Start**<br>**End** | 11-Dec-2015<br>30-Mar-2017 | 05-Feb-2016<br>08-Sep-2017 |
| **Age** | 13 years old (planted 2002) | 3 years old (planted 2013) |
| **Rootstock** | Swingle | |
| **Orchard size** | 4.8 ha | 4.2 ha |
| **GPS co-ordinates** | 32°32'28.39" S<br>19°00'44.70" E | 32°30'30.73" S<br>18°59'31.77" E |
| **Tree spacing** | 2.0 x 5.0 m (10.00 $m^2$) planted on ridges (50 cm high) | 2.5 x 5.5 m (13.75 $m^2$) planted on ridges (70 cm high) |
| **Row orientation** | North-South | |
| **Irrigation** | Drip irrigation, 2 drip lines per tree row. Drippers are spaced 0.8 m apart and has a delivery rate of 1.6 L $hr^{-1}$ = 7.5 drippers per tree | |
| **Canopy dimension – average of 4 individual trees *(STDev)** | Height – 4.92 m (0.55)<br>Width – 2.68 m (0.48)<br>Breadth/depth – 4.17 m (1.2) | Height – 2.32 m (0.24)<br>Width – 1.90 m (0.35)<br>Breadth/depth – 1.53 m (0.55) |
| **Canopy cover** | 0.81 | 0.19 |
| **Leaf area index**<br>**– orchard ($\bar{x}$ = 5 measurements)** | 1.68 $m^2$ $m^{-2}$ (1.2) | 2.24 $m^2$ $m^{-2}$ (0.3) |
| **– average of 4 individual tree *(STDev)** | 2.78 $m^2$ $m^{-2}$ (1.2) | 2.87 $m^2$ $m^{-2}$ (0.35) |
| **Experimental trees** | 4 | 5 |
| **Trunk circumferences** | 1 – 52.5 cm<br>2 – 34, 23, 31 cm (3 stems)<br>3 – 51.0 cm<br>4 – 41, 33, 40.5 cm (3 stems) | 1 – 24.2 cm<br>2 – 23.8 cm<br>3 – 22.9 cm<br>4 – 25.5 cm<br>5 – 26.5 cm |
| **Yield (orchard)** | 75 t $ha^{-1}$ | 21 t $ha^{-1}$ |
| **Water use efficiency** | 7.9 kg $m^{-3}$ | 5.4 kg $m^{-3}$ |
| **Soil texture** | Sandy clay loam | Sand |

*Standard deviation is in brackets

### 3.2.2 Summer rainfall region

The campaign to measure water use in citrus in the summer rainfall region commenced in 2015 on various farms, owned by Mahela Boerdery, in Letsitele. A total of eight orchards were instrumented with sap flow equipment (HR method). In compliance with the terms of reference of the project, three different sized orchards of each species were instrumented, except in the case of the 'Valley Gold' mandarins, where we could not locate a suitable mature orchard on the farm. The location of the AWS and orchards used in this study are presented in Figure 3.7.

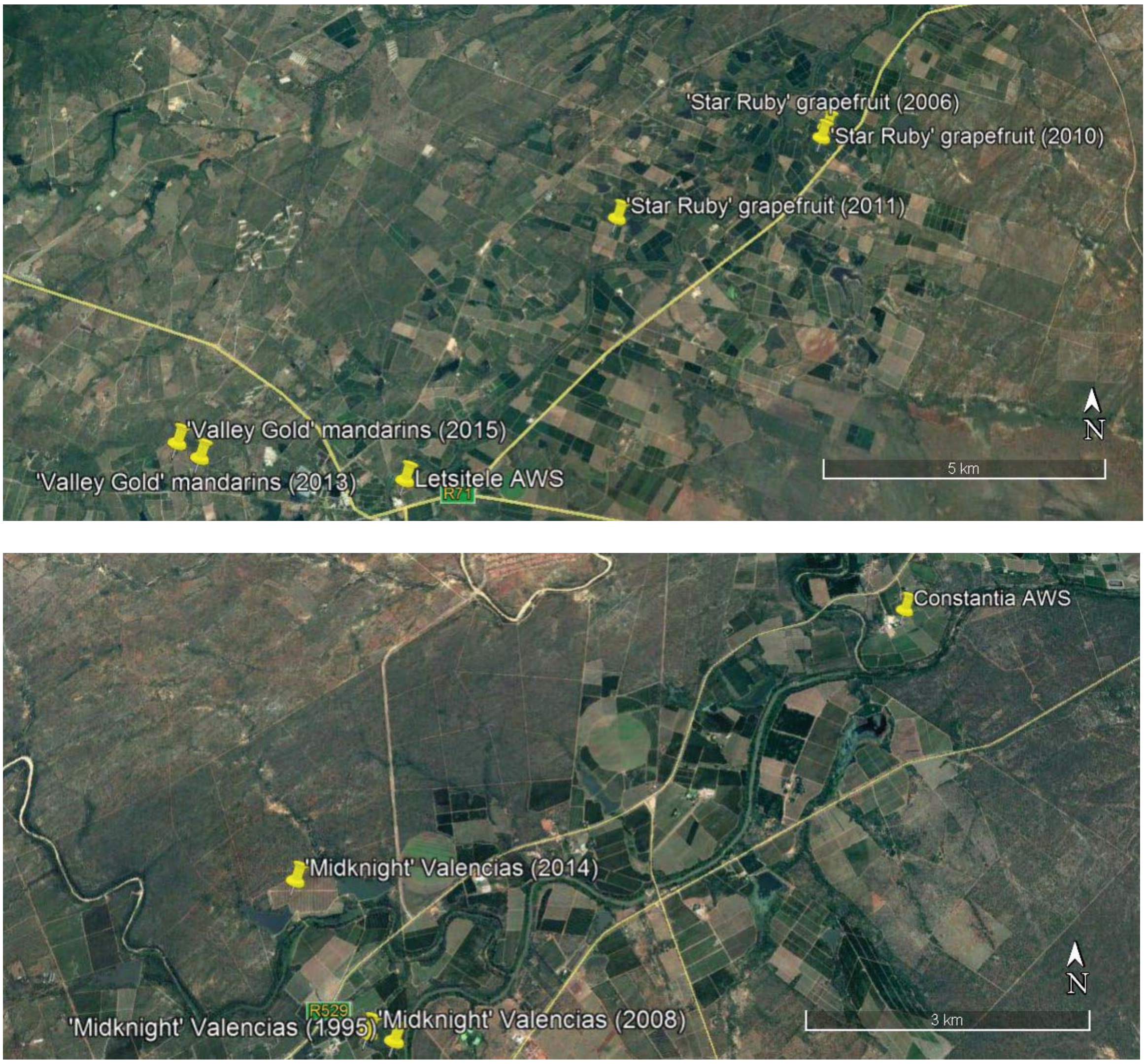


**Figure 3.7 Selection of orchards for water use measurements in the summer rainfall region (Letsitele) of South Africa**

#### 3.2.2.1 Orchard characteristics of the 'Star Ruby' grapefruits

Transpiration measurements in the 'Star Ruby' grapefruit orchards commenced in February and March 2016. Water use measurements for the 2006 and 2010 'Star Ruby' grapefruit orchards were terminated in July 2017 and for the 2011 'Star Ruby' grapefruit orchard in January 2018 (Figure 3.8).

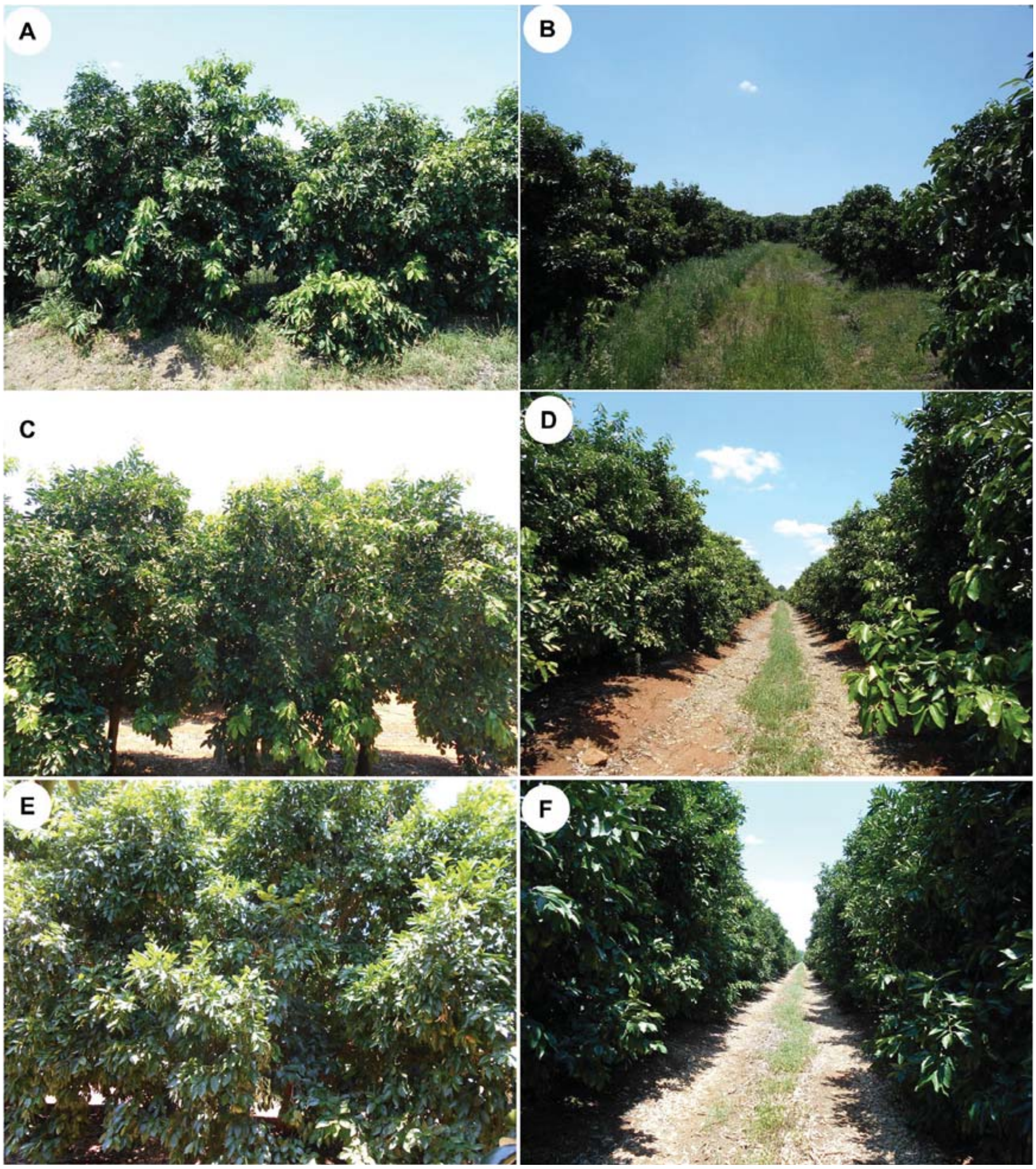


**Figure 3.8 Grapefruit orchards at Mahela Boerdery. A) and B) 'Star Ruby' grapefruit orchard planted in 2011 (5 years old). C) and D) 'Star Ruby' grapefruit orchard planted in 2010 (6 years old). E) and F) 'Star Ruby' grapefruit orchard planted in 2006 (10 years old)**

The different orchard details are presented in Table 3.4. The average LAI, of the four measured trees, for the 'Star Ruby' grapefruit trees were 4.67 $m^2\,m^{-2}$ (canopy cover 0.71) for the 2006 'Star Ruby' grapefruit, 6.30 $m^2\,m^{-2}$ (canopy cover 0.59) for the 2010 'Star Ruby' grapefruit and 3.63 $m^2\,m^{-2}$ (canopy cover 0.41) for the 2011 'Star Ruby' grapefruit at the end of the trial.

**Table 3.4 Orchard details for 'Star Ruby' grapefruit orchard planted in 2006, 2010 and 2011 in the summer rainfall region of South Africa**

| **Cultivar** | **'Star Ruby' grapefruit** | | |
|---|---|---|---|
| **Measurement period:** **Start** **End** | 05-Feb-2016 08-Sep-2017 | 05-Feb-2016 05-Aug-2017 | 23-Mar-2016 16-Mar-2018 |
| **Age** | 10 years old (planted 2006) | 6 years old (planted 2010) | 5 years old (planted 2011) |
| **Rootstock** | Swingle Citrumelo | | |
| **Orchard size** | 4.84 ha | 3.40 ha | 2.03 ha |
| **GPS co-ordinates** | 23°48'16.09" S 30°28'12.03" E | 23°48'18.69" S 30°28'08.60" E | 23°49'12.75" S 30°25'47.63" E |
| **Tree spacing** | 7.0 x 3.0 m (21.00 $m^2$) planted on ridges | | |
| **Irrigation** | Micro sprinklers (1 sprinkler per tree). 30 L $h^{-1}$ | | |
| **Canopy dimension *(STDev)** | Height – 4.2 m (0.5) Width – 4.96 m (0.36) Breadth – 3.72 m (0.3) | Height – 3.77 m (0.18) Width – 4.15 m (0.34) Breadth – 3.25 m (0.2) | Height – 2.87 m (0.14) Width – 2.87 m (0.26) Breadth – 3.0 m (0.18) |
| **Canopy cover** | 0.71 | 0.59 | 0.41 |
| **Leaf area index – orchard ($\bar{x}$ = 5 measurements)** | 3.1 $m^2$ $m^{-2}$ (0.6) | 3.5 $m^2$ $m^{-2}$ (0.47) | 2.6 $m^2$ $m^{-2}$ (0.3) |
| **– average of 4 individual tree *(STDev)** | 4.67 $m^2$ $m^{-2}$ (0.37) | 6.30 $m^2$ $m^{-2}$ (0.72) | 3.63 $m^2$ $m^{-2}$ (0.51) |
| **Experimental trees** | 4 | | |
| **Trunk circumferences** | 1 – 54.0 cm 2 – 51.0 cm 3 – 42.0 cm 4 – 56.2 cm | 1 – 39.9 cm 2 – 38.8 cm 3 – 38.0 cm 4 – 36.8 cm | 1 – 29.0 cm 2 – 27.0 cm 3 – 27.0 cm 4 – 28.2 cm |
| **Yield** | 57.9 t $ha^{-1}$ | 59.7 t $ha^{-1}$ | 27.7 t $ha^{-1}$ |
| **Water use efficiency** | 14.9 kg $m^{-3}$ | 19.0 kg $m^{-3}$ | 15.4 kg $m^{-3}$ |
| **Soil texture** | Silt clay loam | Silt clay loam | Sandy clay |

*Standard deviation is in brackets

### 3.2.2.2 Orchard characteristics of the 'Midknight' Valencias

Transpiration measurements in 'Midknight' Valencia orchards commenced in April 2016 for the orchards planted in 1995 and 2008, whereas the 2014 'Midknight' Valencias were only instrumented in March 2017. Three different sized orchards were instrumented in compliance with the terms of reference of the project and are presented Figure 3.9.

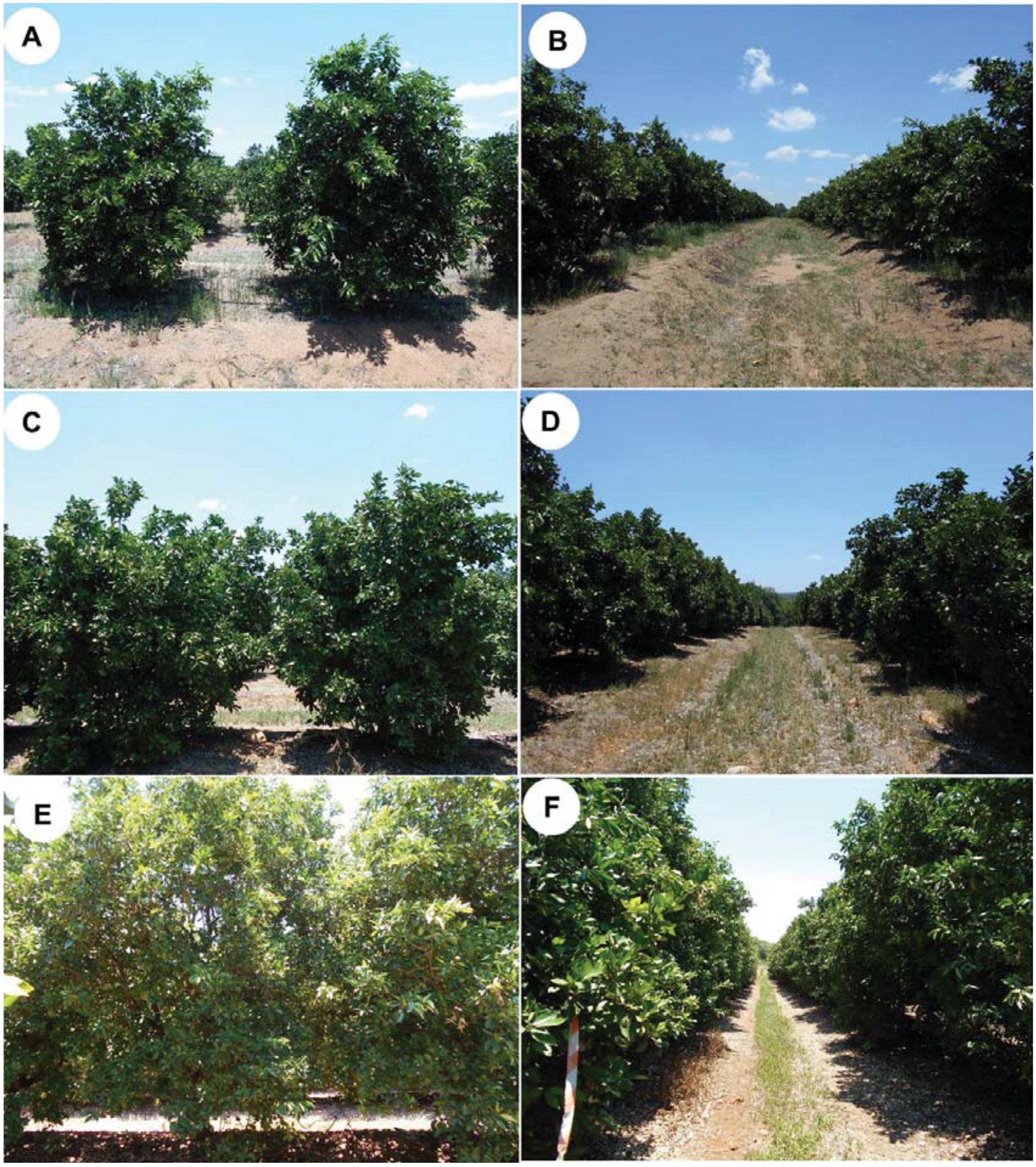


**Figure 3.9 The Valencia orchards at Mahela Boerdery. A) and B) 'Midknight' Valencia orchard planted in 2014 (3 years old). C) and D) 'Midknight' Valencia orchard planted in 2008 (8 years old). E) and F) 'Midknight' Valencia orchard planted in 1995 (21 years old)**

The different orchard details are presented in Table 3.5. The average LAI, of the four measured trees, for the 'Midknight' Valencia trees were 4.31 $m^2\ m^{-2}$ (canopy cover 0.74) for the 1995 'Midknight' 4.54 $m^2\ m^{-2}$ (canopy cover 0.51) for the 2008 'Midknight' and 3.33 $m^2\ m^{-2}$ (canopy cover 0.27) for the 2014 'Midknight' at the end of the trial.

**Table 3.5 Orchard details for 'Midknight' Valencias planted in 1995, 2008 and 2014 in the summer rainfall region of South Africa**

| **Cultivar** | **Midknight' Valencia** | | |
|---|---|---|---|
| **Measurement period: Start End** | 08-Apr-2016 16-Mar-2018 | 08-Apr-2016 16-Mar-2018 | 19-Mar-2017 16-Mar-2018 |
| **Age** | 21 years old (planted 1995) | 8 years old (planted 2008) | 3 years old (planted 2014) |
| **Rootstock** | MXT | Carizzo Citrange | |
| **Orchard size** | 2.58 ha | 2.11 ha | 10.33 ha |
| **GPS co-ordinates** | 23°42'00.95'' S 30°34'58.72'' E | 23° 41'57.61'' S 30° 34'47.05'' E | 23º41'05.10" S 30º34'18.75" E |
| **Tree spacing** | 7.0 x 3.0 m (21.00 $m^2$) planted on ridges | | |
| **Irrigation** | Micro sprinklers (1 sprinkler per tree). 30 L $h^{-1}$ | | |
| **Canopy dimension *(STDev)** | Height – 4.30 m (0.32) Width – 5.2 m (0.18) Breadth – 3.5 m (0.17) | Height – 3,23 m (0.26) Width – 3,75 m (0.27) Breadth – 3.6 m (0.24) | Height – 2.16 m (0.32) Width – 2.42 m (0.18) Depth – 2.32 m (0.16) |
| **Canopy cover** | 0.74 | 0.51 | 0.27 |
| **Leaf area index – orchard ($\bar{x}$ = 5 measurements)** | 3.15 $m^2$ $m^{-2}$ (0.37) | 2.30 $m^2$ $m^{-2}$ (0.61) | 1.72 $m^2$ $m^{-2}$ (0.23) |
| **– average of 4 individual tree *(STDev)** | 4.31 $m^2$ $m^{-2}$ (0.23) | 4.54 $m^2$ $m^{-2}$ (0.58) | 3.33 $m^2$ $m^{-2}$ (0.51) |
| **Experimental trees** | 4 | | |
| **Trunk circumferences** | 1 – 61.0 cm 2 – 59.0 cm 3 – 58.5 cm 4 – 56.2 cm | 1 – 32.5 cm 2 – 32.0 cm 3 – 33.0 cm 4 – 36.0 cm | 1 – 19.0 cm 2 – 19.0 cm 3 – 18.0 cm 4 – 18.5 cm |
| **Yield** | 63.8 t $ha^{-1}$ | 37.2 t $ha^{-1}$ | 20.5 t $ha^{-1}$ |
| **Water use efficiency** | 11.4 kg $m^{-3}$ | 13.5 kg $m^{-3}$ | 9.6 kg $m^{-3}$ |
| **Soil texture** | Loamy sand | Loamy sand | Sandy clay |

*Standard deviation is in brackets

### 3.2.2.3 Orchard characteristics of the 'Valley Gold' mandarins

Transpiration measurements for the 'Valley Gold' mandarins planted in 2013 and 2015 only commenced in February 2017. Unlike the other species only two different sized canopies were installed, as we could not locate a suitable mature orchard on the farm. The two orchards are presented in Figure 3.10 and the orchard details are presented in Table 3.6.


**Figure 3.10 The mandarin orchards at Mahela Boerdery. A) and B) 'Valley Gold' mandarin orchard planted in 2013 (4 years old). C) and D) 'Valley Gold' mandarin orchard planted in 2015 (2 years old)**

The different orchard details are presented in Table 3.6. The average LAI, of the four measured trees, for the 'Valley Gold' mandarin trees were 3.14 $m^2\,m^{-2}$ (canopy cover 0.42) for the 2013 'Valley Gold' and 1.09 $m^2\,m^{-2}$ (canopy cover 0.34) for the 2015 'Valley Gold' at the end of the trial.

**Table 3.6 Orchard details for 'Valley Gold' mandarin orchards planted in 2013 and 2015 in the summer rainfall region of South Africa**

| Cultivar | 'Valley Gold' | |
|---|---|---|
| Measurement period:<br>Start<br>End | 08-Feb-2017<br>16-Mar-2018 | 09-Feb-2017<br>16-Mar-2018 |
| Age | 4 years old (planted 2013) | 2 years old (planted 2015) |
| Rootstock | Carizzo Citrange | |
| Orchard size | 4.89 ha | 1.4 ha |
| GPS co-ordinates | 23°51'34.72" S<br>30°21' 27.40" E | 23°51'28.27" S<br>30°21' 11.21" E |
| Tree spacing | 7.0 x 3.0 m (21.00 $m^2$) planted on ridges | |
| Irrigation | Micro sprinklers (1 sprinkler per tree). 30 l $h^{-1}$ | |
| Canopy dimension *(STDev) | Height – 2.87 m (0.19)<br>Width – 2.87 m (0.16)<br>Depth – 2.81 m (0.18) | Height – 2.28 m (0.24)<br>Width – 2.5 m (0.13)<br>Breadth – 2.43 m (0.24) |
| Canopy cover | 0.42 | 0.34 |
| Leaf area index<br>– orchard ($\bar{x}$ = 5 measurements)<br><br>– average of 4 individual tree *(STDev) | 3.53 $m^2$ $m^{-2}$ (0.42)<br><br>3.14 $m^2$ $m^{-2}$ (1.4) | 2.24 $m^2$ $m^{-2}$ (0.6)<br><br>1.09 $m^2$ $m^{-2}$ (0.42) |
| Experimental trees | 4 | |
| Trunk circumferences | 1 – 32.5 cm<br>2 – 32.0 cm<br>3 – 33.0 cm<br>4 – 36.0 cm | 1 – 19.0 cm<br>2 – 19.0 cm<br>3 – 18.0 cm<br>4 – 18.5 cm |
| Yield | 8.8 t $ha^{-1}$ | 4 t $ha^{-1}$ |
| Water use efficiency | 5.3 kg $m^{-3}$ | 2.9 kg $m^{-3}$ |
| Soil texture | Sandy clay | Sandy clay |

*Standard deviation is in brackets

## 3.3 Water use measurements

### 3.3.1 Transpiration

#### 3.3.1.1 The heat ratio method

Sap flow measurements were performed using the HR method as described by Burgess et al. (2001) on four trees in each orchard in Citrusdal and Letsitele. Trees were selected in the centre of each block, with the objective of selecting trees with different stem circumferences, which represent the variation found within the orchard. 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. 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 equidistant (0.5 cm) upstream and downstream of the stainless steel heater probe (1.8 mm), which was inserted into a brass collar (2.5 mm) to avoid problems associated with resin causing corrosion of the probes. Heat pulse velocities (HPV) 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 HPV to SFD, taking into account wounding, were performed according to Burgess et al. (2001). Wound width was determined at the end of measurements in each orchard by chiselling out a wood sample for a minimum of four probe sets per orchard. Whole stem sap flux (assumed to be equal to T) was calculated as a product of SFD and weighted sapwood cross-sectional area represented by each probe set. The presence of heartwood was determined by staining conducting tissue *in situ* using safranin O dye and then using a corer to extract a core sample from the tree. Integrated volumetric sap flow (VSF) of the individual trees (L day$^{-1}$) was upscaled to orchard water use, using a weighted average based on a tree circumference survey of at least 50 trees in the orchard. Transpiration (L day$^{-1}$) was then converted to T (mm day$^{-1}$) using the ground area allocated to each tree in the orchard. The only exception was for the 'Afourer' mandarins planted in 2002 (winter rainfall region), where the tree architecture prevented (the trees started to branch very close to the soil surface) the use of tree circumferences to upscale tree water use to orchard level. In this case T (L day$^{-1}$) was calculated as an average of the sample trees and upscaled to orchard T (mm day$^{-1}$) using the ground area allocated to each tree in the orchard. Wood samples were taken from all the study orchards to determine sapwood properties (density, water content and xylem depth) and wound widths. Additional samples were taken from the 'Delta' Valencia orchard to examine wood anatomy prior to and after probe insertion to determine the impact of probe insertion on tissue wounding.

Validation of the orchard T measurements was performed according to Taylor et al. (2015) using ET (determined with the eddy covariance technique) and $E_s$ (determined with micro-lysimeters) in the 9-year-old 'Washington' navel orchard in March 2015. Whilst these results were provided in Volume I (Chapter 7), it is important to provide these results in Volume II to demonstrate the accuracy of the SFD method in determining T of the orchards. With this method of calibration orchard T was underestimated by 5% on average per day, which is considered reasonable. The close match of the HR method to the eddy covariance (EC) technique (Figure 3.11) shows that if the parameters (wound width, sapwood depth and heartwood radius) for determining SFD with the HR method are measured accurately, accurate measurements of T in *Citrus sinensis* can be achieved.

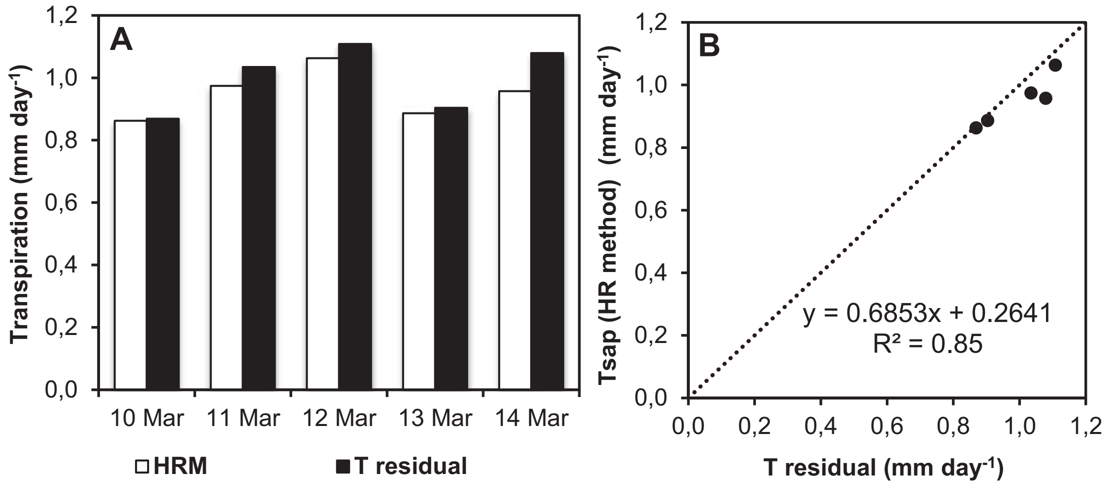


**Figure 3.11 A) Daily total residual transpiration and sap flow by the heat ratio (HR) method and B) regression analysis of daily transpiration with the HR method 'Washington' navel orchard. The dashed black line is the 1:1 line**

More detail on the theoretical background and the validation and calibration of the HR method is provided in Volume I of this report.

### 3.3.1.2 Stem steady state heat energy balance method

Transpiration in an immature 4-year-old 'Cambria' navel orchard and an immature 3-year-old 'Afourer' mandarin orchard was determined using the stem steady state heat balance method (Dynagage$^{TM}$, Dynamax, Houston, Texas, USA). This method estimates sap flow (g $h^{-1}$) and is therefore very useful for determining whole plant water use (Vandegehuchte and Steppe, 2013). In addition it does not require calibration (Baker and Van Bavel, 1987), which is seen as a major advantage. However, this method can only be used for small trees with fairly straight and round trunks and is therefore, although ideal, not suited for larger citrus trees. Additional disadvantages of this method include the high power requirements and the cost of the collars. SGB50 collars (45-65 mm diameter) were fitted to five trees. These collars were logged using a standard Flow 32A-1K system from Dynamax, consisting of a CR1000 logger, AM16/32B multiplexer and an AVRD voltage regulator. Sap flow was estimated according to Figure 3.12. Data was processed using an Excel spreadsheet provided by Dynamax. A preliminary stem thermal conductivity ($K_{st}$) value of 0.42 W $m^{-1}$ $K^{-1}$ was used. Gauge thermal conductance ($K_{sh}$) used for calculation of sap flow was determined each day by using the average $K_{sh}$ values for each collar between 02:00 and 04:00 when sap flow was considered to be zero. The energy balance was computed for every sap flow measurement. If a reasonable energy balance was found for more than 80% of the individual daily sap flow measurements, the results were then used to calculate the water use for the navel orchards.

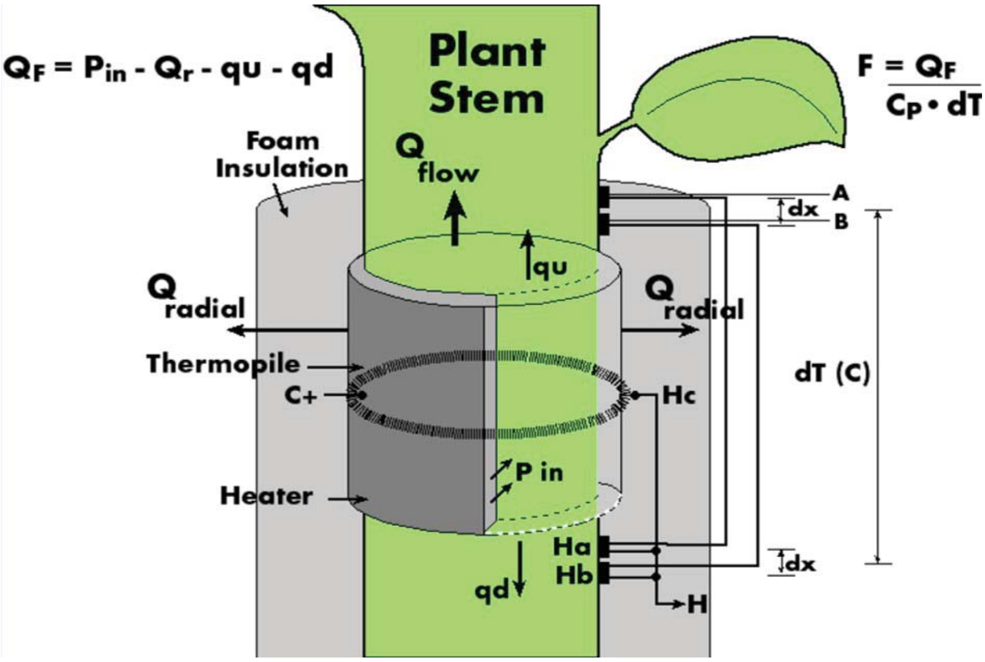


**Figure 3.12 Sap flow sensor operation and the calculation of sap flow**

### 3.3.2 Eddy covariance

#### 3.3.2.1 Citrusdal

An extended Open Path eddy covariance (OPEC) system, comprising a CSAT3 (Campbell Scientific Inc., Logan, Utah, USA) three-dimensional sonic anemometer for sensible heat flux (H) and an LI-7500 open path infrared gas analyzer (IRGA) (LI-COR Inc., Lincoln, NE, USA) for latent heat flux (LE), mounted on average 2 m above average canopy height, was used to determine total evaporation (ET) for the orchard. Additional measurements of air temperature ($T_a$) and humidity were sampled using an HMP45C Vaisala temperature and humidity probe (Vaisala Oyj, Vantaa, Finland). Net irradiance ($R_n$) was measured using a NR-Lite (Kipp and Zonen, Delft, The Netherlands) net radiometer. Soil heat flux (G) was determined using HFP-01 (Hukseflux, Delft, Netherlands) soil heat flux plates buried 80 mm below the soil surface. In addition, TCAV-L soil temperature averaging probes (Campbell Scientific Inc., Logan, Utah, USA) were installed at 2 locations representing within-row and between-row conditions, and were positioned 20 mm and 60 mm below the soil surface to correct the measured soil heat flux data for the energy stored above the plates. A CS616 time domain reflectometer water content sensor (Campbell Scientific Inc., Logan, UT, USA) linked to the OPEC system was positioned in the upper 60 mm of the soil. Measurements were sampled at a frequency of 10 Hz and logged on a CR5000 data logger (Campbell Scientific Inc., Logan, Utah, USA) every 30 minutes. The height of the sensors differed for each orchard according to tree height and orchard size and are detailed in Table 3.7 and Figure 3.13.

**Table 3.7 Details of instrumentation configuration for the eddy covariance measurements in orchards in Citrusdal**

| Orchard | Measurement dates | Canopy height (m) | Height of sensors from the ground (m) | | |
|---|---|---|---|---|---|
| | | | 3D Sonic and IRGA | Temperature and relative humidity | Net radiometer |
| ‘Bahianinha’ navel | 12-15 Nov 2013<br>5 March-20 April 2014 | 3 | 5 | 4.5 | 8 |
| ‘Washington’ navel | 3-17 March 2015 | 3.5 | 5.5 | 4 | 8 |
| ‘Midknight’ Valencia | 15-27 April 2015 | 3.5 | 5.5 | 4 | 8 |
| ‘Afourer’ mandarin | 8-17 March, 27 May-20 June, 6-21 July, all 2016 | 5 | 7 | 3 | 9 |

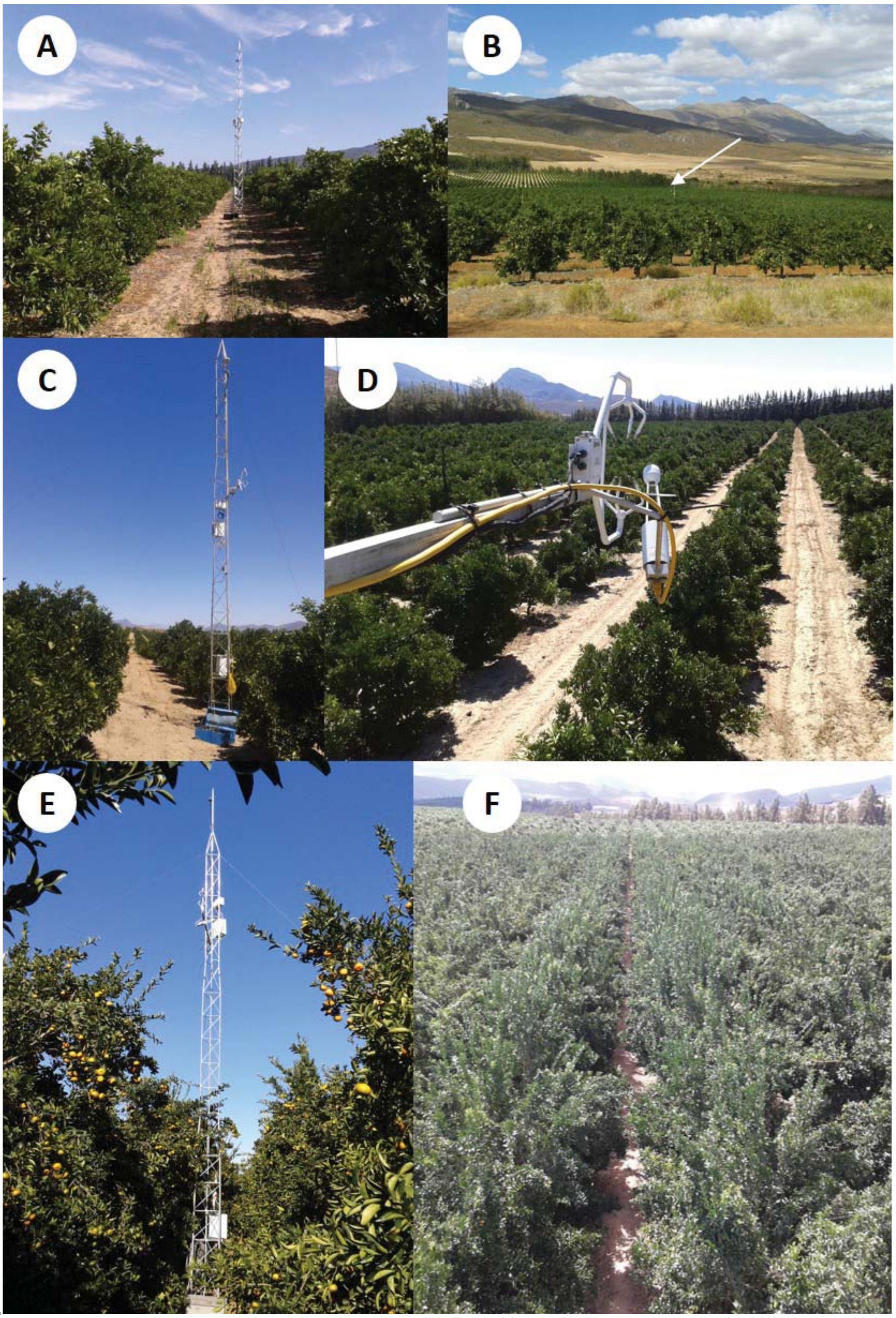


**Figure 3.13 Positioning and configuration of the eddy covariance instrumentation in the various orchards in Citrusdal. A) 'Bahianinha' navel orchard planted in 2001. B) 'Midknight' Valencia orchard planted in 2008 (the arrow indicates the position of the tower). C) and D) 'Washington' navel orchard planted in 2006 and E) 'Afourer' mandarin orchard planted in 2002. F) The 'Afourer' mandarin orchard as seen from the eddy covariance tower. Note that the soils between the rows are relative weed free**

#### 3.3.2.2 Letsitele

Fluxes of latent (LE) and sensible heat (H) were measured with an extended open path eddy covariance (OPEC) system, comprising an EC150 IRGASON open-path analyser and sonic anemometer (Campbell Scientific Inc., Logan, Utah, USA), which was mounted on a lattice mast. Air temperature and humidity were measured using a HygroClip2 HC2-S(3) thermohygrometer probe (Rotronic Instruments, Bassersdorf, Switzerland). Net radiation (Rn) was measured using a CNR4 four component net radiometer or a NR-Lite net radiometer (Model 240-110 NR-Lite, Kipp & Zonen, Delft, Netherlands). Four soil heat flux plates (model HFT-S, REBS, Seattle, Washington, USA) were used to measure 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 two time domain reflectometers (CS616, Campbell Scientific Inc., Logan, Utah, USA) placed near the heat flux plates. Measurements were sampled at a frequency of 10 Hz and logged on a CR3000 data logger (Campbell Scientific Inc., Logan, Utah, USA) using the Easyflux-DL software from Campbell Scientific. The program applies the most common open-path EC corrections to fluxes. The height of the sensors differed for each orchard according to tree height and orchard size and are detailed in Table 3.8 and Figure 3.14.

**Table 3.8 Details of instrumentation configuration for the eddy covariance measurements in orchards in Letsitele**

| Orchard | Measurement dates | Canopy height (m) | Height of sensors from the ground (m) | | |
|---|---|---|---|---|---|
| | | | 3D Sonic and IRGA | Temperature and relative humidity | Net radiometer |
| 'Star Ruby' grapefruit | 28 October 2016-9 April 2017 | 6 | 7.5 | 6 | 7 |
| 'Midknight' Valencia | 11 April-22 May 2017 | 3.2 | 4.5 | 4.5 | 3 |
| 'Valley Gold' mandarin | 29 July-16 August 2017 | 3 | 5.3 | 4.8 | 5.3 |

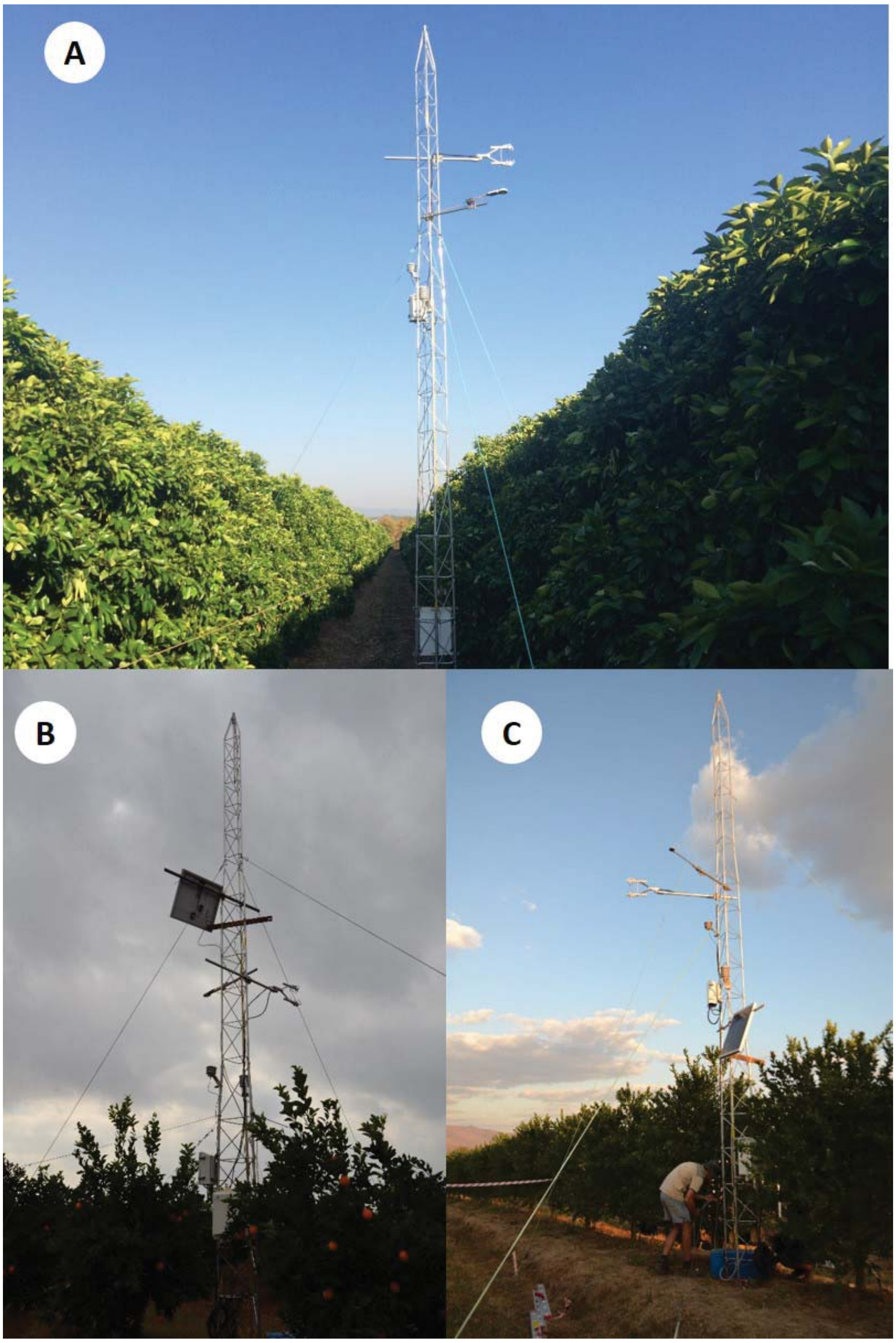


**Figure 3.14 Positioning and configuration of the eddy covariance instrumentation in the various orchards in Letsitele. A) 'Star Ruby' grapefruit orchard planted in 2006, B) 'Midknight' Valencia orchard planted in 2014 and C) 'Valley Gold' mandarin orchard planted in 2013**

#### 3.3.2.3 Data analysis and correction

In Citrusdal the separation of the IRGA and sonic was between 10 and 20 cm. The high frequency data was further processed using EddyPro v 6.2.1 (LI-COR, Nebraska, USA) to correct for water vapour density fluctuations, sensor tilt (coordinate rotation), sensor separation, and time lags, and quality checks according to Foken et al. (2004). Sensible heat (H) and latent (λE) heat fluxes were corrected using Webb-Pearman-Leuning correction procedure. In Letsitele the new IRGASON and Easyflux software were used which allows post processing of data on the logger.

Some of the data was further corrected for the lack of surface energy balance closure. If $R_n$ is the net radiation absorbed by the orchard (treated as a flat surface), and G is the soil heat flux, then the shortened surface energy balance equation for the orchard can be written as:

$$R_n - G = H + \lambda E \qquad (\text{W m}^{-2}) \qquad (2)$$

Latent heat flux is the energy equivalent of ET and λ is the latent heat of vaporization. The ratio of the sensible to the latent heat flux is called the Bowen ratio (B). Substituting the Bowen ratio into equation 3 and re-arranging the equation gives the latent heat flux as;

$$\lambda E = \frac{R_n - G}{1 + B} \qquad (\text{W m}^{-2}) \qquad (3)$$

This relationship was used to correct the ET data for lack of energy balance closure which has been widely reported for the EC method (Twine et al., 2000).

### 3.3.3 Irrigation volumes

Irrigation events and volumes were recorded in the various orchards using a combination of techniques. In Citrusdal, where the orchards were drip irrigated, irrigation volumes were quantified by placing a tipping bucket rain gauge under the dripper and recording tips using the CR1000 logger for the sap flow system. This volume was scaled up to a per tree basis by multiplying by the number of drippers per tree. Volume was then converted to mm by dividing by the area allocated to each tree in the orchard. Volumes were also recorded using water meters (ARAD Measuring Technologies Ltd, Dalia, Israel) to confirm measurements from the tipping buckets. In Letsitele, where the orchards were irrigated with microsprinklers, irrigation events and volumes were recorded using logging water meters (Aquacheck (Pty) Ltd). These logging water meters were connected to the Aquacheck capacitance probes and data was downloaded every 6-8 weeks during visits.

## 3.4 Weather data

In Citrusdal hourly and daily weather data were obtained from the Campbell Scientific AWS on Patrysberg (32°27’2.57’S and 18°58’6.23”E) and from October 2015 on Brakfontein (32°29’30.46’S and 18°59’48.79”E) (Figure 3.15), which were both installed according to standard conditions specified in FAO-56 (Allen et al., 1998). Both short grass reference evapotranspiration ($ET_o$) and alfalfa reference evapotranspiration ($ET_r$) were calculated according to the procedure outlined by Pereira et al. (2015) on an hourly and a daily basis. 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 at Patrysberg. Whilst the irrigated orchards would have conditioned the boundary layer, the height of the orchards may impact wind speed. This may result in an underestimation of $ET_o$ (Allen et al., 2011). At Brakfontein the AWS was installed in an open field, with an avenue of tall trees 50 m to the South. There were no irrigated fields within 1 km of the AWS in any direction. Under these fairly dry conditions, calculated $ET_o$ is likely to be slightly overestimated, as compared to data collected over a reference surface (Allen, 2008). The Constantia (23°40’54.96’’S and 30°35’27.19’’E) and Letsitele (23°52’08.07’’S and 30°22”50.10’’E) weather stations were surrounded by irrigated orchards and buildings. Whilst the irrigated orchards would have conditioned the boundary layer, the height of the orchards may impact wind speed. This may result in an underestimation of $ET_o$ (Allen, 2008). Both the weather stations at Letsitele are operated and maintained by QMS Laboratories.

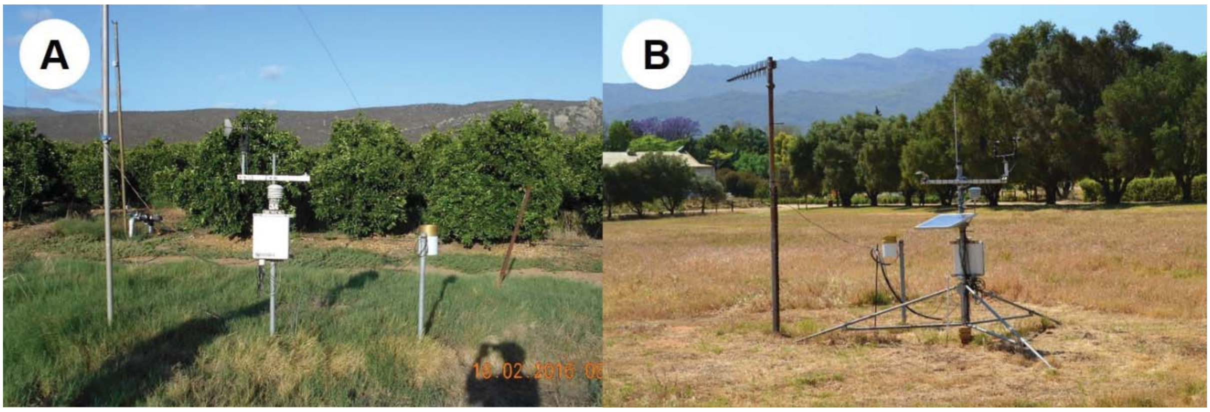


**Figure 3.15 Automatic weather stations at A) Patrysberg and B) Brakfontein**

The weather parameters recorded were wind speed, solar radiation ($R_s$), temperature, relative humidity and rainfall. Quality assessment and quality control of the data was performed according to the procedures described by Allen (2008). Solar radiation was found to be routinely underestimated at both Citrusdal weather stations and was corrected according to the procedure outlined by Allen (2008). No corrections were made to the other variables measured.

## 3.5 Tree characteristics and physiological measurements

### 3.5.1 Tree size and canopy volumes

Tree height, width (across the tree row) and breadth (within the tree row) of each orchard were routinely measured every 6-12 weeks. Canopies were approximately ellipsoidal, therefore, the canopy volume was calculated using the formula for an ellipsoid.

### 3.5.2 Leaf area index and fractional interception of photosynthetically active radiation

Leaf area index of individual trees and the orchard as a whole was determined using an LI-2200 Plant Canopy Analyser (Li-Cor Biosciences, Lincoln, Nebraska, USA) under diffuse light conditions. For determining the LAI for individual trees, measurements were made at the four cardinal points under each tree, with clear sky readings taken in the open next to the orchard. For orchard LAI measurements under the canopy were made across the work row from the trunk of one tree to the trunk of the tree in the next row. Once again clear sky readings were taken in the open next to the orchard.

Fractional interception of PAR was determined with a Decagon AccuPAR LP-80 ceptometer (Decagon Devices, Pullman, WA, USA) in a grid pattern around a representative tree in each orchard. The grid consisted of transect lines across the tree row, with 1 m in between transects and 1 m between the grid points. The number of measurements in each orchard depended on the planting density of the orchard. Measurements were conducted throughout the course of the day on the hour every hour under clear sky conditions. Full sun readings were taken in an open area next to the orchard.

Five calibrated tube solarimeters (Delta-T) were used to continuously measure $R_s$ received at the orchard floor for all the study orchards, for selected window periods. The solarimeters were positioned in the work row on both the east and west sides of the tree row, with the 5$^{th}$ solarimeter placed directly under the canopy in the tree row as shown in Figure 3.16.


**Figure 3.16 Tube solarimeters used to continuously measure solar radiation received at the orchard floor**

### 3.5.3 Water potential and stomatal conductance measurements

Leaf and stem water potentials were measured hourly using a Scholander pressure chamber (PMS Instrument Company, Albany, USA) from before sunrise to sunset on selected days. Three sunlit leaves and three shaded leaves were measured on the four trees instrumented with sap flow equipment. Stem water potential ($\Psi_{stem}$) was also measured hourly by selecting two leaves on the inside of the canopy and enclosing them in aluminium foil covered plastic bags for at least 30 min prior to measurement. Predawn leaf water potentials ($\psi_{pd}$) were measured during all measurement campaigns.

Stomatal conductance measurements were performed using a SC-1 leaf porometer (Decagon Device Inc, Pullman, WA, USA) at the beginning of the project and an AP4 porometer (Delta-T Devices Ltd, Cambridge, United Kingdom) towards the end of the project. Three leaves on the east of the tree, three on the west and three shaded leaves were measured on the four trees instrumented with sap flow equipment. Measurements were performed from sunrise to sunset at hourly intervals on healthy mature leaves. On days with early morning dew on the leaves, $g_s$ measurements only commenced once the leaf surface was dry.

Hydraulic conductance (k) was estimated according to Cohen and Naor (2002), where k was separated into the pathway from the soil to the stem ($k_{soil\text{-}stem}$) and from the stem to the leaves ($k_{stem\text{-}leaf}$). The root-stem interface was calculated using equation 4, where T is transpiration and $\psi_{soil}$ was assumed to be equal to $\psi_{pd}$ under well-watered conditions, as were present for the majority of the time in this study. The hydraulic conductance between the stem and leaf interface was calculated based on equation 5, with the fraction of sunlit canopy leaf area ($\propto$) of a mature citrus tree being estimated at 0.3, as described by Moreshet et al. (1990). Whole tree hydraulic conductance ($k_{soil\text{-}leaf}$) was calculated by means of equation 6.

$$k_{soil\text{-}stem} = T/(\psi_{soil} - \psi_{stem}) \quad (4)$$

$$k_{stem\text{-}leaf} = T/(\psi_{stem} - (\propto\psi_{sun\ leaf} + (1-\propto)\psi_{shade\ leaf})) \quad (5)$$

$$k_{soil\text{-}leaf} = T/(\psi_{soil} - (\propto\psi_{sun\ leaf} + (1-\propto)\psi_{shade\ leaf})) \quad (6)$$

## 3.6 Impact of water stress on yield and fruit quality

### 3.6.1 Experimental site and layout

Trials were conducted on a 13.2 ha 'Delta' Valencia orchard (Leeukraal farm, Groblersdal, 29°23'45.6" ° and 25°11'49.2"E at 959 masl), with trees planted in 1996 that were grafted on a Swingle rootstock (Figure 3.17).


**Figure 3.17 Location of the 'Delta' Valencia orchard and the experimental layout**

The orchard was divided into 10 treatment blocks (Figure 3.17). Treatment blocks 2, 3 and 8 were water stressed during phase I of fruit development, blocks 7, 10 and 6 B were water stressed during phase II of fruit development and lastly, block 1, 4 and 5 were water stressed during phase III of fruit development. Block 6 A was used as a control and was irrigated according to the scheduling practice on the farm. Each treatment block consisted of three treatment tree rows comprising 10 trees per treatment row. For each treatment row an irrigation line, which by-passed the main line (Figure 3.18) was installed with a separate valve to control the amount of water applied to the treatment trees.

**Figure 3.18 Installation of the extra irrigation line**

Tensiometers were installed at 30 and 60 cm in each orchard and readings were taken daily, early in the morning, to monitor the soil matric potential. Within the treatment rows three trees were selected for frequent measurements of $\Psi_{pd}$, mid-day $\Psi_{stem}$ and $g_s$. This was done to assess if the trees were water stressed. All trees were managed according to industry standards in terms of fertilisation and pruning practices. Water stress was induced by reducing irrigation for approximately 60 days and covering the soil underneath these trees with a plastic sheet to prevent the rewetting of the soil by rain (Figure 3.19).

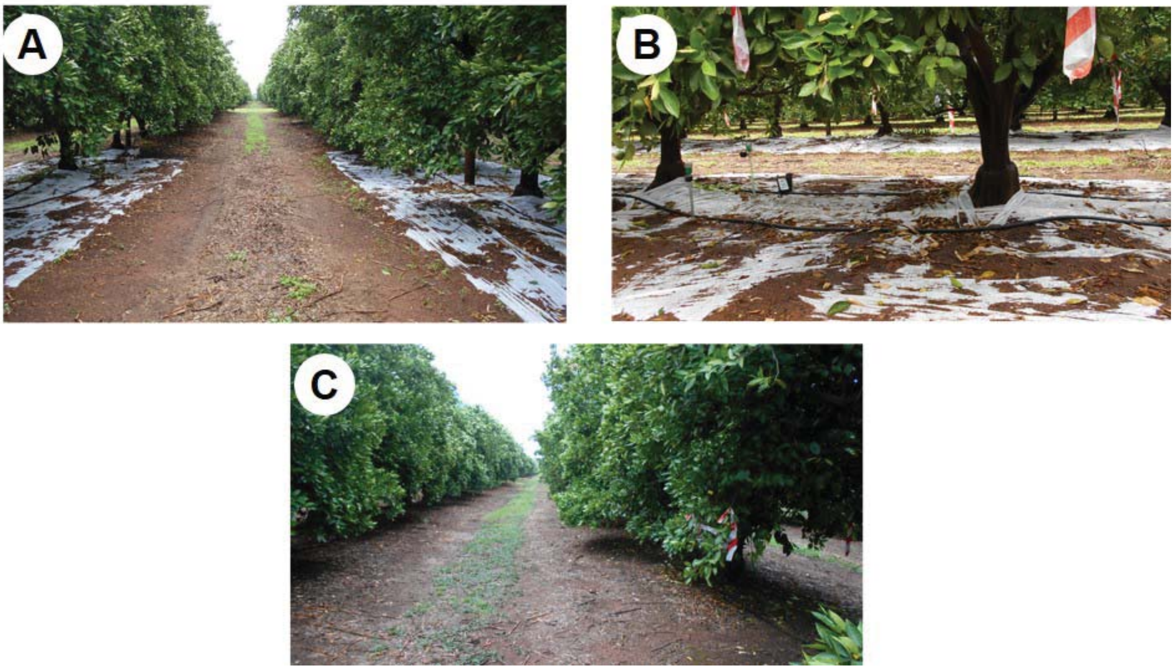


**Figure 3.19 A) and B) shows the covering of the ground with plastic sheeting to avoid re-wetting from the rain and C) is the control block which was uncovered throughout the season**

### 3.6.2 Leaf water potential measurements

Leaf and stem water potentials were measured with a Scholander Pressure Chamber (PMS3000, PMS Instruments Company, Corvallis, Oregon, USA) on three sunlit and three shaded, fully expanded healthy, leaves as described by Cohen and Naor (2002). For $\psi_{stem}$, leaves were bagged and covered with aluminium foil for at least two hours before measurements. Measuring campaigns consisted of 2-3 days of field measurements that were conducted frequently (most of the time at 1-2 week intervals). Due to limited equipment, measurements were cycled between two different treatment blocks per day for the measuring period.

### 3.6.3 Stomatal conductance measurements

Stomatal conductance measurements were conducted with an AP4 leaf porometer (Delta-T Devices Ltd, Cambridge, UK) at 2 hourly intervals from 08:00 to 17:00. Measurements were conducted on nine selected leaves per tree on three trees (three east side, three west side and three shaded with virtually no radiation interception throughout the day). These measurements were averaged to give an average tree $g_s$. The frequency and arrangement of field measurements followed the same as for the $\Psi_{leaf}$ measurements. Typically $\Psi_{leaf}$ and $g_s$ will be measured for the same trees on the same day.

### 3.6.4 Fruit, yield and postharvest measurements

At harvest, fruit from the middle four trees in the middle treatment row were harvested from each treatment block and weighed at the pack house to determine the yield (in kg) of each block. Concurrently, fruit from the specific block was weighed individually in a pack house and the average fruit mass was determined. Additionally 10 random fruit samples from each block were selected and stored at -0.6°C and 4°C for a month. At the end of the cold storage treatment the juice content, rind colour, acid level and brix of the fruits were evaluated by Kim Stoltz at the CRI in Nelspruit. Duncan's multi range test was used to evaluate if differences between the treatments and the control were significant ($P = 0.05$).

# 4 RESULTS – WINTER RAINFALL REGION

## 4.1 Root distribution

The root distribution of a 'Bahianinha' navel tree from orchards planted in 2001 and in 1990 is given in Figure 4.1 and for a 'Midknight' Valencia tree from orchards planted in 2008 and 2000 in Figure 4.2. Both the soils of the 'Midknight' Valencia orchards planted in 2008 and 2000 can be classified as a clay soil. The soil from the 'Bahianinha' navel orchard planted in 2001 was classified as a sand, while the soil for the 1990 'Bahianinha' navel orchard was classified as a sandy clay loam (Soil Classification Working Group, 1991). Field measurements and observations revealed that the roots of the 2008 'Midknight' Valencia trees were thinner than the roots of the 'Bahianinha' navel trees. A typical bimodal distribution of the roots was 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 4.1 and Figure 4.2). More than 84% 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 between the tree rows (Figure 4.1 and Figure 4.2 A) and within the tree row (Figure 4.1 and Figure 4.2 B).

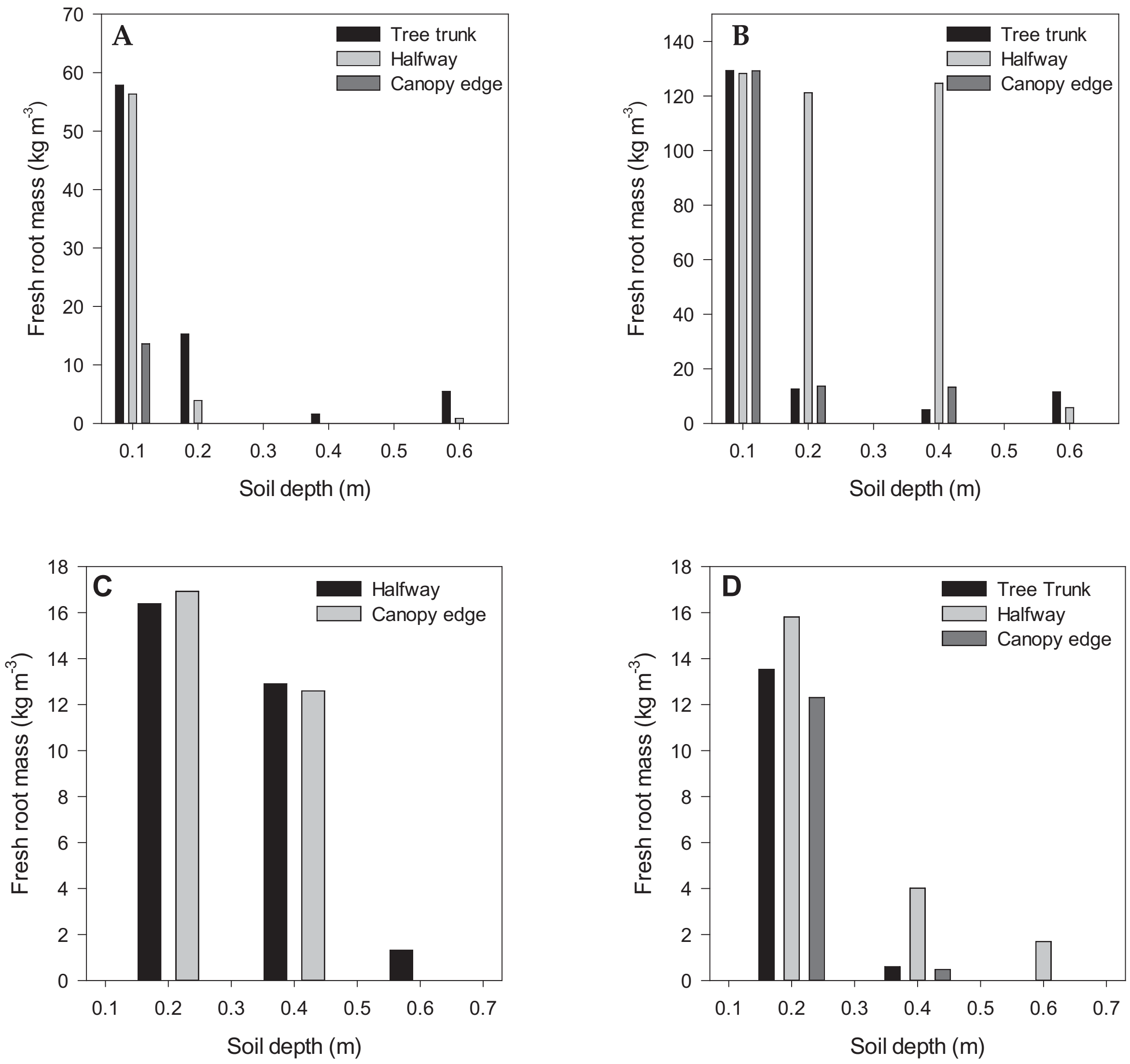


**Figure 4.1 Root distribution (kg m$^{-3}$), A) between the rows and B) within the row in a 'Bahianinha' navel orchard planted in 2001 and C) between the rows and D) within the row in a 'Bahianinha' navel orchard planted in 1990. Trees in both orchards were grafted on a Carrizo citrange rootstock**

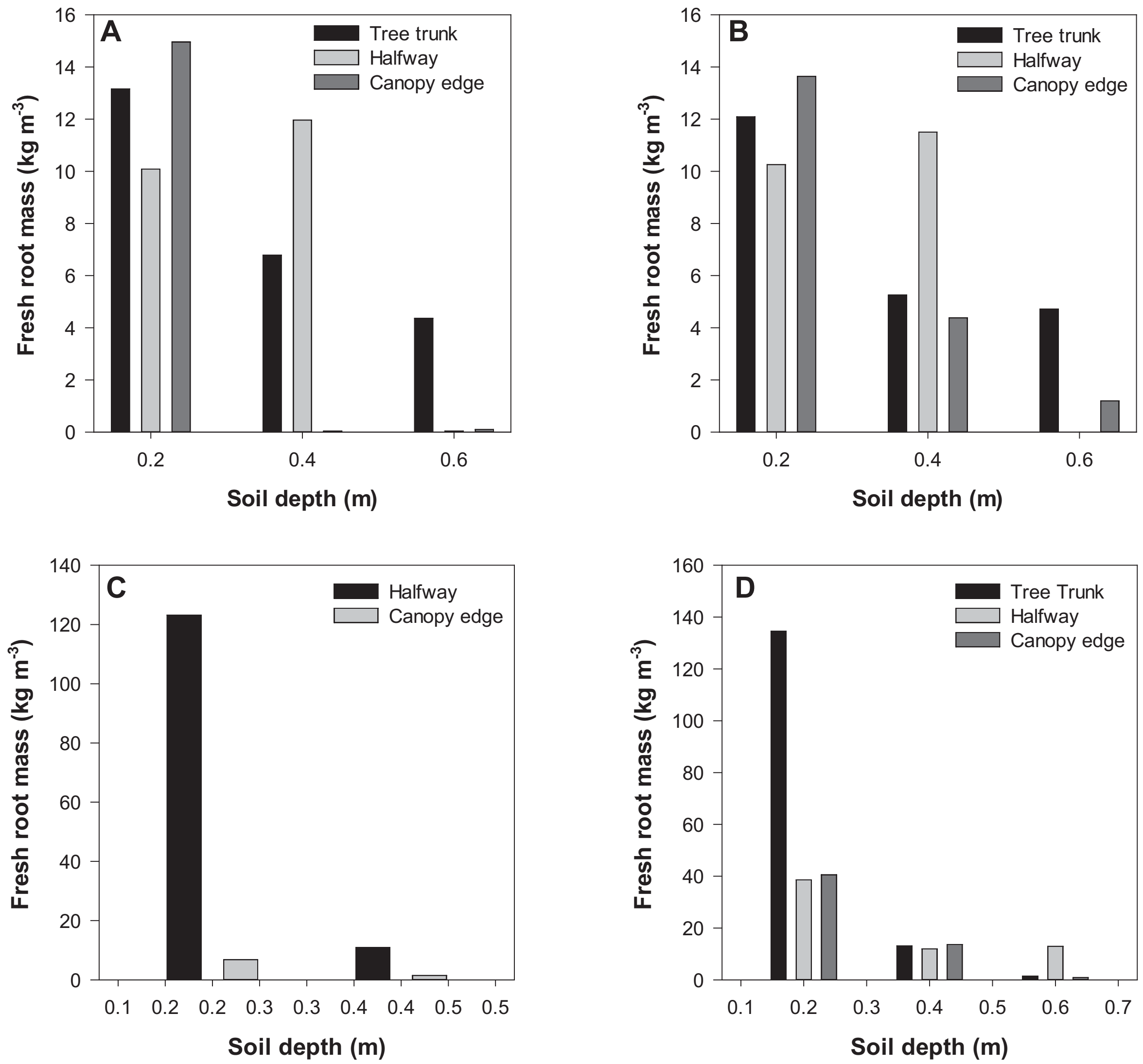


**Figure 4.2 Root distribution (kg m$^{-3}$), A) between the rows and B) within the row in a 'Midknight' Valencia orchard planted in 2008 and C) between the rows and D) within the row in a 'Midknight' Valencia orchard planted in 2000. Trees in both orchards were grafted on a Carrizo citrange rootstock**

## 4.2 Weather variables

Weather data from the AWS at Patrysberg and Brakfontein are presented in Figure 4.3 A and B respectively. Warm summers and cool winters are experienced in this region, with an average $T_a$ of 23.1°C in summer and 14.6°C in winter. The minimum temperature from 1 August 2013-30 November 2017 was -2.9°C, whilst the maximum was 43.9°C (Figure 4.3). There were a total of 87 days above 40°C over the course of the study and a total of 20 days below 0°C. The total rainfall recorded at Brakfontein weather station was 379.5 mm during the period of 7 October 2015-7 July 2017 and a total of 587.7 mm was recorded on Patrysberg weather station during the period of 1 August 2013-28 October 2016.

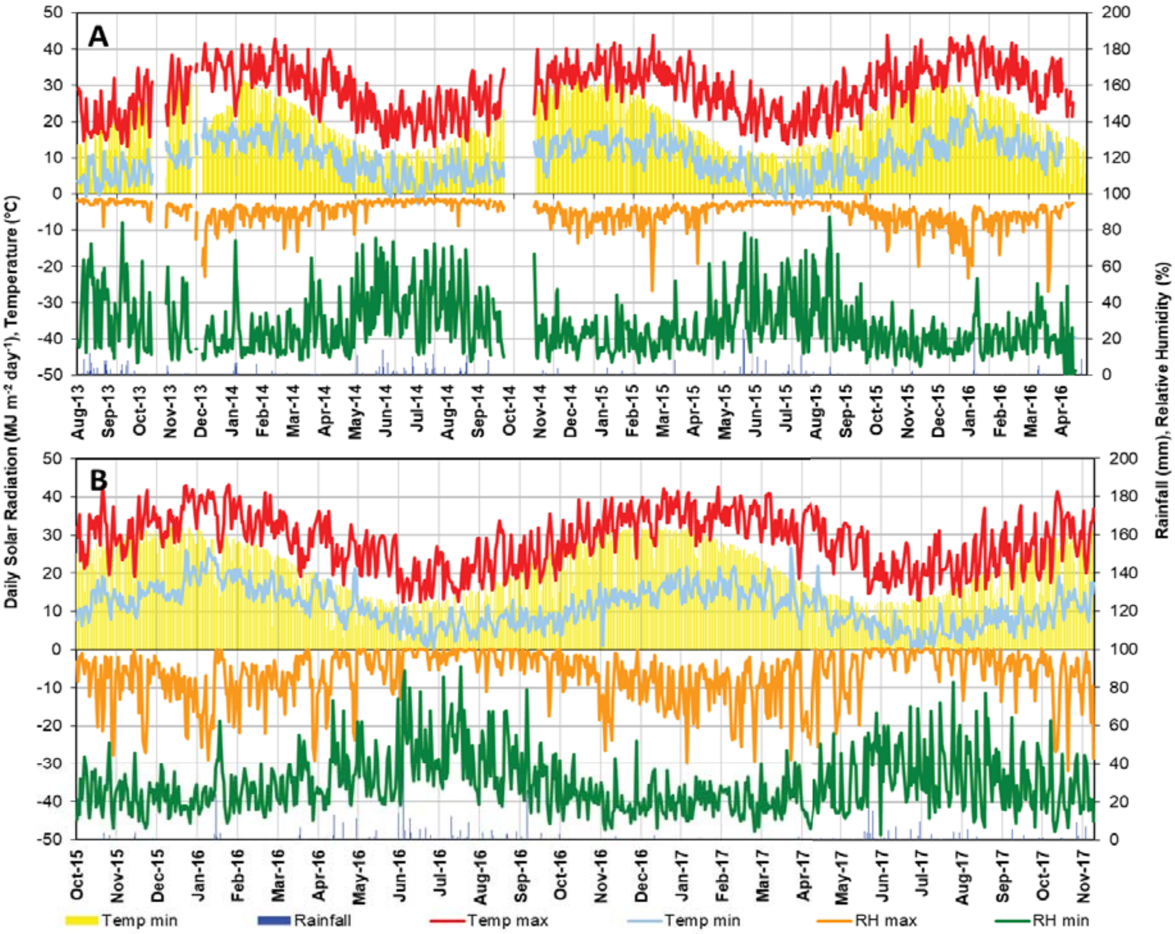


**Figure 4.3 Daily values of maximum and minimum temperatures (°C), solar radiation (MJ.m$^{-2}$.day$^{-1}$), rainfall (mm), and maximum and minimum relative humidity (%) at A) Patrysberg and B) Brakfontein. Missing data is due to battery failure**

Vapour pressure deficit and reference evapotranspiration ($ET_o$ – short crop and $ET_r$ – tall crop) are important determinants of water use in plants and therefore these parameters should be considered when estimating water use and determining the drivers of water use (Figure 4.4). A clear seasonal trend existed for VPD, $ET_o$ and $ET_r$, with the lowest values in winter and highest values in summer. For the measuring period (7 October 2015-29 October 2016) the average VPD for the summer seasons was 2.07 kPa, with a daily maximum of 4.35 kPa and the average for winter seasons was 1.00 kPa, with a daily minimum of 0.08 kPa. The average $ET_o$ for the summer seasons was 4.56 mm (6.92 for $ET_r$), with a daily maximum of 8.09 mm (10.79 for $ET_r$), while the average $ET_o$ for the winter seasons was 2.09 mm (2.72 for $ET_r$), with a daily minimum of 0.23 mm (0.75 for $ET_r$) (Figure 4.4).

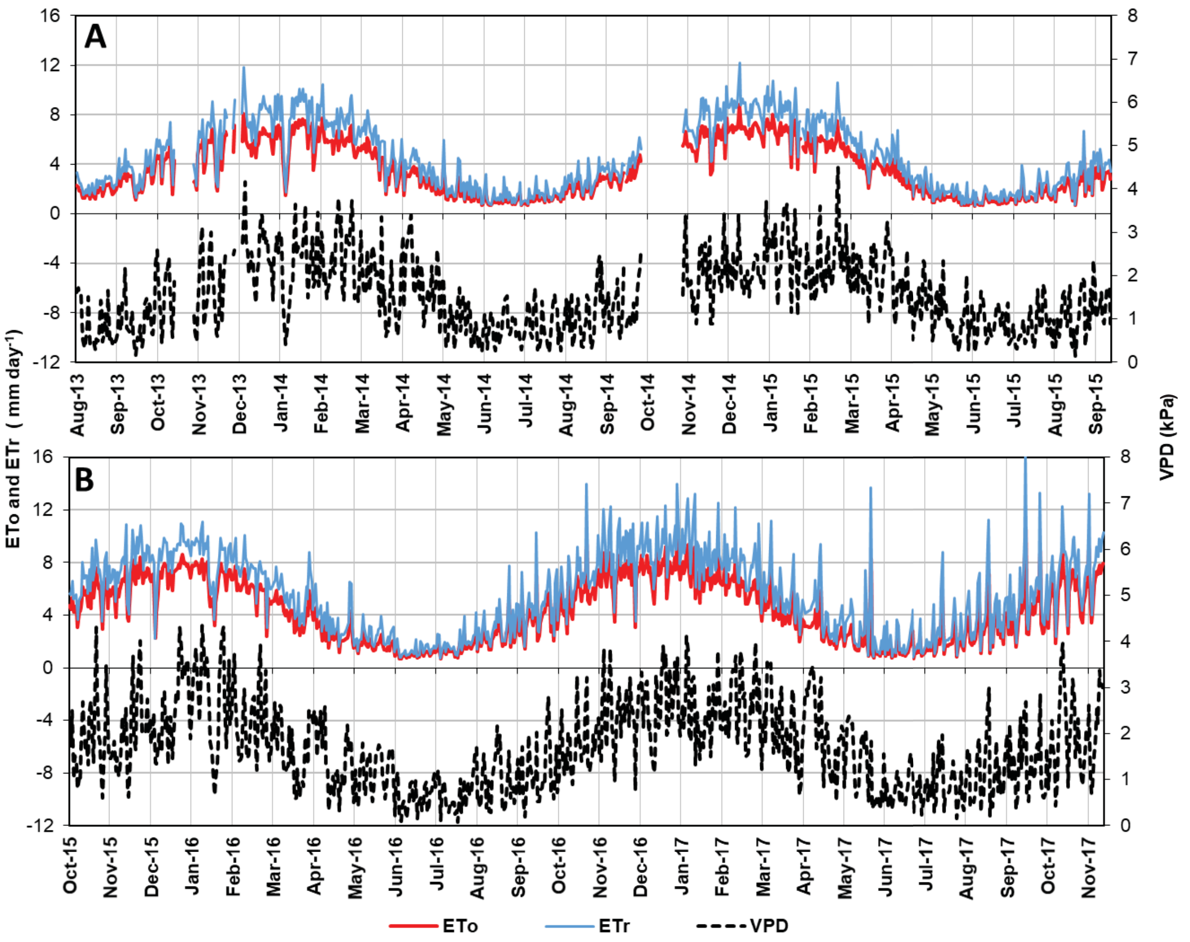


**Figure 4.4 Reference evaporation (short crop – $ET_o$ and tall crop – $ET_r$) and vapour pressure deficit (VPD) at A) Patrysberg and B) Brakfontein weather stations**

## 4.3 Valencia orchards

### 4.3.1 Canopy measurements

In general, throughout the measurement period the canopy volume increased in all measured trees (Figure 4.5). In addition, there were clear differences in canopy sizes between the three orchards. The only exception was for the 2000 'Midknight' Valencias trees, where a decrease in canopy volume was observed, due to heavy pruning in October 2015, after which the canopy volume increased again. Canopy volume for the 2000 'Midknight' Valencias trees ranged between 19.9 and 34.7 $m^3$, with an average of 27.4 $m^3$ and for the 2008 'Midknight' Valencias trees, between 10.8 and 19.0 $m^3$ with an average of 14.8 $m^3$. Over the measurement period no large changes in the canopy volume of the 'McLean' Valencia trees were observed, with the canopy volume ranging between 8.2-10.8 $m^3$, with an average of 9.2 $m^3$.

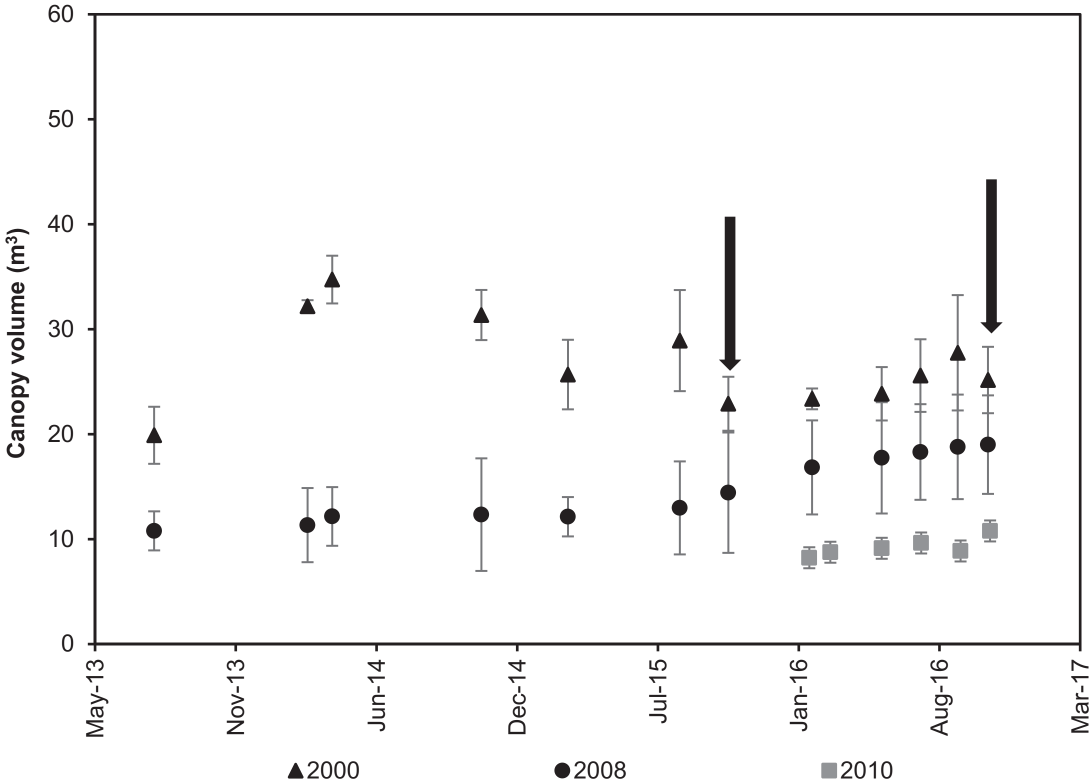


**Figure 4.5 Canopy volume, calculated as an ellipsoid, for three separate Valencia orchards planted in 2000, 2008 and 2010. Each point represents the average of four trees and the error bars the standard deviation. The arrow indicates pruning**

The 'Midknight' Valencia orchard planted in 2000 had a large canopy, with a maximum orchard LAI of 7.0 $m^2$ $m^{-2}$ and a canopy cover of 0.8, as measured on 12 March 2015. Thus, the ground surface was nearly completely covered by the canopy of the trees. This was also evident from field observations that the canopies of adjacent tree rows nearly converged, which may also explain why the measured orchard LAI is slightly higher than the average LAI (6.5 $m^2$ $m^{-2}$) of the four experimental trees. The LAI for the orchard varied between 2.7 and 7.0 $m^2$ $m^{-2}$ during the period 7 March 2014-29 October 2016 (Figure 4.6), with the lowest value recorded in October 2016 after the trees were pruned. The average LAI of the four measured trees followed the same trend as the orchard LAI, with the highest LAI measured (6.6 $m^2$ $m^{-2}$) on 6 November 2014 and the lowest (3.5 $m^2$ $m^{-2}$) measured on 29 October 2016 (Figure 4.6).

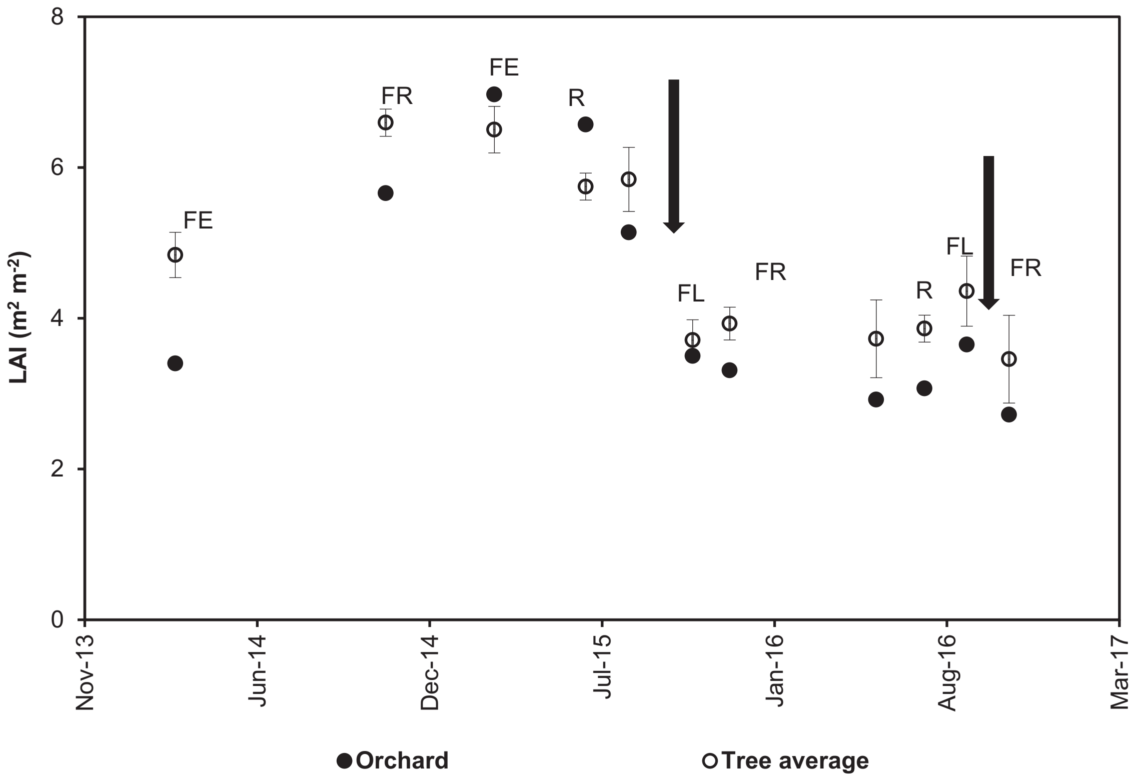


**Figure 4.6 The 2000 'Midknight' Valencias orchard leaf area index (LAI) and the average LAI of the four experimental trees, with error bars indicating the standard deviation. Letters give phenological stages: FE (fruit enlargement) R (ripening period), FL (flowering period) and FR (fruitlets). The arrow indicates pruning**

The orchard LAI for the 2008 'Midknight' Valencia orchard decreased from a maximum (4.1 $m^2\ m^{-2}$) in November 2014 until it reached a minimum (1.8 $m^2\ m^{-2}$) in October 2015, after which the orchard LAI gradually increased again (Figure 4.7). The average LAI for the four experimental trees varied between 3.5 and 5.11 $m^2\ m^{-2}$ over the three-year period of measurements. This indicated significant growth during the season, which was also observed in the measured canopy volumes (Figure 4.5). The decrease in LAI from October 2015 to December 2015 was due to pruning, which was also evident in the 2000 ‘Midknight’ Valencia orchard.

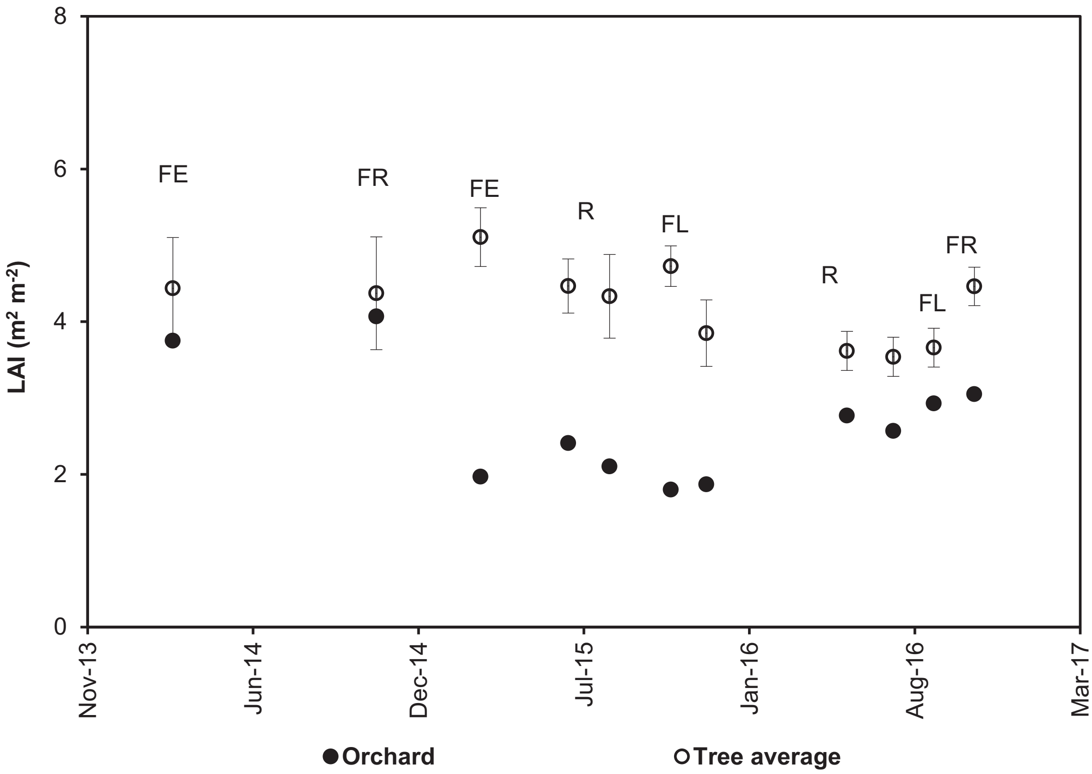


**Figure 4.7 The 2008 'Midknight' Valencia orchard leaf area index (LAI) and the average LAI of the four experimental trees, with error bars indicating the standard deviation. Letters indicate phenological stages: FE (fruit enlargement) R (ripening period), FL (flowering period) and FR (fruitlets)**

The orchard LAI for the 2010 'McLean' Valencia stayed constant during the 2016 season (1.8-2.0 $m^2$ $m^{-2}$), ranging from 0.7-2.0 $m^2$ $m^{-2}$ over the measurement period (28 October 2015-29 October 2016). The LAI of the four measured trees followed the same trend and ranged from 2.6-3.2 $m^2$ $m^{-2}$ (Figure 4.8). From these results it is also evident that the canopies of this orchard were small, with the canopy cover ranging between 0.35 and 0.50.

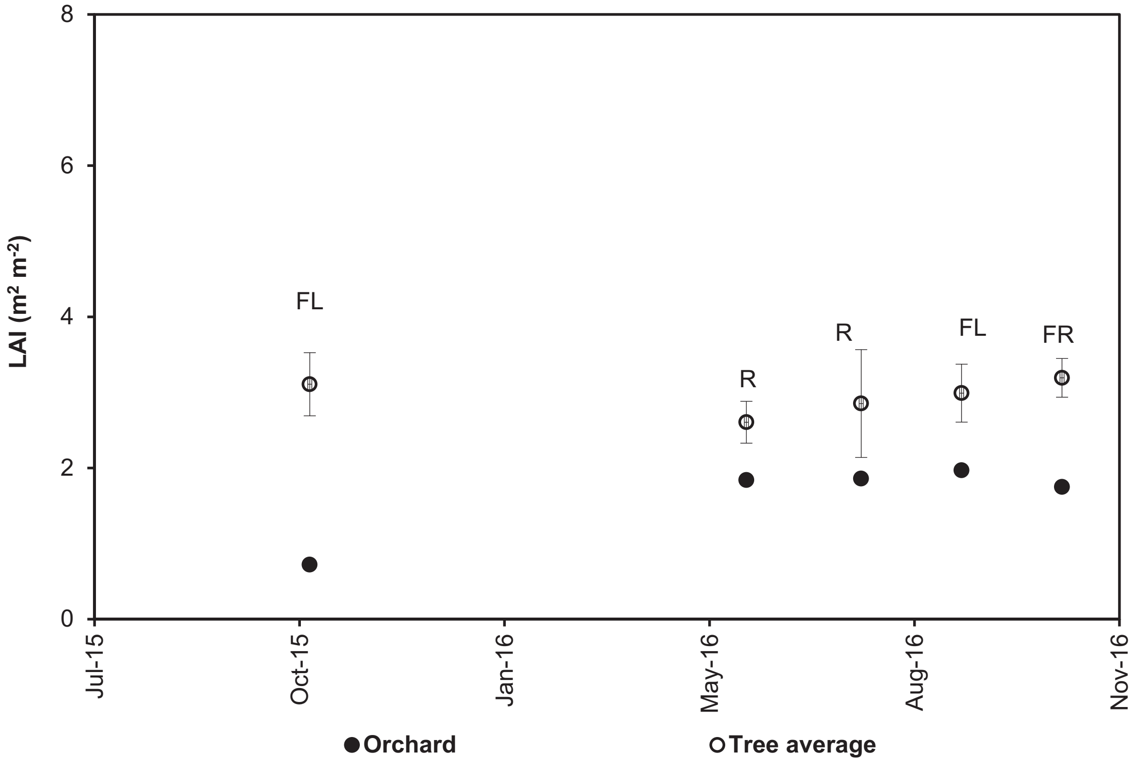


**Figure 4.8 The 2010 'McLean' Valencia orchard leaf area index (LAI) and the average LAI of the four experimental trees, with error bars indicating the standard deviation. Letters give phenological stages: FE (fruit enlargement) R (ripening period), FL (flowering period) and FR (fruitlets)**

### 4.3.2 Transpiration

Transpiration of the 'Midknight' Valencia orchards in the winter rainfall region showed large day-to-day variation, which was largely a result of the prevailing environmental conditions, as seen from the $ET_o$ data (Figure 4.9). The daily trend in T for the Valencia orchards followed canopy size, with the daily T measured in the 2000 'Midknight' Valencia being generally the highest and the lowest transpiration occurring in the 2010 'McLean' Valencia. For the period 2014/16, $ET_o$ ranged between 0.61 mm day$^{-1}$ and 8.85 mm day$^{-1}$. Transpiration in the 2000 'Midknight' Valencia orchard on the days when the maximum and minimum $ET_o$ was measured, was 2.72 mm day$^{-1}$ and 0.81 mm day$^{-1}$ respectively. Transpiration in the 2008 'Midknight' Valencia orchard on the days when the maximum and minimum $ET_o$ was measured, was 2.30 mm day$^{-1}$ and 0.39 mm day$^{-1}$. Despite the differences in canopy sizes (Figure 4.5 and Figure 4.9) the 2000 and 2008 'Midknight' Valencia orchards had similar average T values for the 2016 winter, 1.25 mm day$^{-1}$ (2000 'Midknight' Valencia) and 0.97 mm day$^{-1}$ (2008 'Midknight' Valencia). However, in summer months the 2000 'Midknight' Valencia orchard transpired more water than the 2008 'Midknight' Valencia orchard, i.e. an average of

3.02 and 1.76 mm day$^{-1}$ respectively for the 2015/16 season. Equipment was installed in the 2010 'McLean' Valencia orchard later than the other two orchards. The $ET_o$ for period of measurements in the 'McLean' Valencia orchard ranged between 0.89 mm day$^{-1}$ and 8.84 mm day$^{-1}$. A T value of 0.08 mm day$^{-1}$ was recorded for the day when the lowest $ET_o$ was recorded and 1.21 mm day$^{-1}$ for the maximum $ET_o$. In the summer of 2015/16 season the average water use of the 'McLean' Valencia orchard was 0.68 mm day$^{-1}$, which increased by 55% to an average of 1.05 mm day$^{-1}$ for the 2016/17 season. The increase observed was attributed to an increase in irrigation volumes and an increase in canopy size.

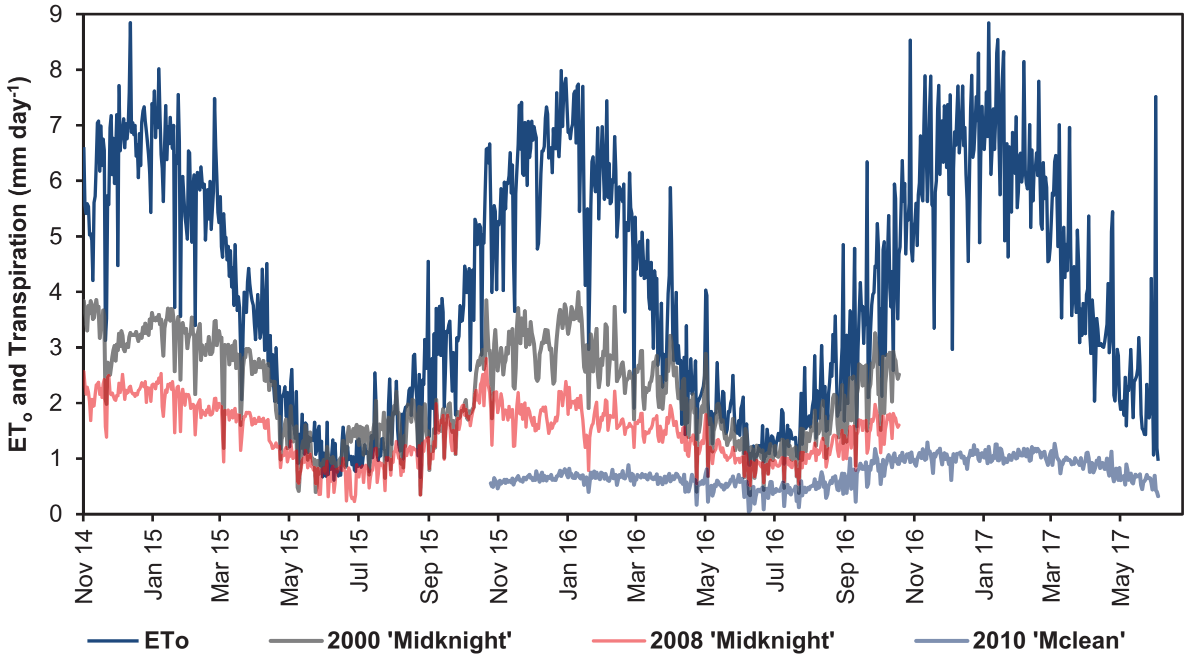


**Figure 4.9 Daily transpiration (mm day$^{-1}$) and reference evapotranspiration ($ET_o$, mm day$^{-1}$) for the 'Midknight' Valencia orchards planted in 2000 and 2008 and 'McLean' Valencia orchard planted in 2010**

Daily $K_t$ values for the 'Midknight' Valencia orchards varied considerably (Figure 4.10). Transpiration crop coefficient values ranged from 0.05-0.61, 0.17-1.21 and 0.22-2.00 for the 2010 'McLean', 2008 and 2000 'Midknight' Valencia orchards. Although daily $K_t$ values varied substantially throughout the season and between the different orchards, a clear seasonal trend was observed (Figure 4.10). Values were typically higher in winter and lower in summer.

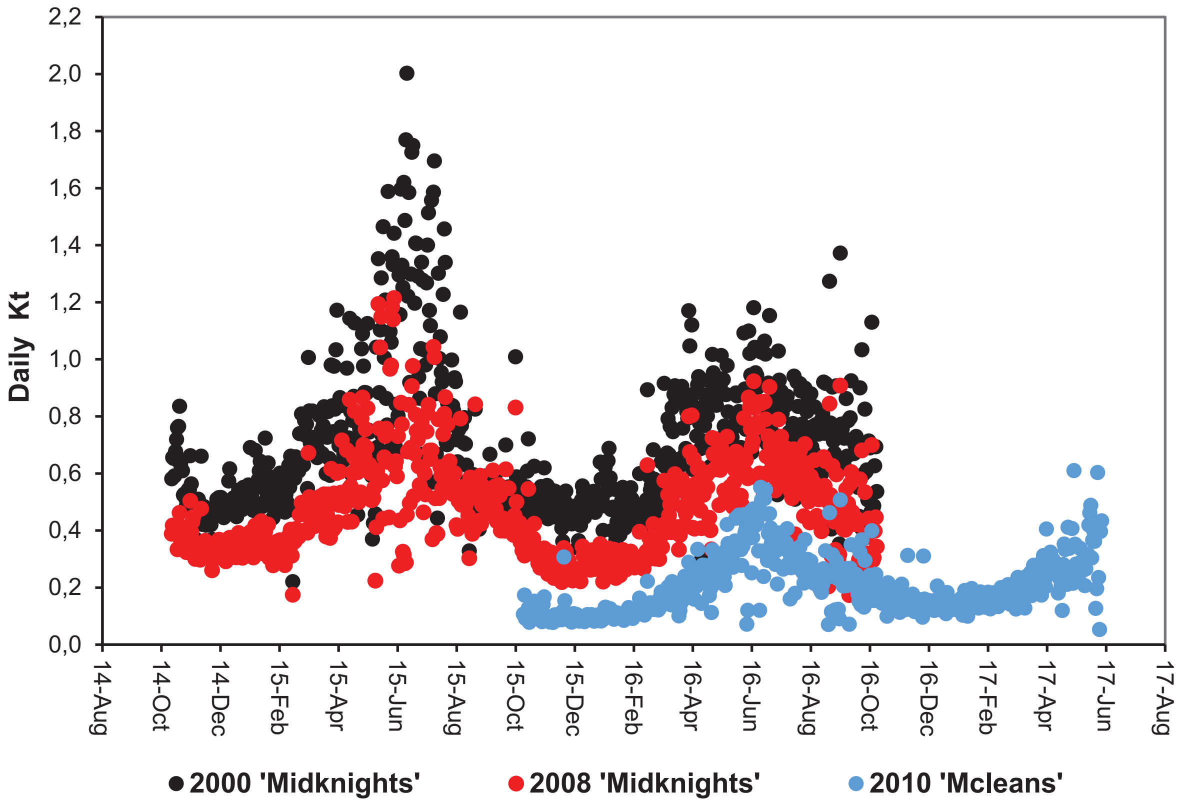


**Figure 4.10 Daily transpiration crop coefficients ($K_t$) for the 'Midknight' Valencia orchards planted in 2000, 2008 and the 'McLean' Valencia orchard planted in 2010**

Average monthly $K_t$ values showed a similar trend between the Valencia orchards (Figure 4.11), which also indicates the proportional relationship between water use and canopy size, when normalised for environmental conditions. In September and October 2015 the same $K_t$ values were recorded for the 'Midknight' Valencia orchards planted in 2010 and 2008. This was a result of heavy pruning in 2000 of the 'Midknight' Valencia orchard that resulted in reduced water use.

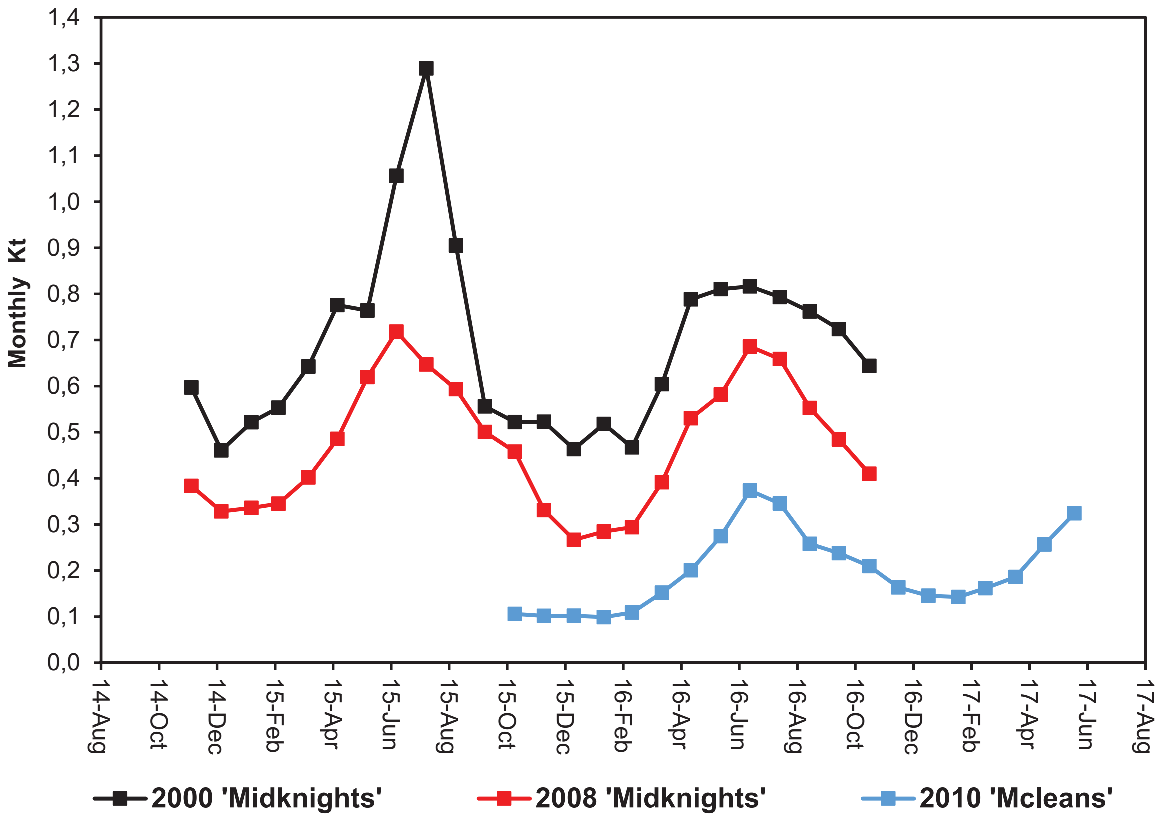


**Figure 4.11 Monthly transpiration coefficients ($K_t$) for the 2010 'McLean' Valencia, 2008 and 2000 'Midknight' Valencia orchards**

Transpiration was measured for 718 days for both the 2000 and the 2008 'Midknight' Valencia orchards and 587 days in the 2010 'McLean' Valencia orchard. Total T recorded for the measurement periods were 1 601, 1 064 and 436 mm respectively in the 2000, 2008 and 2010 Valencia orchards. On average 2.2, 1.5 and 0.7 mm day$^{-1}$ of water were transpired, over the measuring period, in the 2000, 2008 and 2010 Valencia orchards respectively. The annual water use for the 2000 "Midknight" Valencia was 812 mm and 539 mm for the 2008 "Midknight" Valencia for the period 1 January-31 December 2015. For the 2010 'McLean' orchard the annual water use measured was 251 mm for 1 January-31 December 2016 (Table 4.1).

**Table 4.1 Average tree water use for the 2010 'McLean' Valencia orchard and the 2008 and 2000 'Midknight' Valencia orchards**

| | 2000 'Midknight' Valencia | | 2008 'Midknight' Valencia | | 2010 'McLean' Valencia | |
|---|---|---|---|---|---|---|
| **Transpiration** | **mm** | **L tree$^{-1}$** | **mm** | **L tree$^{-1}$** | **mm** | **L tree$^{-1}$** |
| **Total** | 1 601 | 20 014 | 1 064 | 15 959 | 436 | 6 537 |
| **Maximum per day** | 4.0 | 49.9 | 2.8 | 42.0 | 1.3 | 19.4 |
| **Minimum per day** | 0.3 | 4.2 | 0.2 | 3.4 | 0.1 | 0.7 |
| **Average per day** | 2.2 | 27.9 | 1.5 | 22.2 | 0.7 | 11.1 |
| **Annual water use** | 812 | 10 152 | 539 | 8 078 | 251 | 3 765 |
| **Measurement period (days)** | 718 | | 718 | | 588 | |

## 4.4 Navel orchards

### 4.4.1 Canopy measurements

In general, throughout the measuring period the canopy volume increased in all measured trees (Figure 4.12). Canopy volume for the1990 'Bahianinha' navel orchard ranged from 12.7-24.6 m$^3$. Over the measuring period no large changes in the canopy volume were observed for the 2006 'Washington' navel orchard and 2010 'Cambria' navel orchard. The canopy volume for the 2006 'Washington' navel orchard, ranged from 9.8-10.5 m$^3$, with an average of 10.1 m$^3$ and for the 2010 'Cambria' navel orchard the canopy volume ranged from 5.7-6.9 m$^3$, with an average of 6.1 m$^3$.

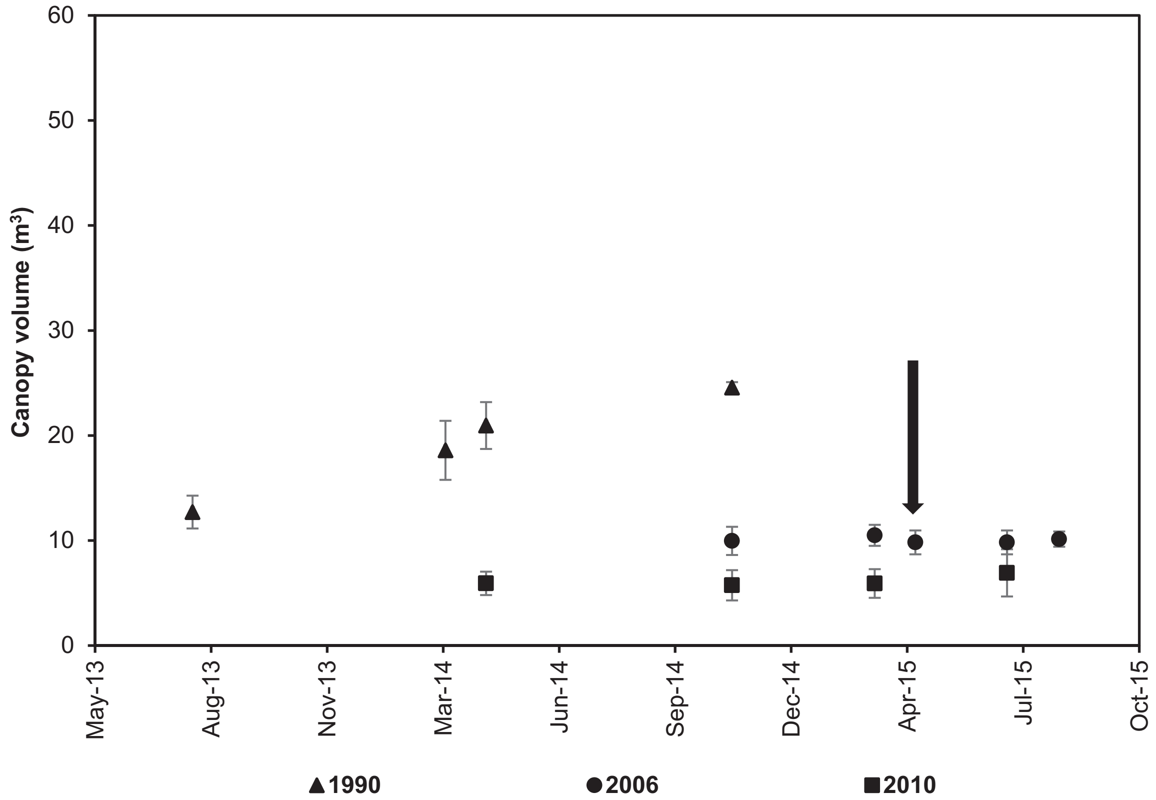


**Figure 4.12 Canopy volume calculated as an ellipsoid for three separate navel orchards planted in 1990, 2006 and 2010. Each point represents the average of 4 trees and the error bars the standard deviation. The arrow indicates pruning**

The LAI for a 'Bahianinha' navel orchard planted in 1990 varied between 3.5 and 4.8 $m^2$ $m^{-2}$ during the period 7 March 2014-06 August 2014 (Figure 4.13), with the lowest value measured at the start of the measuring period. The average LAI of the four measured trees followed the same trend as the orchard LAI, with LAI varying between 3.8 $m^3$ and 4.7 $m^3$ (Figure 4.13).

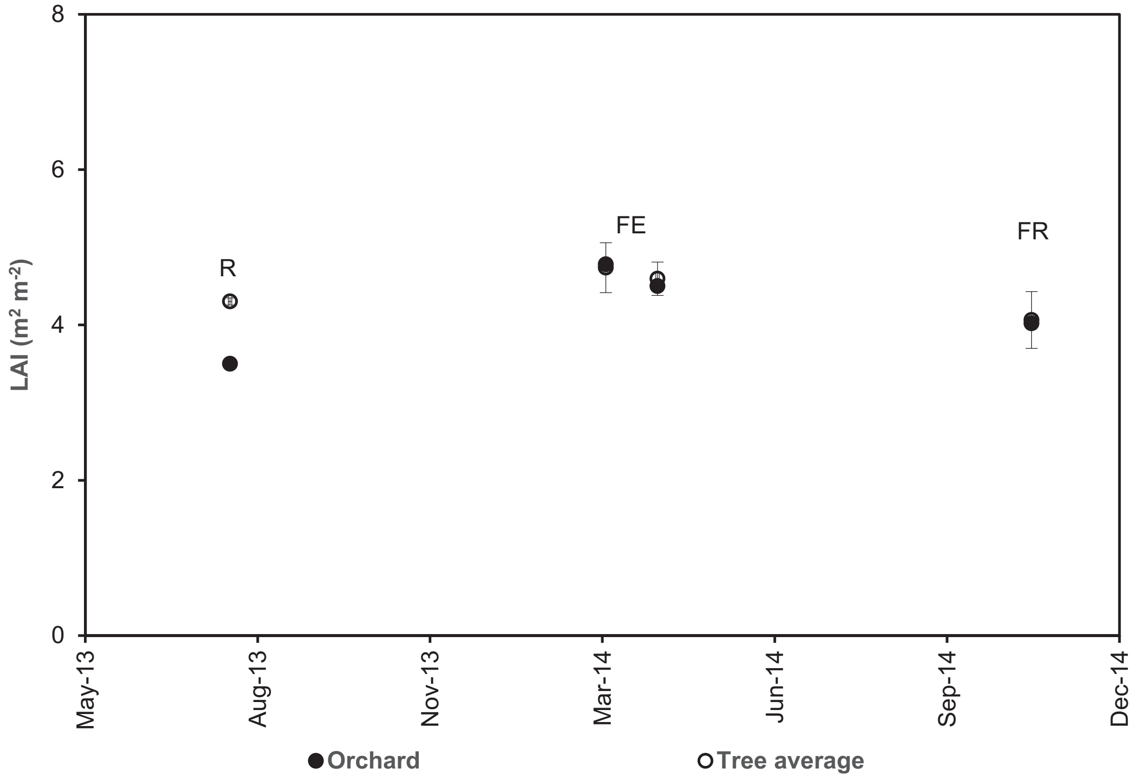


**Figure 4.13 The 1990 'Bahianinha' navel orchard leaf area index (LAI) and the average LAI of the four experimental trees, with error bars indicating the standard deviation. Letters give phenological stages: FE (fruit enlargement) R (ripening period), FL (flowering period) and FR (fruitlets)**

The LAI measurements of the 2006 'Washington' navel are presented in Figure 4.14. Both the LAI of the orchard and average of the measured trees followed the same trend throughout the measuring period. At the start of the measuring period (November 2014) the orchard LAI was 2.7 $m^2$ $m^{-2}$ and 4.0 $m^2$ $m^{-2}$ for the measured trees. The LAI increased, due to summer leaf growth, to a maximum of 3.5 $m^2$ $m^{-2}$ for the orchard LAI and 5.1 $m^2$ $m^{-2}$ for the measured trees, after which it decreased again in April 2014 following pruning (Figure 4.14).

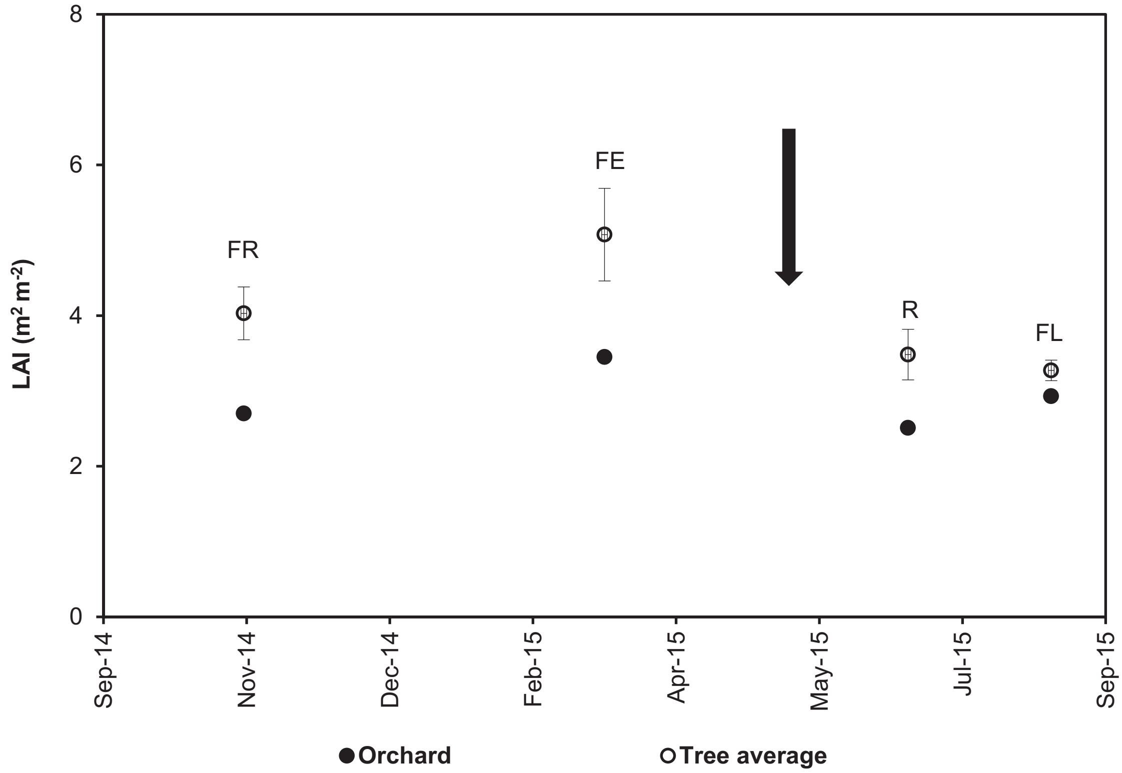


**Figure 4.14 The 2006 'Washington' navel orchard leaf area index (LAI) and the average LAI of the four experimental trees, with error bars indicating the standard deviation. Letters give phenological stages: FE (fruit enlargement) R (ripening period), FL (flowering period) and FR (fruitlets). The arrow indicates pruning**

The LAI measurements of the 2010 ‘Cambria’ navel orchard (Figure 4.15) followed the same trend as the LAI for the 2006 ‘Washington’ navel orchard (Figure 4.14). At the start of the measurement period (November 2014) the orchard LAI was 1.3 $m^2$ $m^{-2}$ and 2.3 $m^2$ $m^{-2}$ for the measured trees. The LAI increased, due to summer leaf growth, to a maximum of 2.9 $m^2$ $m^{-2}$ for the orchard LAI and 3.8 $m^2$ $m^{-2}$ for the measured trees (March 2015), after which it decreased to 2.3 $m^2$ $m^{-2}$ (orchard LAI) and 2.8 $m^2$ $m^{-2}$ (measured trees) at the end of the measuring period following after-harvest pruning (August 2015).

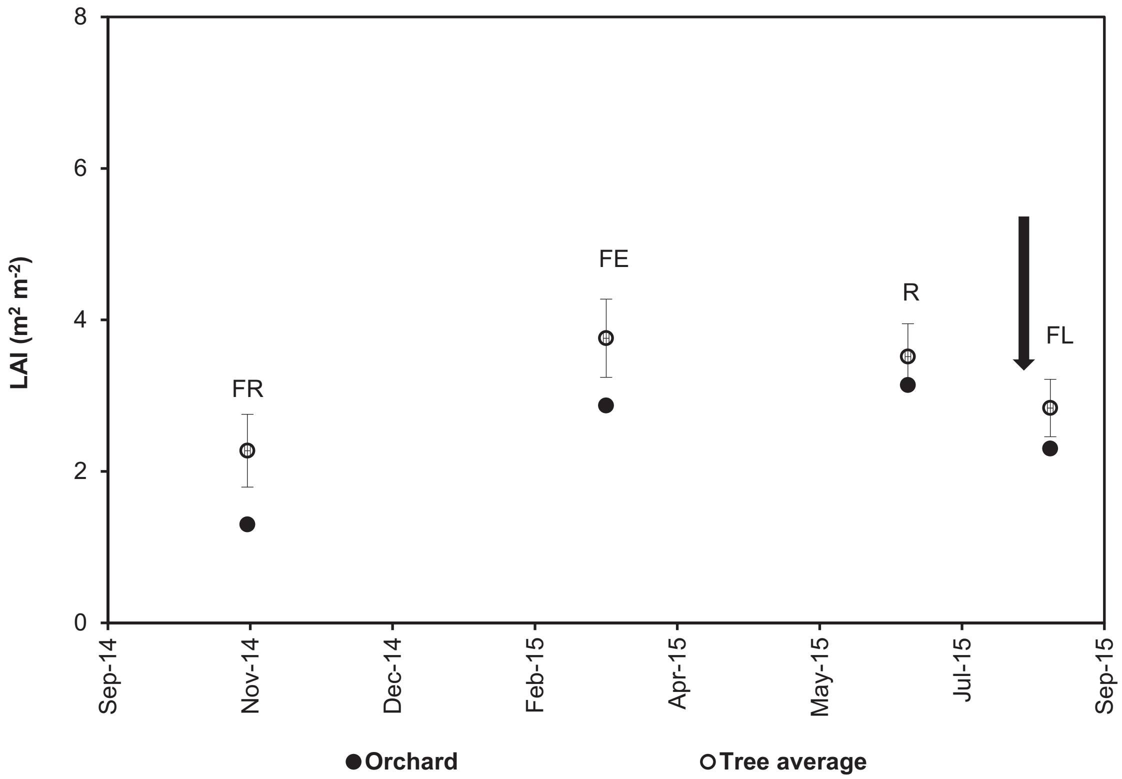


**Figure 4.15 The 2010 'Cambria' navel orchard leaf area index (LAI) and the average LAI of the four experimental trees, with the error bars indicate the standard deviation. Letters give phenological stages: FE (fruit enlargement) R (ripening period), FL (flowering period) and FR (fruitlets). The arrow indicates pruning**

### 4.4.2 Transpiration

Due to equipment problems and gumming of the measured trees in the navel orchards, during the early stages of the project, reliable water use data covers only a period of 9 months in the 'Washington' navels and 4 months in the 'Bahianinha' navels (Figure 4.16). As with the Valencia orchards, T of the navel orchards was very similar to $ET_o$ in winter, whilst values were significantly different in summer. For the 2014/15 season in the 1990 'Bahianinha' navel orchard , $ET_o$ ranged between 0.65 mm day$^{-1}$ and 6.12 mm day$^{-1}$ for the period of measurement and T on the days when the maximum and minimum $ET_o$ observed was 1.70 mm day$^{-1}$ and 0.68 mm day$^{-1}$ respectively. In the 2006 'Washington' navels, $ET_o$ ranged between 0.41 mm day$^{-1}$ and 8.84 mm day$^{-1}$ for the measurement period and T on the days when the maximum and minimum $ET_o$ were observed, was 1.09 mm day$^{-1}$ and 0.12 mm day$^{-1}$ respectively. Also included in Figure 4.16 are short periods of T measurement in 'Cambria' navels when the stem heat balance collars were functioning optimally, as determined through energy balance evaluations. During these measurement windows transpiration varied between 0.06 and 0.54 mm day$^{-1}$.

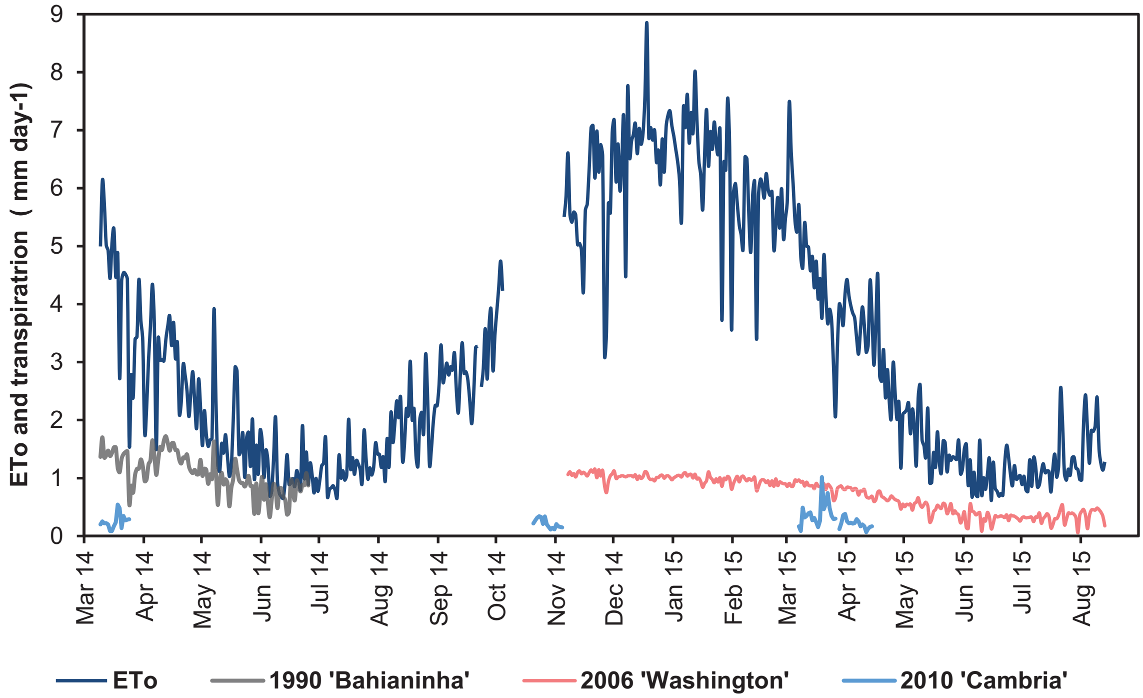


**Figure 4.16 Daily transpiration (mm day$^{-1}$) and reference evapotranspiration ($ET_o$, mm day$^{-1}$) for the 'Bahianinha' navel orchard planted in 1990, the 'Washington' navel orchard planted in 2006 and the 'Cambria' navel orchard planted in 2010**

Daily $K_t$ values for the navel orchards also exhibited significant variation (Figure 4.17 A). Transpiration crop coefficient values ranged from 0.24-1.21 and 0.06-0.57 for the 1990 'Bahianinha' navel orchard and the 2006 'Washington' navel orchard respectively. Average monthly $K_t$ values showed a typical trend like all other citrus orchards (Figure 4.17 B) that indicates a proportional water use to canopy size and higher values in winter than summer.

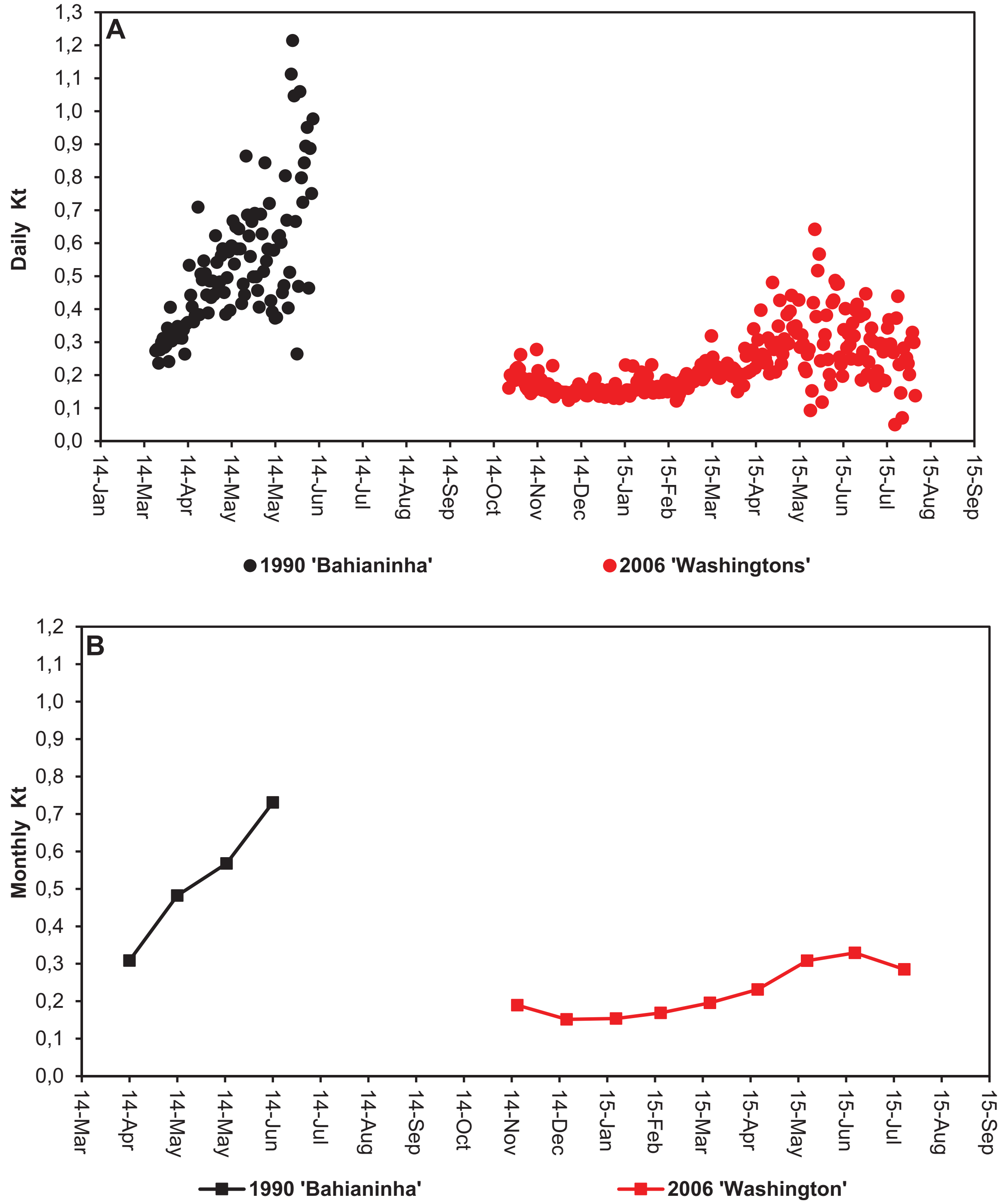


**Figure 4.17 A) Daily and B) monthly transpiration crop coefficients ($K_t$) for the 1990 'Bahianinha' navel and 2006 'Washington' navel orchards**

Transpiration was measured for 109, 280 and 77 days in the 1990 'Bahianinha', 2006 'Washington' and 2010 'Cambria' navel orchards respectively. Total transpiration for the measurement periods were 117, 201 and 20 mm. An average of 1.1, 0.7 and 0.3 mm day$^{-1}$ of water were transpired by the 'Bahianinha', 'Washington' and 'Cambria' navel orchards respectively (Table 4.2).

**Table 4.2 Average tree water use for the 1990 'Bahianinha', 2006 'Washington' and 2010 'Cambria' navel orchards**

| Transpiration | 1990 'Bahianinha' navels | | 2006 'Washington' navels | | 2010 'Cambria' navels | |
|---|---|---|---|---|---|---|
| | mm | L $tree^{-1}$ | mm | L $tree^{-1}$ | mm | L $tree^{-1}$ |
| **Total** | 117 | 1 895 | 201 | 3 009 | 20 | 327 |
| **Maximum per day** | 1.7 | 27.9 | 1.2 | 17.3 | 1.0 | 16.7 |
| **Minimum per day** | 0.3 | 5.3 | 0.1 | 0.9 | 0.1 | 0.8 |
| **Average per day** | 1.1 | 17.4 | 0.7 | 10.7 | 0.3 | 5.0 |
| **Measurement period (days)** | 109 | | 280 | | 77 | |

## 4.5 Mandarin orchards

### 4.5.1 Canopy measurements

A clear change in canopy volume over a season was evident for the 2002 'Afourer' mandarin orchard. Canopy volume increased from its lowest value (20.2 $m^3$) in August 2015 to its highest value (42.2 $m^3$) in May 2016, after which the canopy volume decreased. The decrease in canopy volume, before pruning at the end of July/beginning August (Figure 4.18), is probably due to a large fruit load (Table 3.3) that changed the canopy dimensions, which created the artifice of a smaller canopy volume. During this period the mandarin trees were in full bearing and it was observed from the field visits that large fruit loads resulted in the downwards bending of the branches, which causes width and breadth measurements to be lower. In the case of the smaller 2013 'Afourer' mandarin trees, canopy volume increased gradually from 3.6-12.4 $m^3$ over the measurement period, as the trees started to fill the space allocated to them in the orchard.

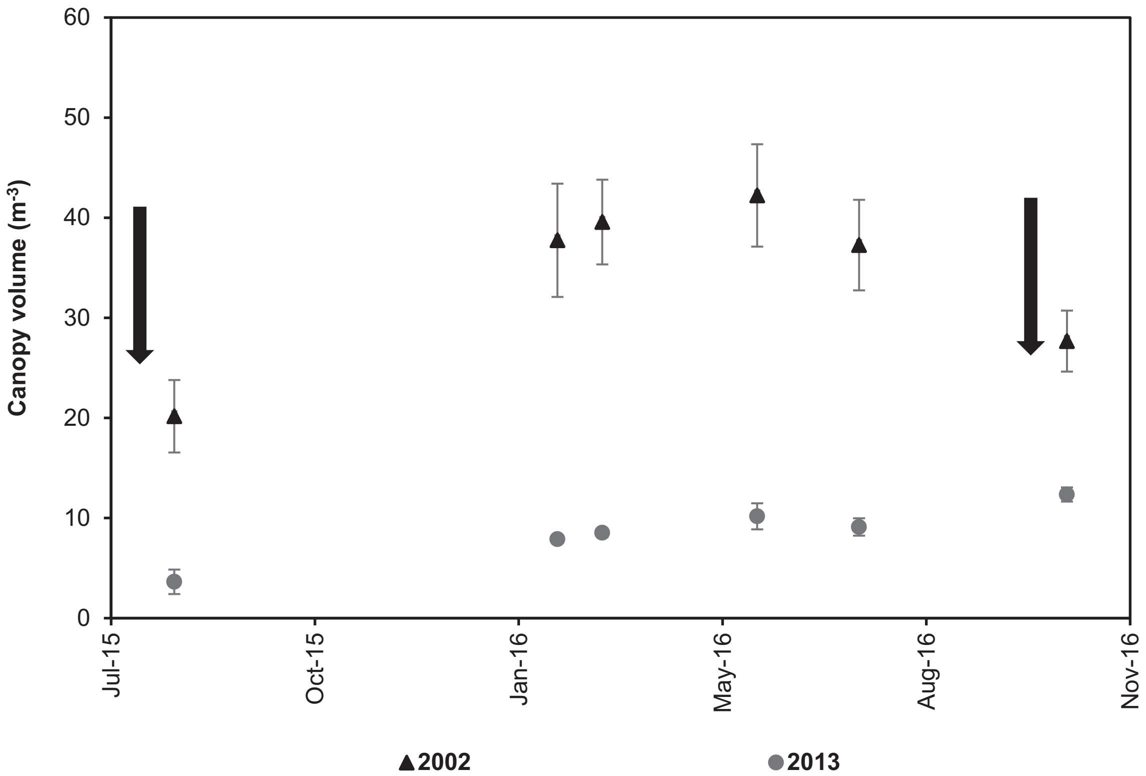


**Figure 4.18 Canopy volume, calculated as an ellipsoid, for the 2002 and 2013 'Afourer' mandarin orchards. Each point represents the average of 4 trees and the error bars the standard deviation. The arrow represents pruning**

The LAI measurements (Figure 4.19) in the 2002 'Afourer' orchard did not follow the trend of the canopy volume over the season. Both the orchard LAI (5.6 $m^2$ $m^{-2}$) and the average LAI of the four measured trees (6.0 $m^2$ $m^{-2}$) began at their highest value, at the start of the measuring period (August 2015) and declined to their lowest value of 2.2 $m^2$ $m^{-2}$, for the orchard LAI and 2.8 $m^2$ $m^{-2}$ for the average LAI of the measured trees near the end of the measurement period. Changes in the canopy structure of the trees were noted when the fruit had sized, as the weight of the fruit caused the branches to bend, thereby opening up the canopy and reducing the LAI of the trees.

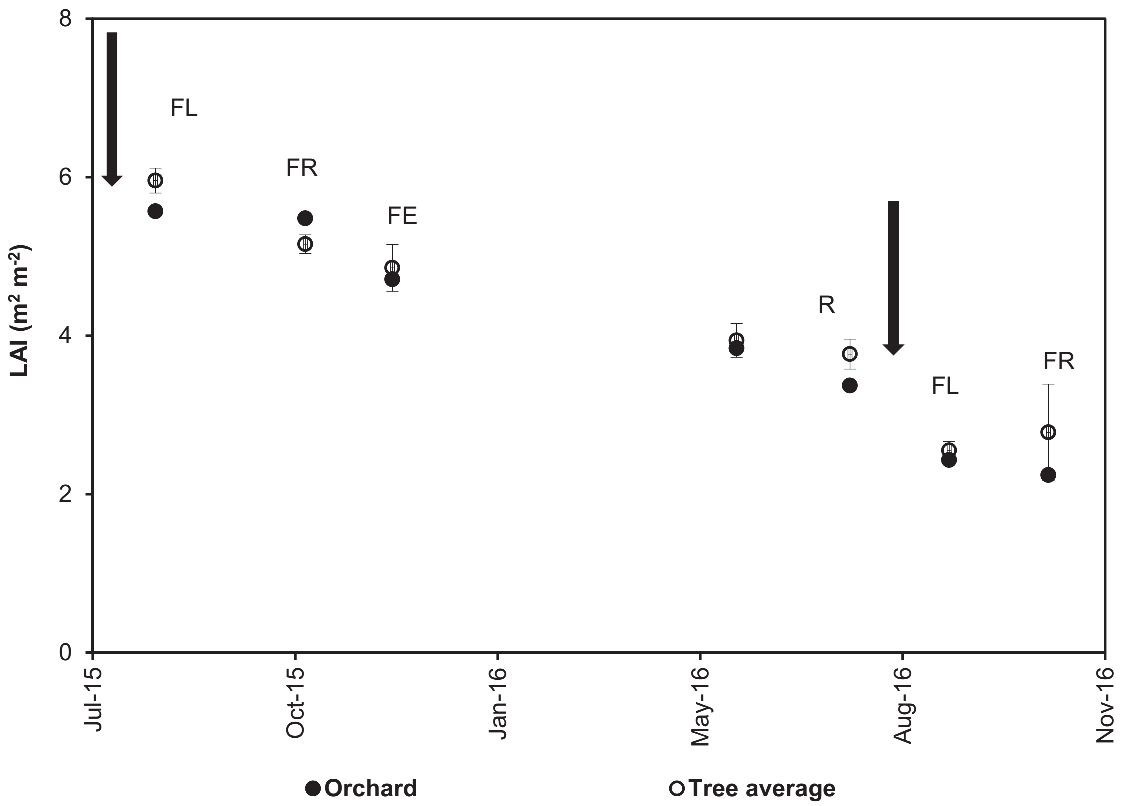


**Figure 4.19 The 2002 'Afourer' mandarin orchard leaf area index (LAI) and the average LAI of the four experimental trees, with error bars indicating the standard deviation. Letters give phenological stages: FE (fruit enlargement) R (ripening period), FL (flowering period) and FR (fruitlets). The arrow indicates pruning**

The canopy LAI and average LAI of the four measured 2013 'Afourer' mandarin trees (Figure 4.20) gradually increased from 0.7 to 1.68 $m^2\ m^{-2}$ for the orchard LAI and from 2.31 to 2.87 $m^2\ m^{-2}$ for the four measured trees over the measurement period from August 2015 to October 2016).

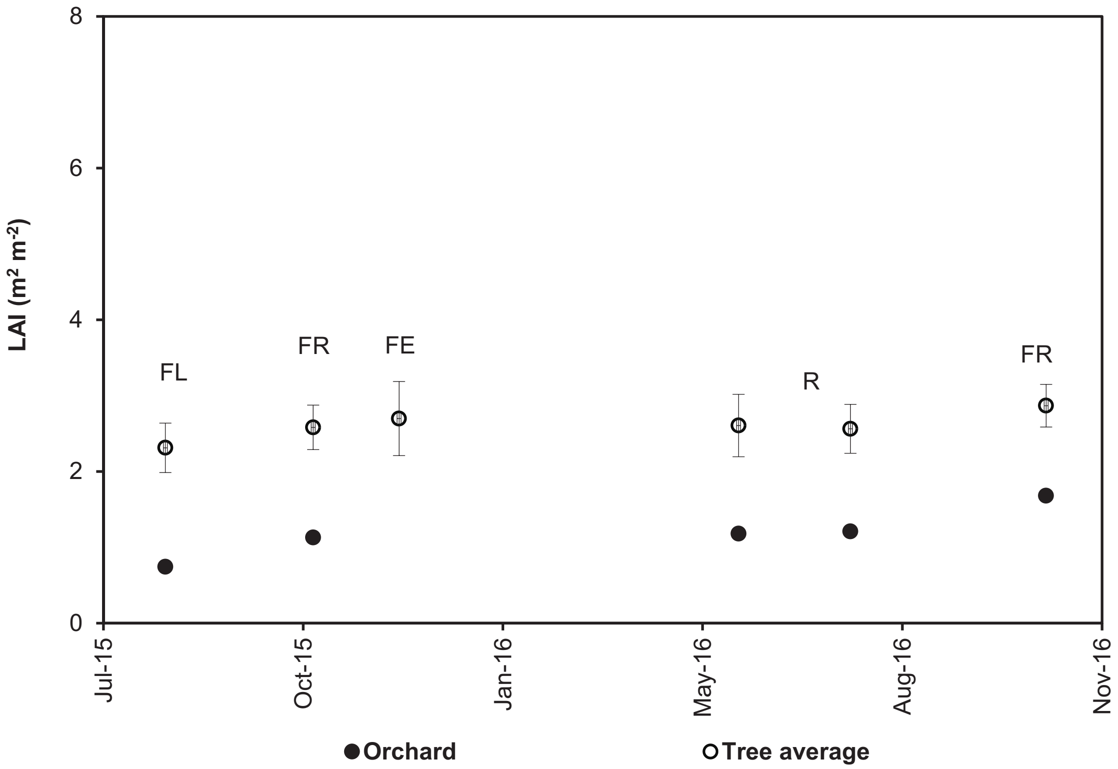


**Figure 4.20 The 2013 'Afourer' mandarin orchard leaf area index (LAI) and the average LAI of the four experimental trees, with error bars indicating the standard deviation. Letters give phenological stages: FE (fruit enlargement) R (ripening period), FL (flowering period) and FR (fruitlets)**

### 4.5.2 Transpiration

Higher daily T was measured in the 2002 ‘Afourer’ mandarin orchard than the 2013 ‘Afourer’ mandarin orchard (Figure 4.21). This is not surprising as the canopy of the 2002 ‘Afourer’ mandarin trees was significantly bigger than the 2013 ‘Afourer’ mandarin trees. For the period 2015-2017, $ET_o$ ranged between 0.66 mm $day^{-1}$ and 9.81 mm $day^{-1}$. Transpiration in the 2002 ‘Afourer’ mandarin followed a typical seasonal trend, with values exceeding or matching $ET_o$ in winter, but being lower than $ET_o$ in summer. The T measured when maximum and minimum $ET_o$ observed was 3.99 mm $day^{-1}$ and 0.41 mm $day^{-1}$ respectively in the 2002 ‘Afourer’ mandarin orchard (Figure 4.21). Although smaller patches of T data were recorded in 2013 ‘Afourer’, it is also evident that T followed a typical seasonal trend with T values ranging from 0.21-2.46 mm $day^{-1}$ (Figure 4.21). Lower T values were recorded during the cooler months (June-September 2017) than the warmer months (March-April and November-December) (Figure 4.3 B).

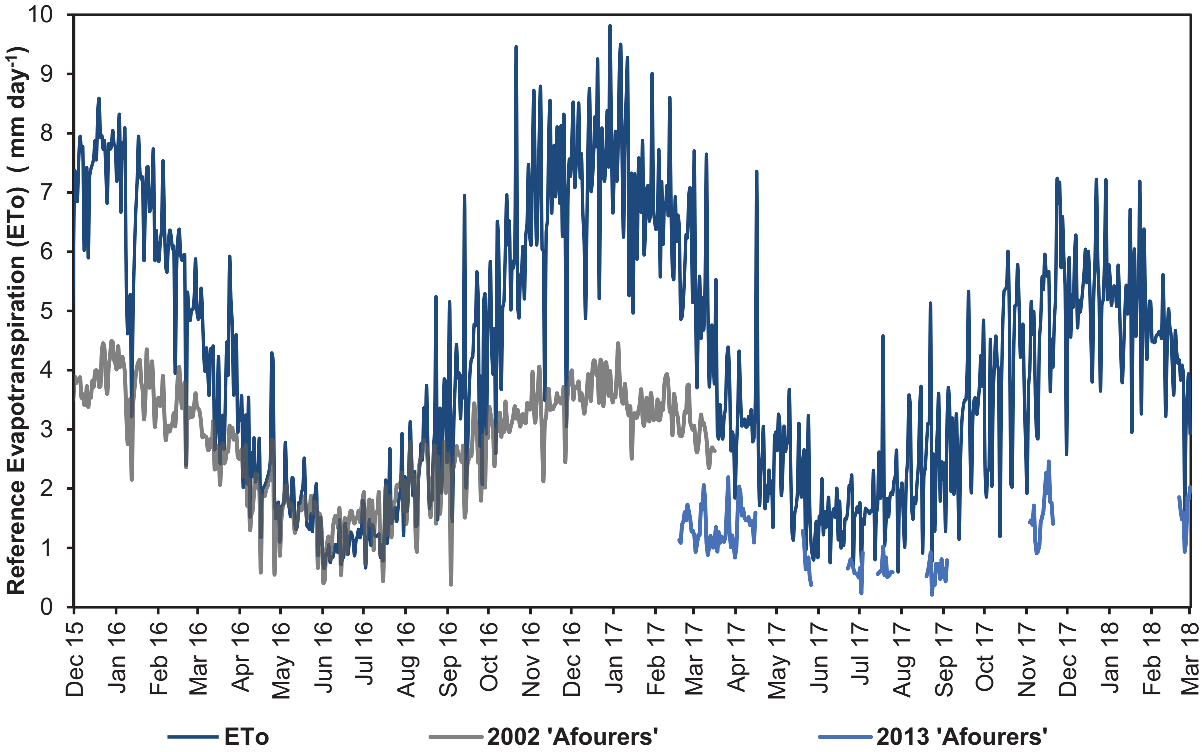


**Figure 4.21 Daily transpiration (mm day$^{-1}$) and reference evapotranspiration ($ET_o$, mm day$^{-1}$) for 'Afourer' mandarin orchards planted in 2002 and 2013**

Daily $K_t$ values also followed a typical seasonal trend with a large day-to-day variation (Figure 4.22 A). Transpiration coefficient values ranged from 0.15-1.63 for the 2002 'Afourer' mandarin. Average monthly $K_t$ values showed a typical seasonal trend like the rest of the citrus orchards measured (Figure 4.22 B).

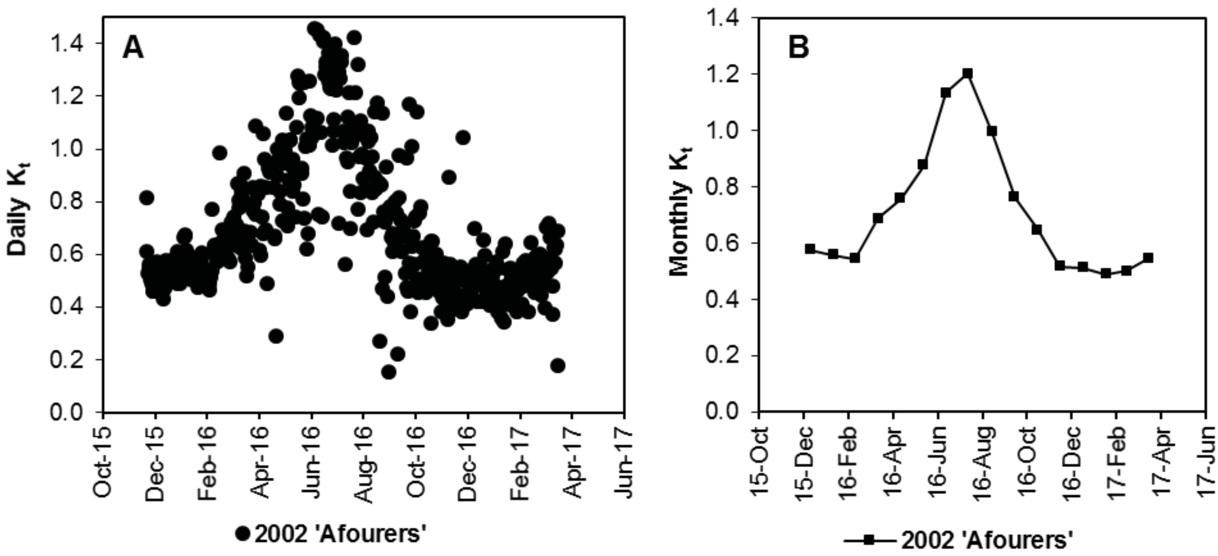


**Figure 4.22 A) Daily and B) monthly transpiration crop coefficients ($K_t$) for the 'Afourer' mandarin orchard planted in 2002**

Transpiration was measured for 475 and 131 days in 2002 and 2013 'Afourer' mandarin orchard respectively. The total T calculated for the 2002 'Afourer' mandarin orchard was 1 325 mm over the measuring period and a total of 150 mm (sum of the different measuring periods) was measured for the 2013 'Afourer' mandarin orchard. On average 2.8 mm $day^{-1}$ and 1.1 mm $day^{-1}$ of water was transpired respectively by the 2002 and 2013 'Afourer' mandarin orchards over the measurement period (Table 4.3). The annual water use measured for the 2002 'Afourer' mandarin orchard was 953 mm for the period 1 January-31 December 2016.

**Table 4.3 Average tree water use for the 2002 and 2013 'Afourer' mandarin orchards**

| Transpiration | 2002 'Afourer' mandarin | | 2013 'Afourer' mandarin | |
|---|---|---|---|---|
| | mm | L $tree^{-1}$ | mm | L $tree^{-1}$ |
| **Total** | 1 325 | 13 248 | 150 | 2 057 |
| **Maximum per day** | 4.5 | 44.9 | 2.5 | 33.8 |
| **Minimum per day** | 0.4 | 3.8 | 0.2 | 2.8 |
| **Average per day** | 2.8 | 27.8 | 1.1 | 15.7 |
| **Annual water use** | 953 | 9 533 | 392* | 5 386* |
| **Measurement period (days)** | 475 | | 131 | |

*Estimated value

## 4.6 Evapotranspiration of the orchards

Evapotranspiration measurements were conducted in four orchards with different canopy sizes in Citrusdal (Table 4.4). In total there were 137 days of ET measurement in Citrusdal, with measurement campaigns in each orchard ranging from 7 days in the 2008 'Midknight' Valencia orchard to 47 days in the 2001 'Bahianinha' orchard. Evapotranspiration in the orchards in Citrusdal exhibited similar trends to the ET in Letsitele (Section 5.5), which was influenced by canopy cover and prevailing environmental conditions. The highest maximum ET rate was observed in the mature 'Afourer' mandarin orchard (Table 4.4), which was expected as this was the orchard with the largest trees. The T fraction of ET was significantly higher in Citrusdal compared to Letsitele. In Citrusdal this value varied between 65% for the 'Washington' navel orchard to 91% in the 'Afourer' Mandarin orchard. This is most likely a result of the sandier soils and drip irrigation in these orchards, resulting in lower evaporation rates from the soil. What is also evident in a comparison with conditions in Letsitele, is that Citrusdal is considerably hotter and drier than Letsitele, as seen in the higher maximum $ET_o$ values in Citrusdal.

In general, there were linear relationships between ET and $ET_o$ in the orchards in Citrusdal, although the relationships did not always yield very good $R^2$ values (data not shown). The dependence of ET on canopy size is clearly seen in Figure 4.23. The slightly different slopes of the relationship between ET and $ET_o$ reflects differences in $K_c$ between orchards, which occur largely as a result of differences in canopy size.

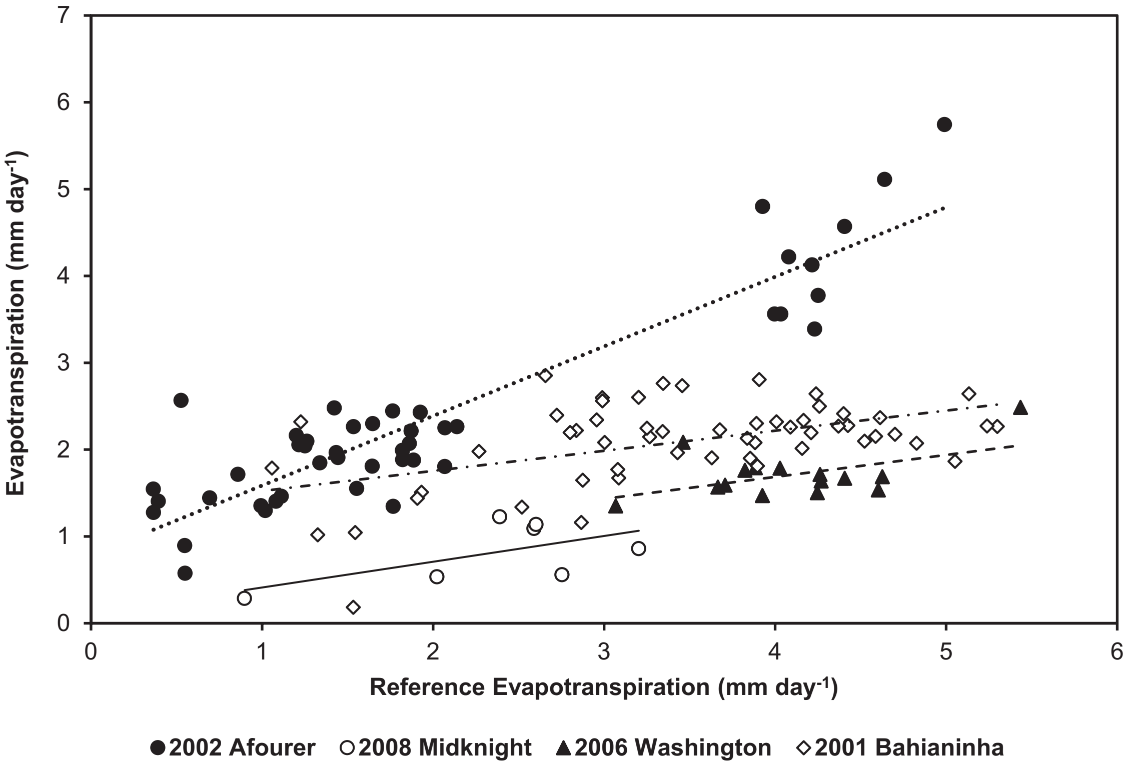


**Figure 4.23 Comparison of evapotranspiration determined using the eddy covariance technique in citrus orchards in Citrusdal**

**Table 4.4 Summary of evapotranspiration (ET), reference evapotranspiration ($ET_o$) and transpiration (T) measurements in the orchards in Citrusdal. Number of measurement days is given in brackets**

| Orchard | Measurement duration (no. of days) | Variable | Maximum (mm day$^{-1}$) | Minimum (mm day$^{-1}$) | Average (mm day$^{-1}$) | Average T fraction of ET |
|---|---|---|---|---|---|---|
| Bahianinha Navel 2001 | 12-25 Nov 2013 (14) 5 March-20 April 2014 (47) | $ET_o$ | 6.12 | 1.33 | 3.82 | – |
| | | ET | 2.77 | 1.02 | 2.08 | |
| | | T | -* | - | - | |
| Washington Navel 2006 | 3-17 March 2015 (15) | $ET_o$ | 5.43 | 3.07 | 4.09 | 65% |
| | | ET | 2.76 | 1.15 | 1.57 | |
| | | T | 1.06 | 0.88 | 0.97 | |
| Midknight Valencias 2008 | 14-27 April 2015 (10) | $ET_o$ | 4.49 | 2.06 | 2.93 | 75% |
| | | ET | 1.93 | 0.54 | 1.14 | |
| | | T | 1.46 | 0.91 | 1.07 | |
| Afourer Mandarin 2002 | 8-17 March (10), 27 May-20 June (25), 6-21 July (17), all 2016 | $ET_o$ | 5.88 | 0.66 | 2.06 | 91% |
| | | ET | 5.57 | 0.20 | 2.10 | |
| | | T | 3.61 | 0.41 | 1.79 | |

*No transpiration data was recorded in this orchard due to heater probe corrosion

## 4.7 Transpiration response to climatic variables

The response of T of all six citrus orchards (three Valencia orchards, two navel orchards and one mandarin orchard) in the winter rainfall region to weather variables ($ET_o$, average daily VPD, total $R_s$ and average daily temperature) is given in Figure 4.24, Figure 4.25 and Figure 4.26. The response of T to increases in $R_s$ was linear in all the orchards, except for the 'McLean' orchard, where the rate of increase in T tended to decline as $R_s$ increased above 20 MJ $m^{-2}$ $day^{-1}$. More than 70% of the variation in T was explained by changes in $R_s$ in the citrus orchards, except for the 'McLean' orchard. A second order polynomial relationship was observed for the response of T to $ET_o$ and VPD. Transpiration increased with VPD up to a certain point, with no further increase in transpiration once VPD exceeded 1.5-2.0 kPa. A similar response was observed for $ET_o$ and no further increase in transpiration was observed when atmospheric demand exceeded approximately 5 to 6 mm.

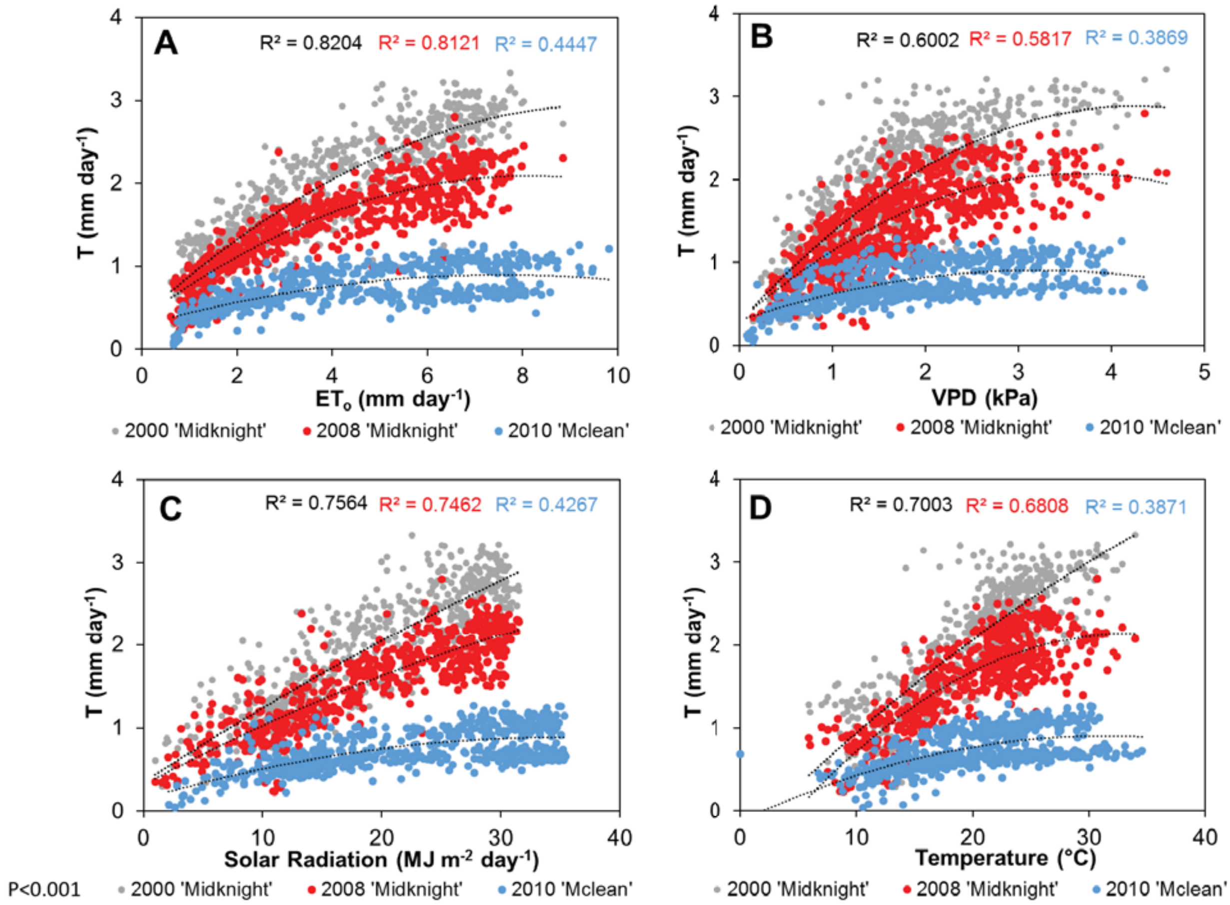


**Figure 4.24 Typical response of daily transpiration (T) of the different Valencia orchards in a winter rainfall region to daily A) total reference evapotranspiration ($ET_o$), B) average vapour pressure deficit (VPD), C) total solar radiation and D) average temperature ($P < 0.001$)**

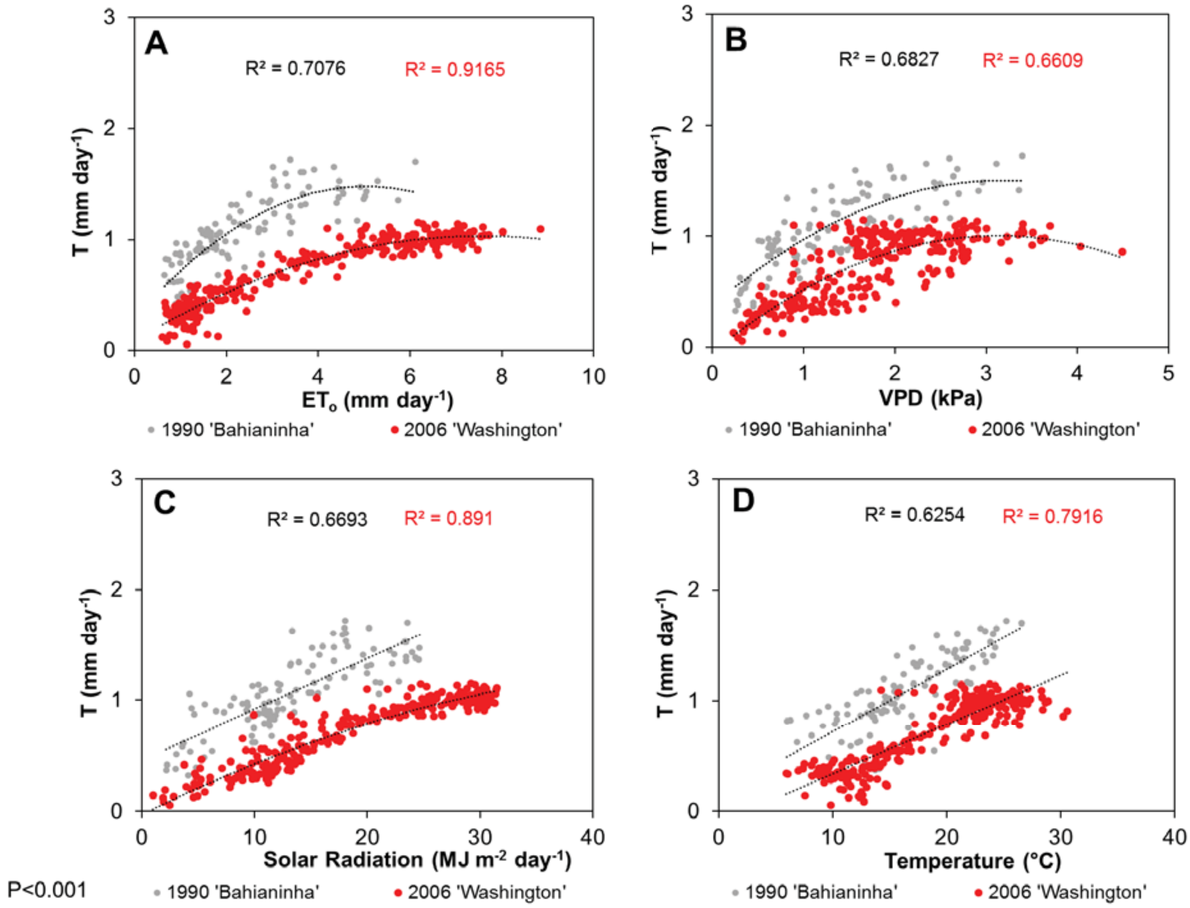


**Figure 4.25 Typical response of daily transpiration (T) of different navel orchards in a winter rainfall region to average A) total reference evapotranspiration ($ET_o$), B) average vapour pressure deficit (VPD), C) total solar radiation and D) average temperature ($P < 0.001$)**

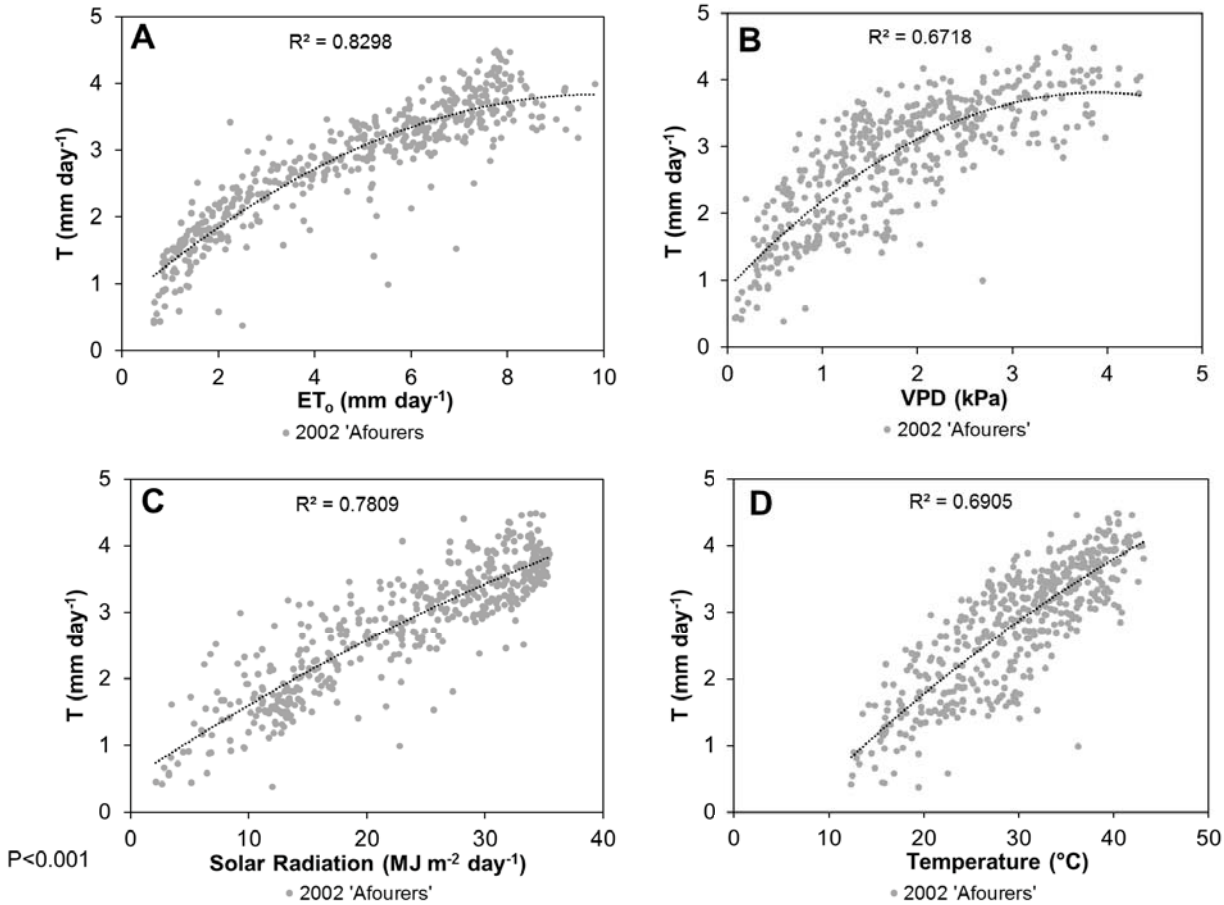


**Figure 4.26 Typical response of daily transpiration (T) of the 2002 'Afourer' mandarin orchard in a winter rainfall region to average A) total reference evapotranspiration ($ET_o$), B) average vapour pressure deficit (VPD), C) total solar radiation and D) average temperature ($P < 0.001$)**

# 5 RESULTS – SUMMER RAINFALL REGION

## 5.1 Weather variables

Weather data for the field trials in the Letsitele region were obtained from two weather stations that are operated and maintained by QMS Laboratories. These weather stations are located at Letsitele junction and Constantia and their relative positions to the different field sites are given in Figure 3.7. The weather station at the Letsitele junction was the closest to the field trials, and data is presented for the period 20 November 2015-25 May 2018 in Figure 5.1 (A and B). The lowest temperature measured, at the two locations, was 0°C, whilst the maximum was 42.1°C (Figure 5.1). There were only three days above 40°C and no days under 0°C, indicating a less extreme environment than Citrusdal. Mild summers and winters were experienced in this region, with an average $T_a$ of 25.3°C in summer and 18.8°C in winter. The total rainfall measured for the period 1 December 2015-25 May 2018 was 1 085 mm.

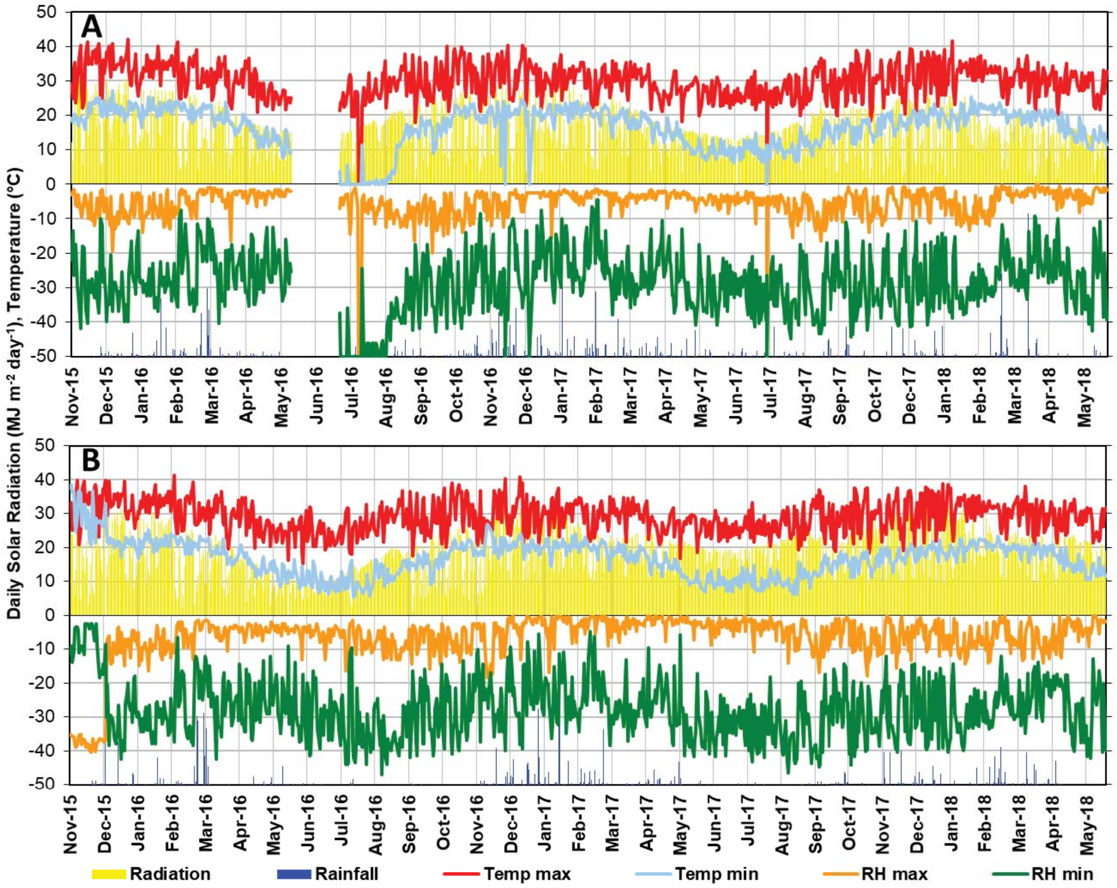


**Figure 5.1 Daily values of maximum and minimum temperatures (°C), solar radiation (MJ.m$^{-2}$.day$^{-1}$), rainfall (mm), and maximum and minimum humidity (%) at A) Constantia and B) Letsitele weather stations. Data was collected from 20 November 2015-25 May 2018**

A clear seasonal trend existed for VPD, $ET_o$ and $ET_r$, with the lowest values measured in winter and the highest in summer (Figure 5.2). Some weather information from the Letsitele AWS for the measuring period, 1 December 2015-5 May 2018 is as follows: the average daily VPD for the summer seasons was 1.51 kPa, with a daily maximum of 3.27 kPa. The average VPD for the winter seasons was 1.20 kPa, with a daily minimum of 0.24 kPa. The average $ET_o$ for the summer seasons was 4.37 mm (4.71 for $ET_r$), with a daily maximum of 6.79 mm (7.60 for $ET_r$), while the average $ET_o$ for the winter seasons was 2.08 mm (2.50 for $ET_r$), with a daily minimum of 0.75 mm (0.80 for $ET_r$).

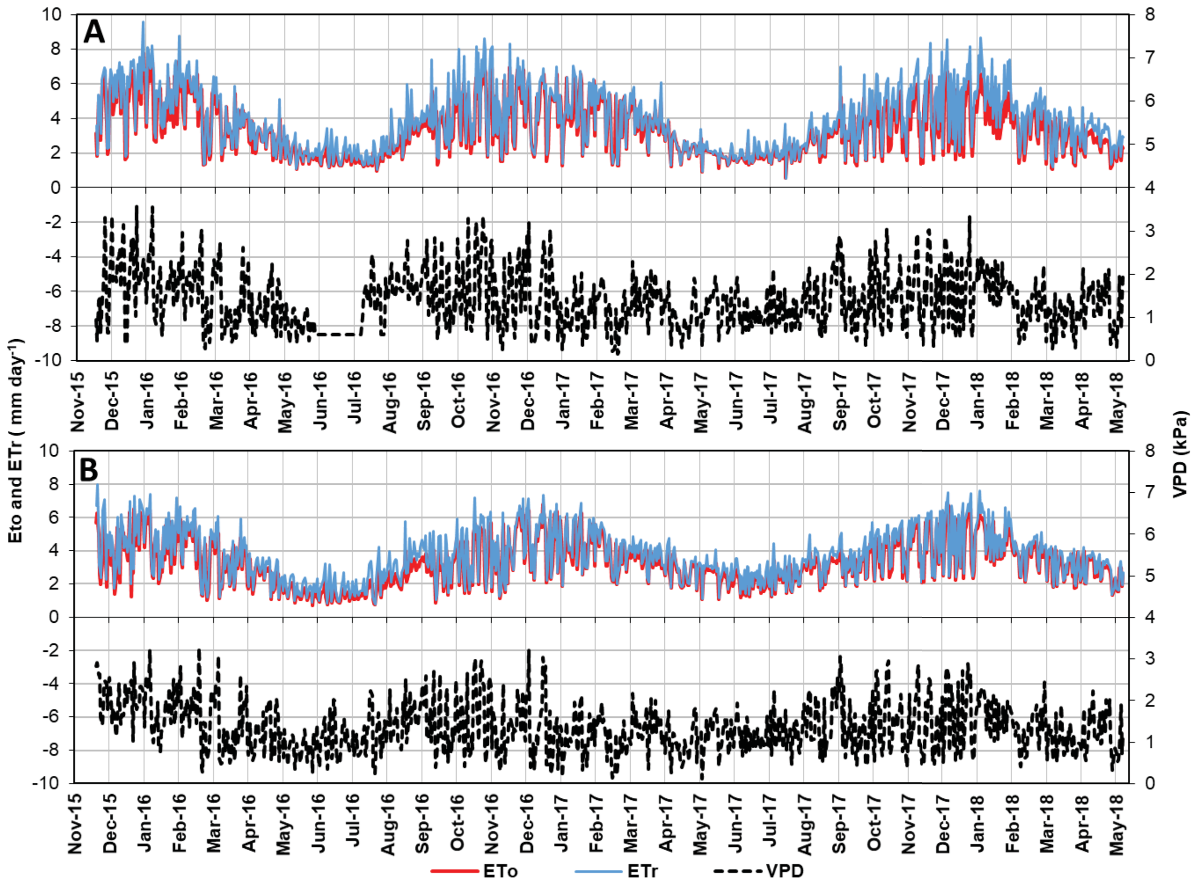


**Figure 5.2 Reference evaporation (short crop – $ET_o$ and tall crop – $ET_r$) and vapour pressure deficit (VPD) at A) Constantia and B) Letsitele weather stations**

## 5.2 Grapefruit orchards

### 5.2.1 Canopy measurements

The canopy volumes of all three 'Star Ruby' grapefruit orchards (planted in 2006, 2010 and 2011) gradually increased over the measuring period (April 2016-May 2017). For the 2006 'Star Ruby' grapefruit trees the canopy volume increased from 40.0-52.4 $m^3$ and for the 2010 planting from 25.9-43.4 $m^3$ and for the 2011 planting from 12.3-21.0 $m^3$. Light pruning was conducted in all three 'Star Ruby' grapefruit orchards at the end of June 2016, as evident in the less than 1.5% reduction in the canopy volumes at this time (Figure 5.3).

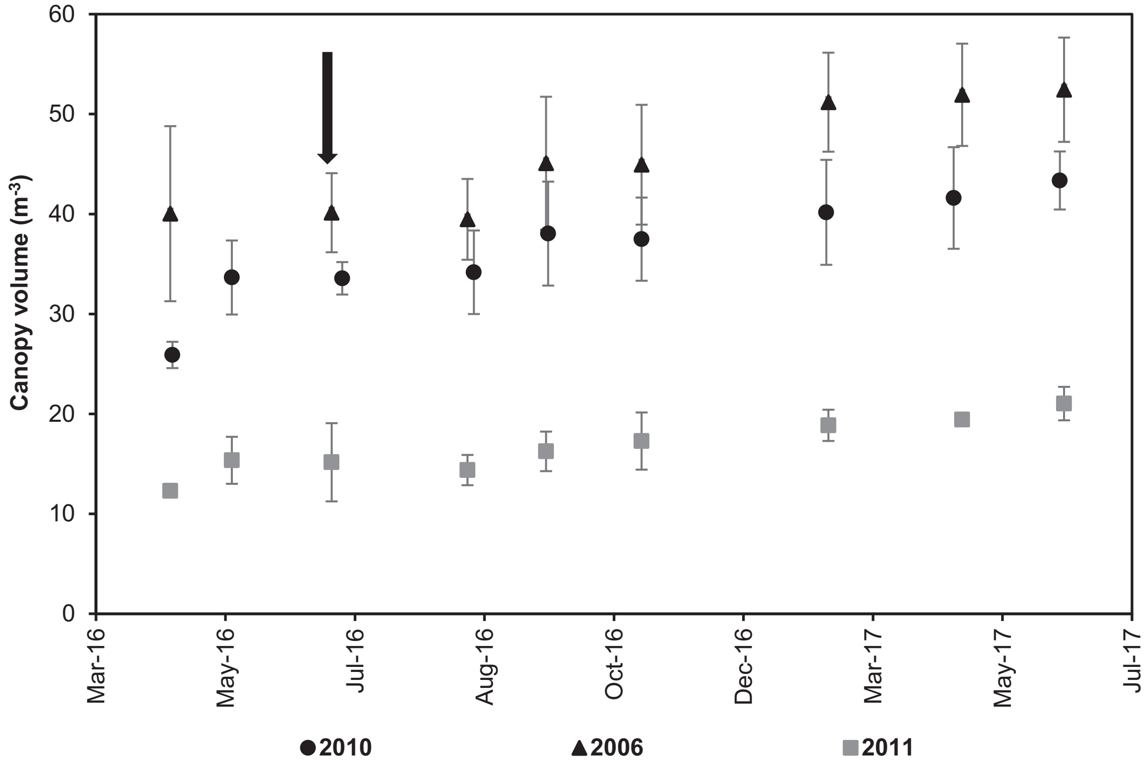


**Figure 5.3 Canopy volume, calculated as an ellipsoid, for the 2006, 2010 and 2011 'Star Ruby' grapefruit orchards. Each point represents the average of four trees and error bars the standard deviation. The arrow indicates pruning**

The average LAI of the four 2006 'Star Ruby' grapefruit measurement trees was 6.3 $m^2$ $m^{-2}$ at the start of the measurements (Figure 5.4) and decreased to 4.6 $m^2$ $m^{-2}$ following pruning at the end of June 2016. It stayed relatively constant for the remainder of the trial, with an average LAI of 4.6 $m^2$ $m^{-2}$. The orchard LAI followed a very similar trend to the average tree LAI and was on average 3.4 $m^2$ $m^{-2}$.

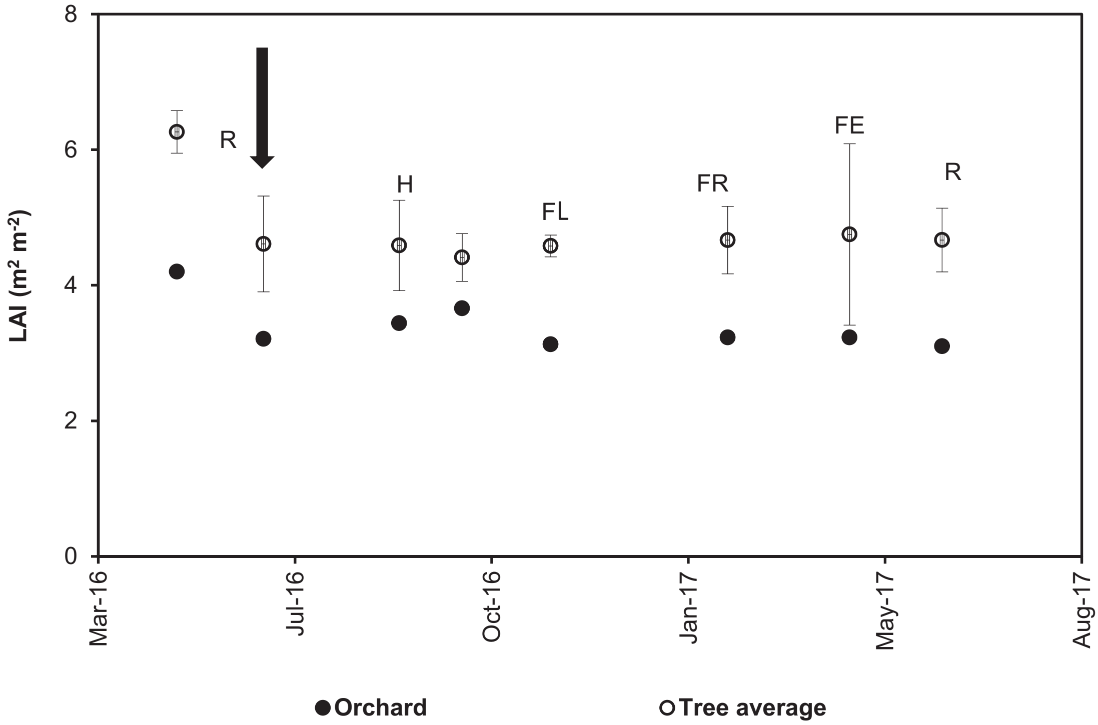


**Figure 5.4 The 2006 'Star Ruby' grapefruit orchard leaf area index (LAI) and the average LAI of the four experimental trees, with error bars indicating the standard deviation. Letters give phenological stages: FE (fruit enlargement) R (ripening period), FL (flowering period), FR (fruitlets) and H (harvesting). The arrow indicates pruning**

The LAI measurements in the 2010 'Star Ruby' grapefruit orchard gradually increased from a minimum value of 4.7 $m^2$ $m^{-2}$ at the beginning of the measurement period in April 2016 to a maximum average value of 6.3 $m^2$ $m^{-2}$ (orchard LAI of 3.1 $m^2$ $m^{-2}$) in May 2017 (Figure 5.5). Both the orchard LAI and the average LAI of the four measured trees showed the same trend during the trial.

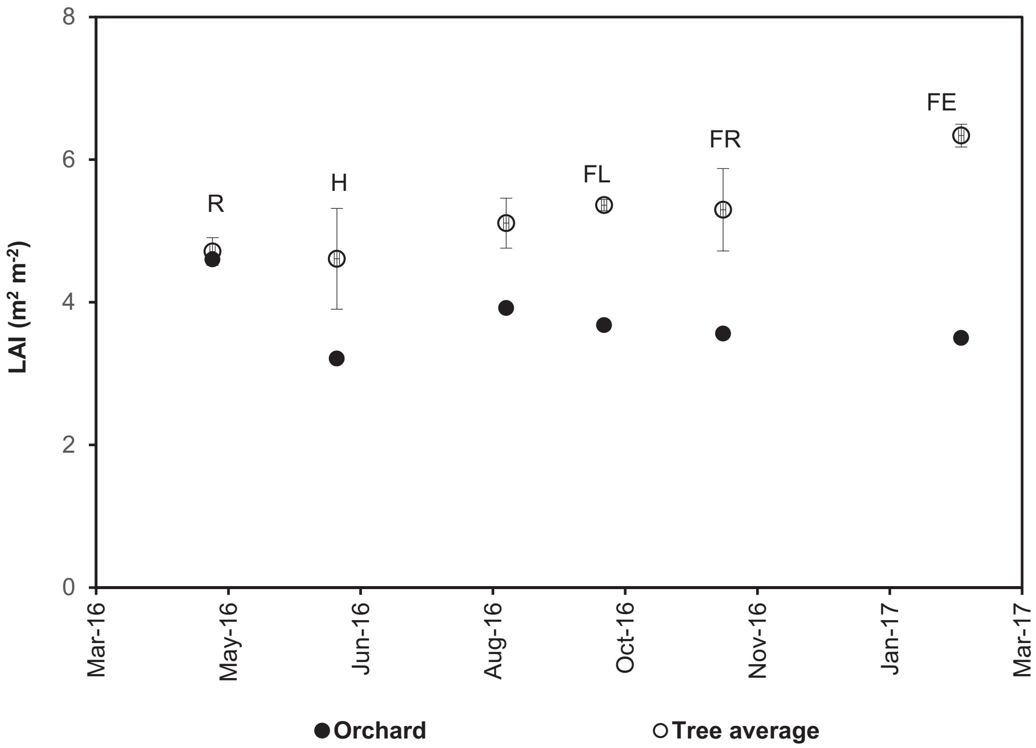


**Figure 5.5 The 2010 'Star Ruby' orchard leaf area index (LAI) and the average LAI of the four experimental trees, with error bars indicating the standard deviation. Letters give phenological stages: FE (fruit enlargement) R (ripening period), FL (flowering period), FR (fruitlets) and H (harvesting)**

The average LAI of the four 2011 'Star Ruby' grapefruit measurement trees increased from a minimum, 4.1 $m^2$ $m^{-2}$, at the start of the trial in April 2016 until it reached a maximum (5.3 $m^2$ $m^{-2}$) in February 2017, after which the orchard LAI gradually decreased again (Figure 5.6). The decline in LAI was because of measurement errors, since the decline in the canopy size was not consistent with any of the other canopy size measurement variables (i.e. the canopy volume and fraction of intercepted PAR). Overall, the four experimental trees experienced significant growth during the season, which was also observed in the measured canopy volumes.

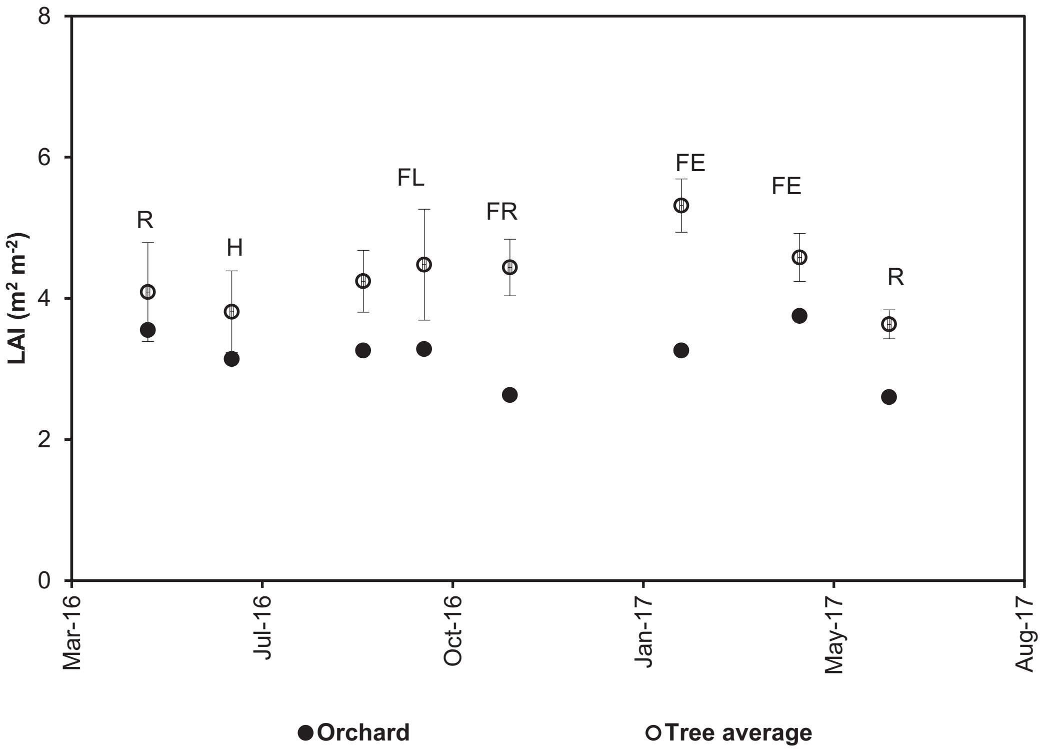


**Figure 5.6 The 2011 'Star Ruby' grapefruit orchard leaf area index (LAI) and the average LAI of the four experimental trees, with error bars indicating the standard deviation. Letters give phenological stages: FE (fruit enlargement) R (ripening period), FL (flowering period), FR (fruitlets) and H (harvesting)**

### 5.2.2 Transpiration

Transpiration in all orchards showed large day-to-day variation, which was largely a result of the prevailing environmental conditions, as seen from the $ET_o$ data (Figure 5.7). The $ET_o$, calculated from weather data from the Constantia AWS, during the study period ranged between 0.54 mm day$^{-1}$ ($ET_r$ 0.54 mm day$^{-1}$) and 7.01 mm day$^{-1}$ ($ET_r$ 8.66 mm day$^{-1}$). Transpiration was consistently lower than $ET_o$ for all three orchards, but did show a consistent response to changes in $ET_o$, especially at very low values. The daily trend in T for the 'Star Ruby' grapefruit orchards followed canopy size, with the daily T measured in the 2006 'Star Ruby' grapefruit orchard being generally the highest and the lowest in the 2011 'Star Ruby' grapefruit orchard (Figure 5.7). Similar T values were, however, measured for the 2006 and 2010 'Star Ruby' orchards during the change in seasons (October-December and July-September). Transpiration in the 2006 'Star Ruby' orchard was 1.31 mm day$^{-1}$ when $ET_o$ was a maximum and 0.77 mm day$^{-1}$ when $ET_o$ was a minimum, whilst for the 2010 'Star Ruby' orchard the transpiration was 1.17 mm day$^{-1}$ and 0.70 mm day$^{-1}$ respectively on the days when the maximum and minimum $ET_o$ were recorded. For the 2011 'Star Ruby' orchard transpiration was 0.65 mm day$^{-1}$ and 0.37 mm day$^{-1}$ respectively for the maximum and minimum $ET_o$. Although a clear seasonal trend for T was observed (Figure 5.7), there was no proportional increase in T with increasing $ET_o$ in the hot summer months.

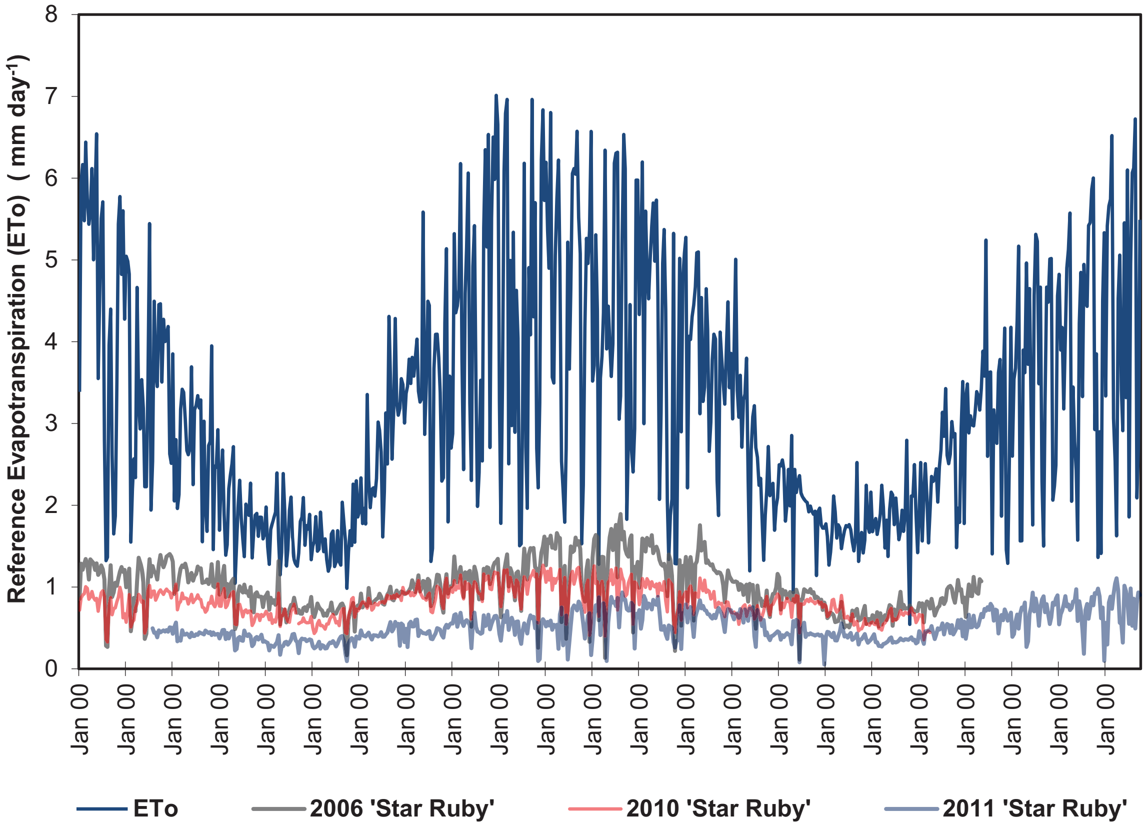


**Figure 5.7 Daily transpiration (mm day$^{-1}$) and reference evapotranspiration ($ET_o$, mm day$^{-1}$) for the 'Star Ruby' grapefruit orchards planted in 2006, 2010 and 2011**

Daily $K_t$ values, presented in Figure 5.8, showed large variation ranging from 0.02-1.42, 0.06-1.29 and 0.02-0.72 for the 2006, 2010 and 2011 'Star Ruby' grapefruit orchards. Differences in the $K_t$ values between the orchards were more clearly observed when average monthly $K_t$ values were determined, with values reflecting differences in canopy size (Figure 5.9). Transpiration crop coefficients were fairly constant in summer for all the orchards and increased in winter. A similar trend was also observed in the citrus orchards in the winter rainfall region.

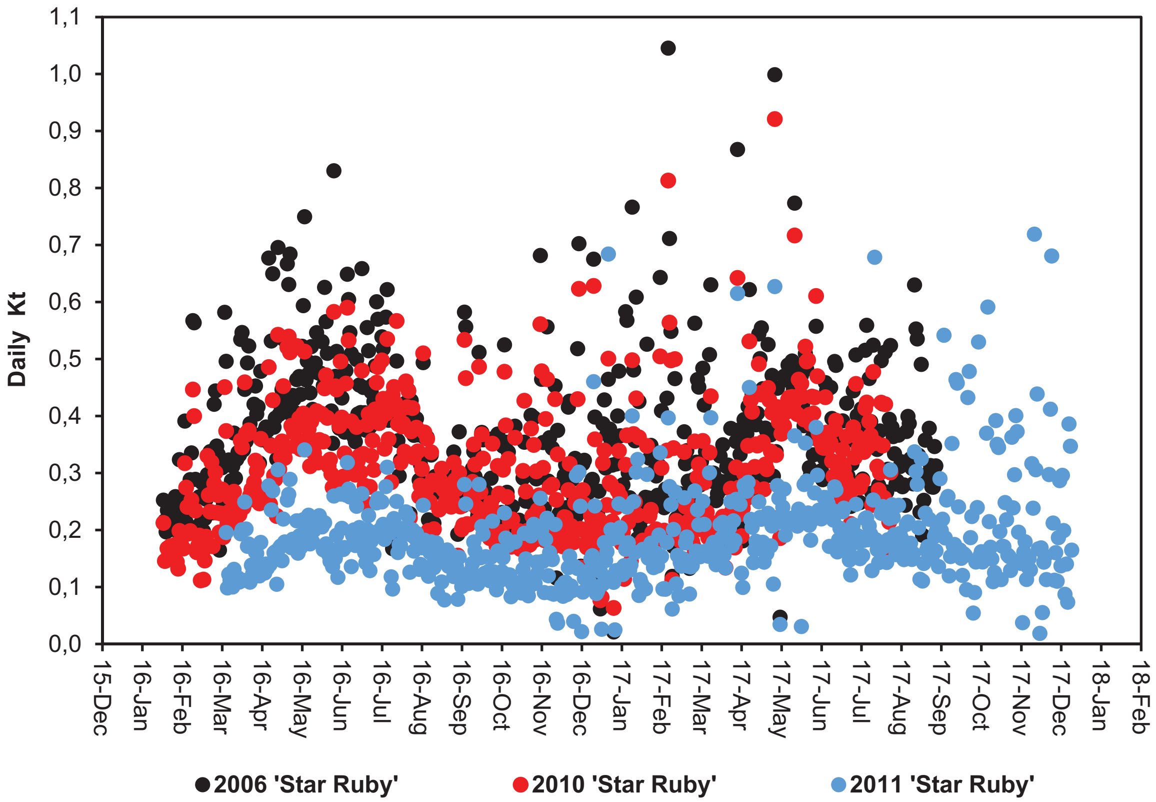


**Figure 5.8** Daily transpiration crop coefficients ($K_t$) for the 'Star Ruby' grapefruit orchards planted in 2006, 2010 and 2011

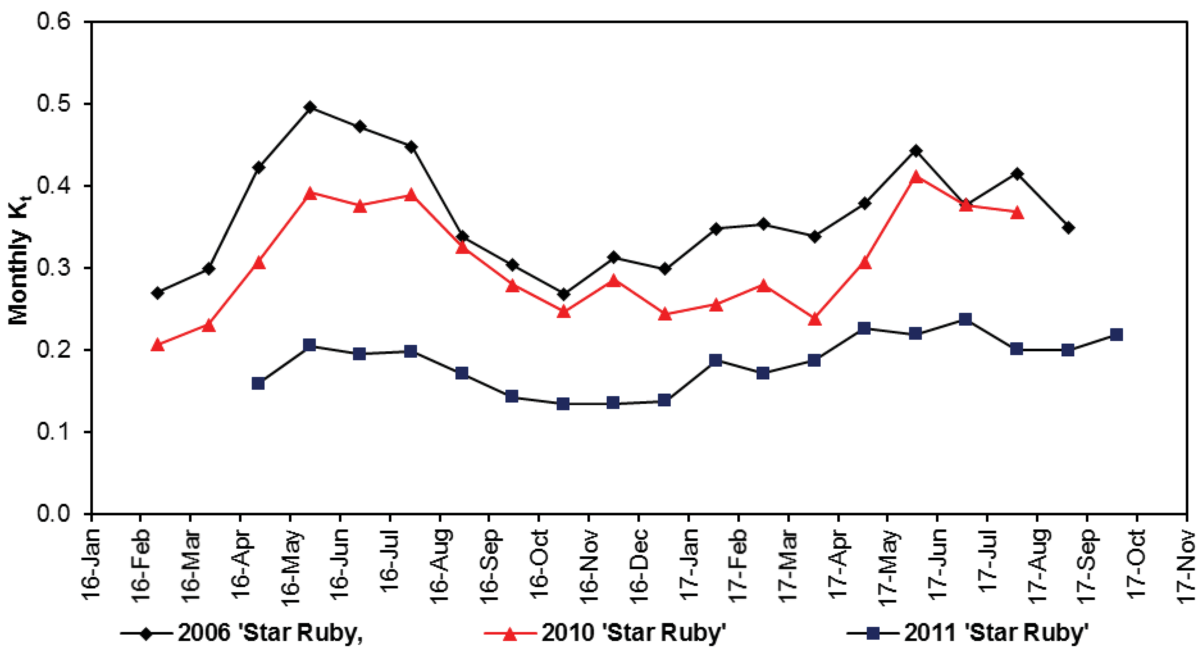


**Figure 5.9** Monthly transpiration crop coefficients ($K_t$) for the 'Star Ruby' grapefruit orchards planted in 2006, 2010 and 2011

Transpiration was measured for periods of 581, 547 and 636 days in the 2006, 2010 and 2011 ‘Star Ruby’ orchards. Total T for the measurement periods were 576, 446 and 328 mm in 2006, 2010 and 2011 ‘Star Ruby’ orchard. On average 0.99, 0.81 and 0.52 mm of water were transpired per day (Table 5.1). The annual water use, for the period 1 April 2016-31 March 2017, was 387 mm for the 2006, 314 mm for the 2010 and 180 mm for the 2011 ‘Star Ruby’ orchards.

**Table 5.1 Average tree water use for the ‘Star Ruby’ grapefruit orchards planted in 2006, 2010 and 2011**

| | **2006 ‘Star Ruby’** | | **2010 ‘Star Ruby’** | | **2011 ‘Star Ruby’** | |
|---|---|---|---|---|---|---|
| **Transpiration** | **mm** | **L tree$^{-1}$** | **mm** | **L tree$^{-1}$** | **mm** | **L tree$^{-1}$** |
| **Total** | 576 | 12 096 | 446 | 9 372 | 328 | 6 885 |
| **Maximum per day** | 1.9 | 39.7 | 1.3 | 26.6 | 1.1 | 23.2 |
| **Minimum per day** | 0.11 | 2.3 | 0.33 | 6.9 | 0.05 | 1.1 |
| **Average per day** | 0.99 | 20.8 | 0.81 | 17.1 | 0.52 | 10.8 |
| **Annual water use** | 387 | 8 135 | 314 | 6 599 | 180 | 3 789 |
| **Measurement period (days)** | 581 | | 547 | | 636 | |

## 5.3 Valencia orchards

### 5.3.1 Canopy measurements

Canopy volume increased from 6.3-13.6 m$^3$ for the 2014, 13.4-22.6 m$^3$ for the 2008 and 41.0-55.5 m$^3$ for the 1995 ‘Midknight’ Valencia measurement trees with an average of 10.3, 18.8 and 48.2 m$^3$ respectively (Figure 5.10).

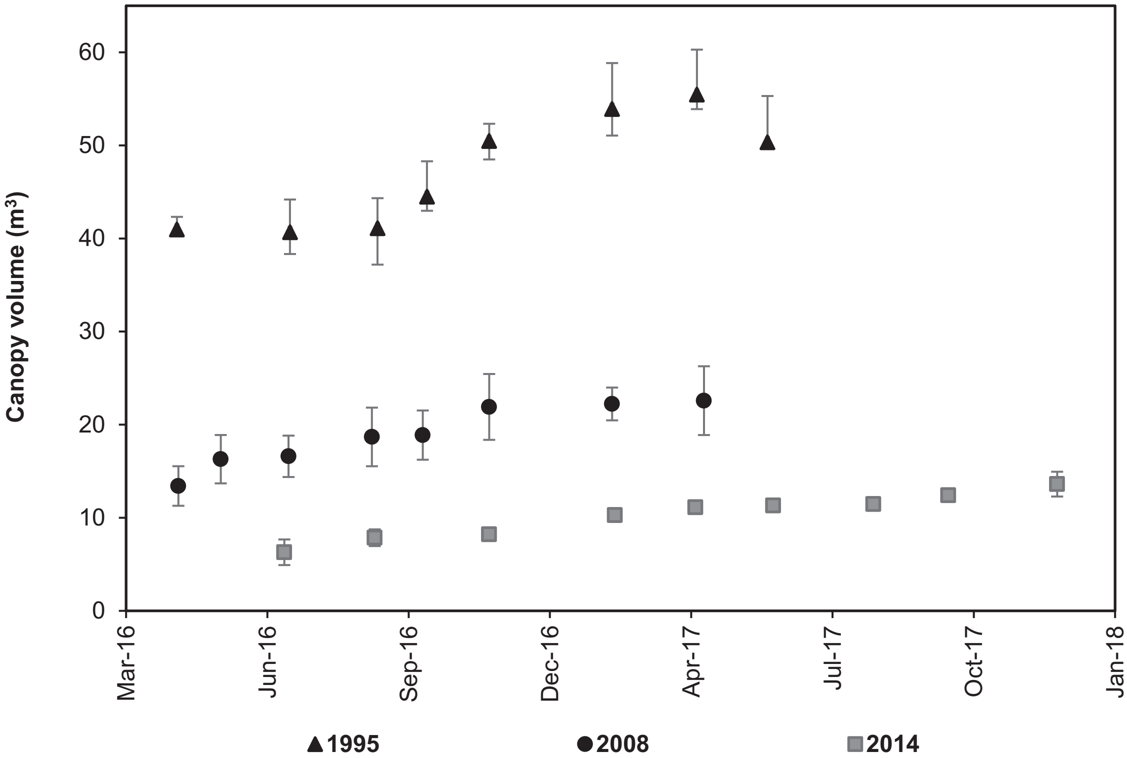


**Figure 5.10 Canopy volume, calculated as an ellipsoid, for the 1995, 2008 and 2014 'Midknight' Valencia orchards. Each point represents the average of four trees and the error bars the standard deviation**

The LAI of the 1995 'Midknight' Valencia orchard remained relatively constant over the data collection period (Figure 5.11). The average orchard LAI was 2.7 $m^2$ $m^{-2}$ and the average LAI of the four measured trees was 4.3 $m^2$ $m^{-2}$.

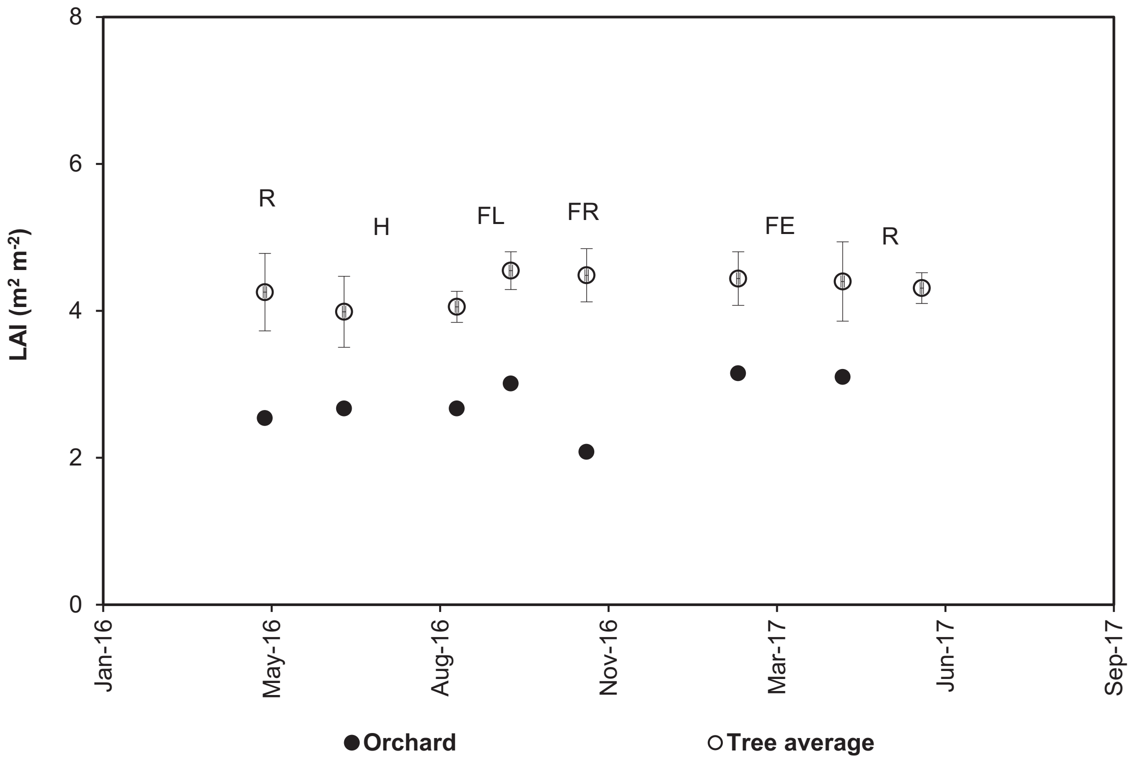


**Figure 5.11 The 1995 'Midknight' Valencia orchards leaf area index (LAI) and the average LAI of the four experimental trees, with error bars indicating the standard deviation. Letters give phenological stages: FE (fruit enlargement) R (ripening period), FL (flowering period), FR (fruitlets) and H (harvesting)**

The LAI of the 2008 'Midknight' Valencia trees showed a gradual increase over the data collection period from 3.5 $m^2$ $m^{-2}$ in May 2016 until it reached a maximum of 5.3 $m^2$ $m^{-2}$ in February 2017, after which it decreased to 4.5 $m^2$ $m^{-2}$ in May 2017 (Figure 5.12). The orchard LAI was quite variable over the measurement period and showed a general decrease after October 2016. The average orchard LAI was 2.8 $m^2$ $m^{-2}$ and the average LAI of the four measured trees was 4.3 $m^2$ $m^{-2}$.

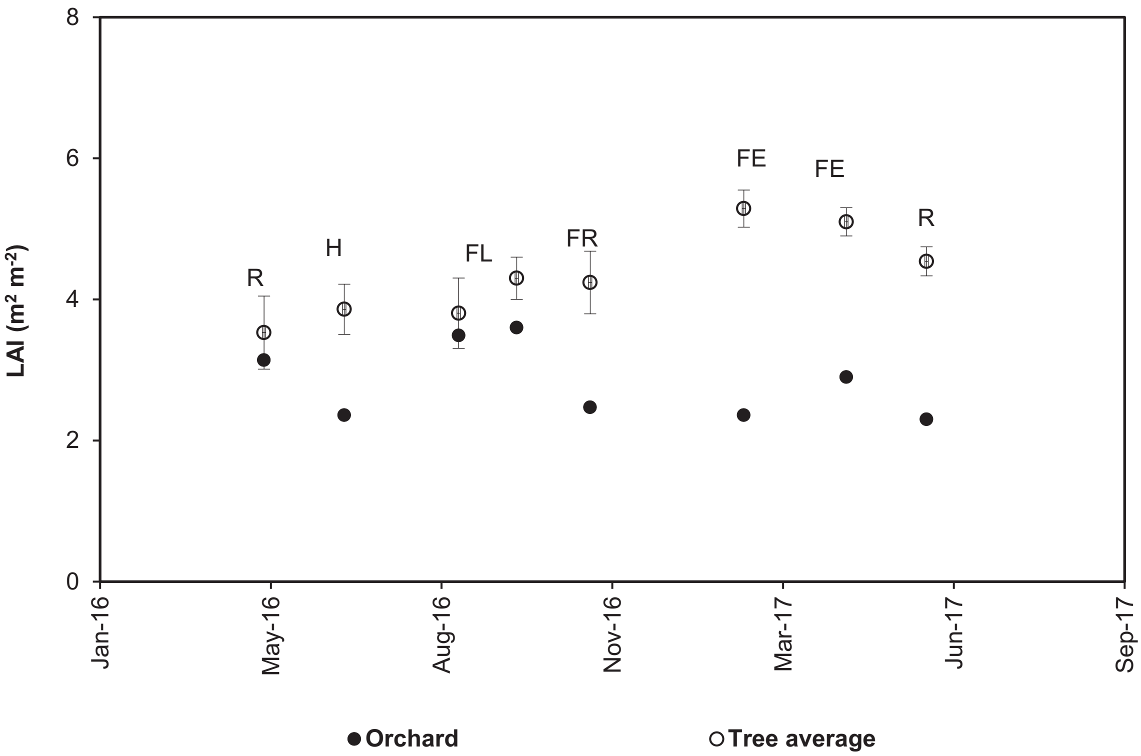


**Figure 5.12 The 2008 'Midknight' Valencia orchard leaf area index (LAI) and the average LAI of the four experimental trees, with error bars indicating the standard deviation. Letters give phenological stages: FE (fruit enlargement) R (ripening period), FL (flowering period), FR (fruitlets) and H (harvesting)**

In general, the LAI of the 2014 'Midknight' Valencia trees showed a gradual increase over the data collection period from 2.2 $m^2$ $m^{-2}$ to a maximum of 3.3 $m^2$ $m^{-2}$ close to the end of the data collection period (Figure 5.13). The orchard LAI trend was very similar to the tree LAI but a more significant decline in LAI was noted toward the end of the data collection period. The average orchard LAI over the data collection period was 1.4 $m^2$ $m^{-2}$ and the average LAI of the four measured trees was 2.8 $m^2$ $m^{-2}$.

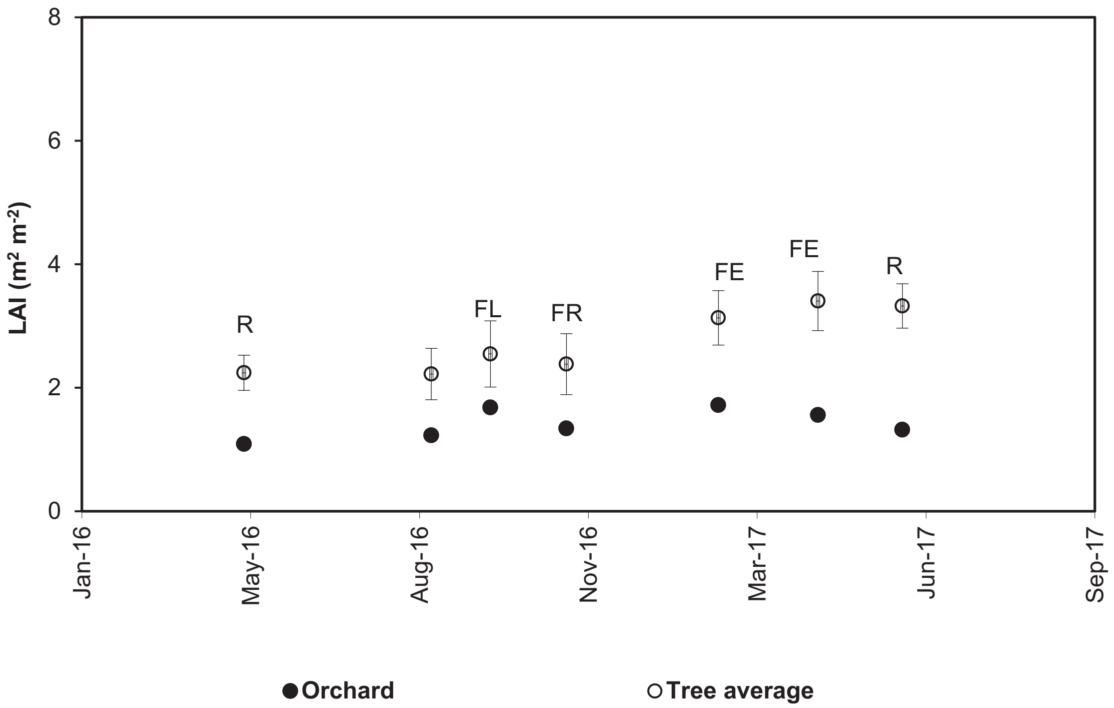


**Figure 5.13 The 2014 'Midknight' Valencia orchards leaf area index (LAI) and the average LAI of the four experimental trees, with the error bars indicate the standard deviation. Letters give phenological stages: FE (fruit enlargement) R (ripening period), FL (flowering period), and FR (fruitlets)**

### 5.3.2 Transpiration

As observed in the 'Star Ruby' grapefruit orchards, T in the 'Midknight' Valencia orchards also followed canopy size (Figure 5.10 and Table 3.5), with higher daily T measured in the 1995 'Midknight' Valencia orchard, than the 2008 and 2014 'Midknight' Valencia orchards (Figure 5.14). Large day-to-day variation in T rates were observed, which was largely as a result of the prevailing environmental conditions, as seen from the $ET_o$ data (Figure 5.14). For the measurement period, for the 1995 and 2008 'Midknight 'Valencia orchards, $ET_o$ ranged between 0.93 mm day$^{-1}$ ($ET_r$, 0.54 mm day$^{-1}$) and 7.01 mm day$^{-1}$ ($ET_r$, 8.66 mm day$^{-1}$). Transpiration in the 1995 'Midknight' Valencia orchard was 2.19 mm day$^{-1}$ on the day when maximum $ET_o$ was recorded and 0.41 mm day$^{-1}$ when minimum $ET_o$ was recorded. Transpiration in the 2008 'Midknight' Valencia orchard, on the days when the maximum and minimum $ET_o$ was recorded, was 1.05 mm day$^{-1}$ and 0.23 mm day$^{-1}$ respectively. For the 2014 'Midknight' Valencia orchard, $ET_o$ ranged between 0.93 mm day$^{-1}$ ($ET_r$, 0.54 mm day$^{-1}$) and 6.72 mm day$^{-1}$ ($ET_r$, 8.66 mm day$^{-1}$) for the measuring period. T was 0.89 mm day$^{-1}$ when maximum $ET_o$ was recorded and 0.10 mm day$^{-1}$ when minimum $ET_o$ was recorded. As observed in the ‘Star Ruby’ grapefruit orchards, a clear seasonal trend for T was observed (Figure 5.14), but T did not increase in proportion to $ET_o$ during the transition from winter to summer.

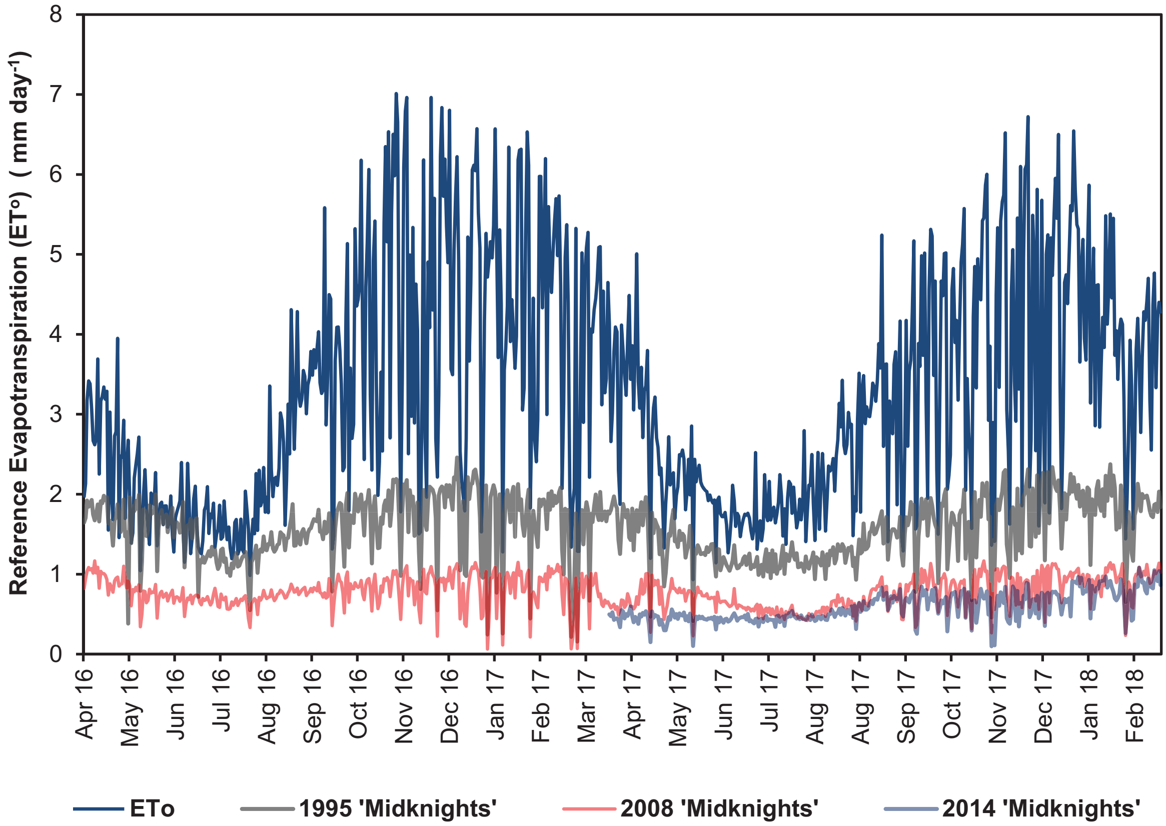


**Figure 5.14 Daily transpiration (mm day$^{-1}$) and reference evapotranspiration ($ET_o$, mm day$^{-1}$) for the ‘Midknight’ Valencia orchards planted in 1995, 2008 and 2014**

Similar to the ‘Star Ruby’, $K_t$ values for the ‘Midknight’ Valencia orchards displayed large daily variation (Figure 5.15). Transpiration crop coefficients ranged from 0.12-1.36 for the 1995, 0.05-0.62 for the 2008 ‘Midknight’ Valencia orchard and 0.07-0.39 for the 2014 ‘Midknight’ Valencia orchard. Average monthly $K_t$ values showed a similar trend between all the ‘Midknight’ Valencia orchards, (Figure 5.16) and reflected a proportional relationship between water use and canopy size. Transpiration crop coefficients were also fairly constant in summer for all the orchards with large variations in the winter months, this observation was consistent in many citrus cultivars.

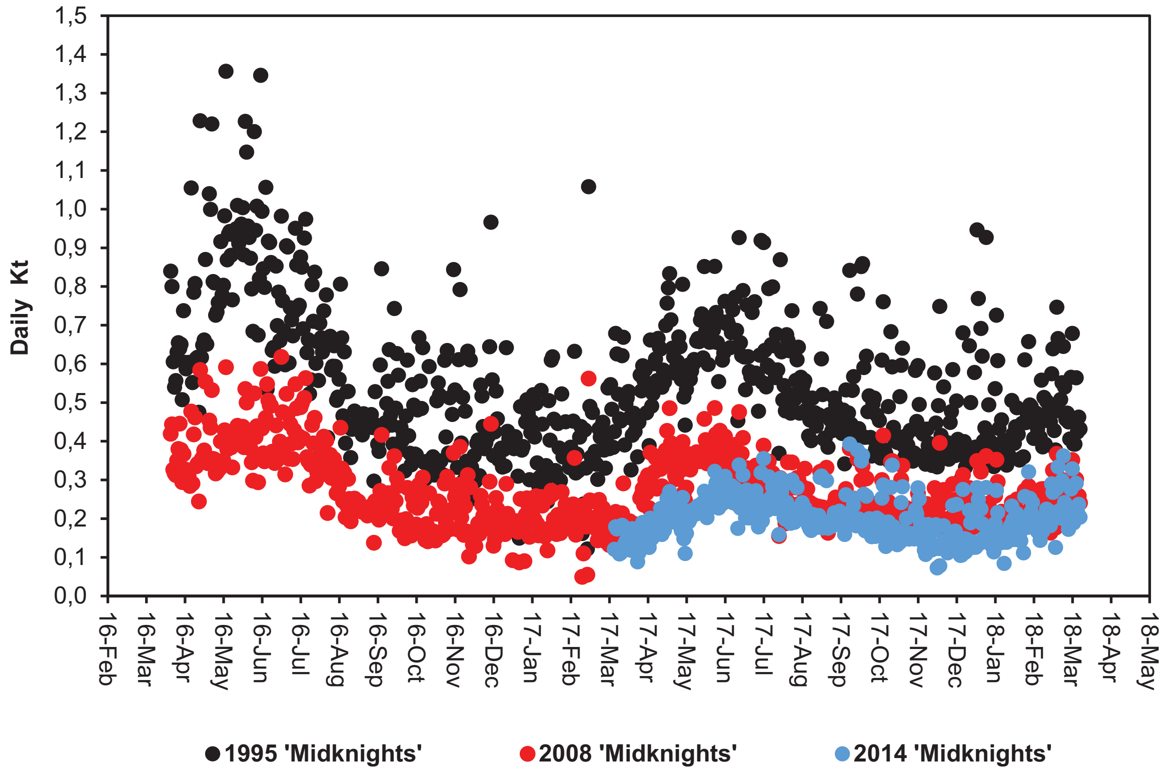


**Figure 5.15 Daily transpiration crop coefficients ($K_t$) for the 'Midknight' Valencia orchards planted in 1995, 2008 and 2014**

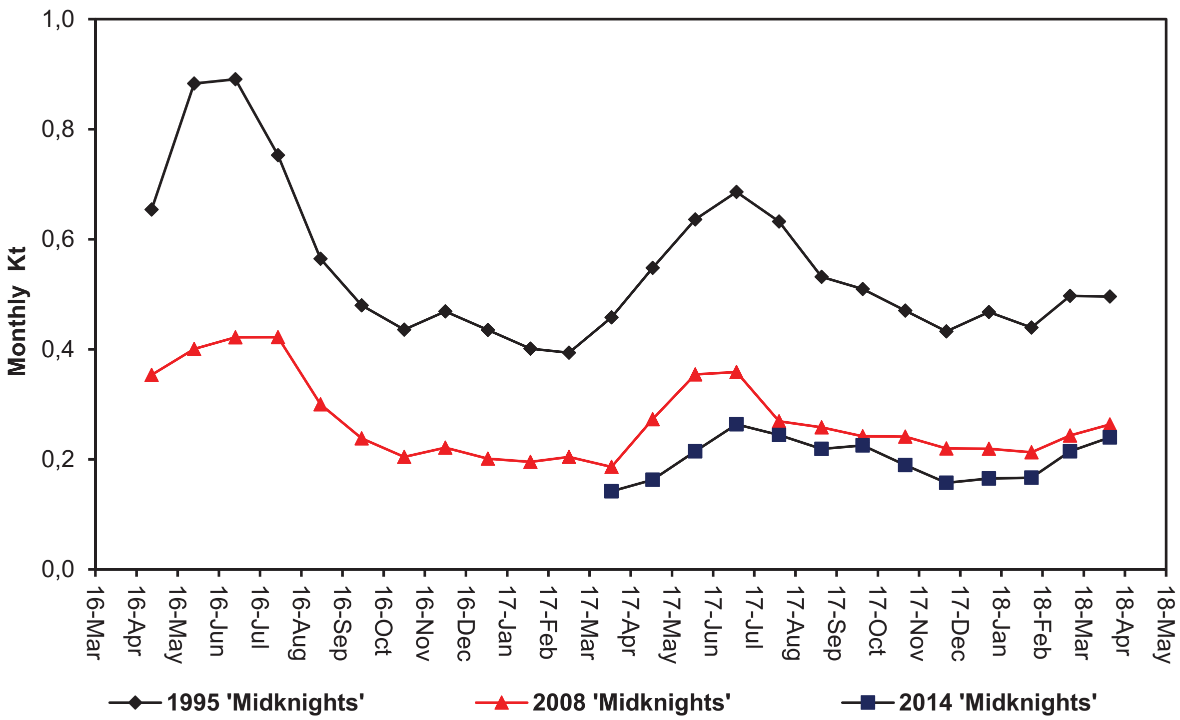


**Figure 5.16 Monthly transpiration crop coefficients ($K_t$) for the 'Midknight' Valencia orchards planted in 1995, 2008 and 2014**

Transpiration was measured for 707 days for both the 1995 and 2008 'Midknight' Valencia orchards and 363 days for the 2014 'Midknight' Valencia orchard. Total T for the measurement periods were 1 028, 547 and 213 mm in the 1995, 2008 and 2014 'Midknight' Valencia orchards respectively. On average 1.45, 0.77 and 0.59 mm day$^{-1}$ of water were transpired in the 1995, 2008 and 2014 'Midknight' Valencia orchards, respectively (Table 5.2).

**Table 5.2 Average tree water use for the 'Midknight' Valencia orchards planted in 1995, 2008 and 2014**

| Transpiration | 1995 'Midknight' | | 2008 'Midknight' | | 2014 'Midknight' | |
|---|---|---|---|---|---|---|
| | mm | L | mm | L | mm | L |
| **Total** | 1 109 | 23 291 | 547 | 11 497 | 213 | 4 472 |
| **Maximum per day** | 2.5 | 51.6 | 1.2 | 24.5 | 1.08 | 22.7 |
| **Minimum per day** | 0.2 | 3.3 | 0.1 | 1.3 | 0.10 | 2.1 |
| **Average per day** | 1.6 | 32.9 | 0.8 | 16.2 | 0.59 | 12. |
| **Annual water use** | 560 | 11 751 | 275 | 5 776 | 212.9 | 4 472 |
| **Measurement period (days)** | 707 | | 707 | | 363 | |

## 5.4 Mandarin orchards

### 5.4.1 Canopy measurements

Canopy volume ranged between and 11.1 and 16.2 m$^3$ and 8.6 and 14.7 m$^3$ for the 2013 and 2015 'Valley Gold' mandarin trees, with an average of 13.4 and 12.0 m$^3$ respectively (Figure 5.17). Although two orchards differed in age by two years, the canopy volume was the same for both orchards.

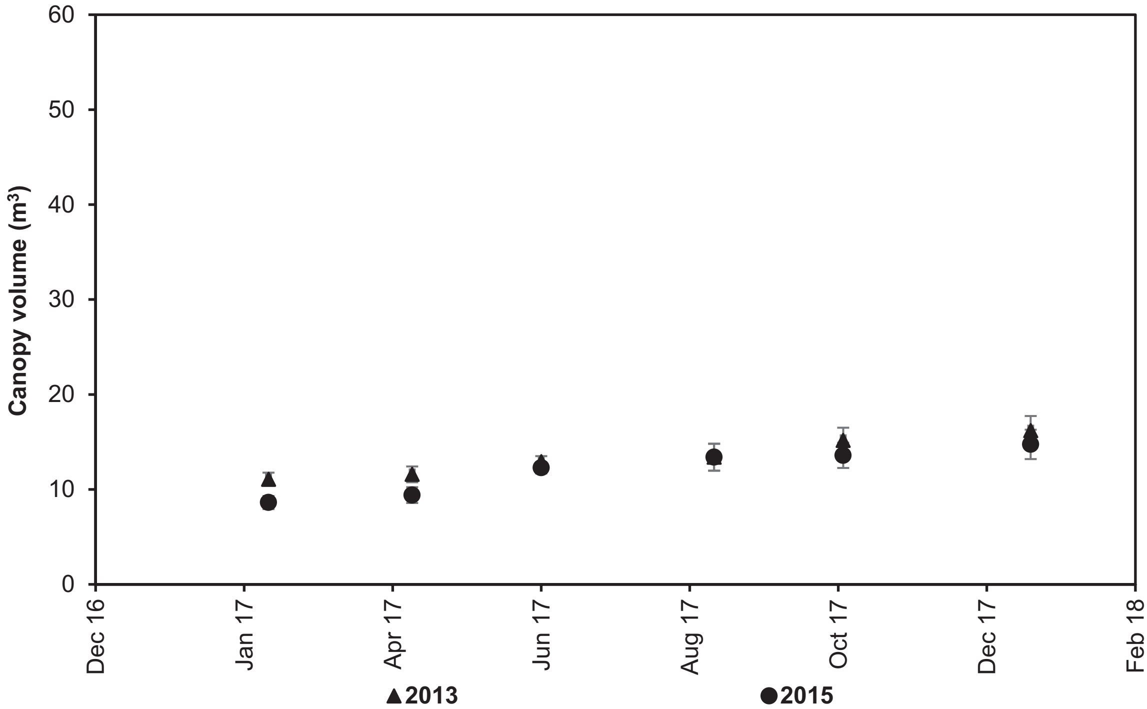


**Figure 5.17 Canopy volume, calculated as an ellipsoid, for the 2013 and 2015 'Valley Gold' mandarin orchards. Each point represents the average of four trees and the error bars the standard deviation**

The LAI of the four measurement trees in the 2013 'Valley Gold' mandarin orchard increased consistently over the data collection period from 2.3 $m^2$ $m^{-2}$ at the start of measurements to 3.9 $m^2$ $m^{-2}$ at the end of the measurement period (Figure 5.18). The orchard LAI did not display the same increasing trend and stayed more constant over the course of the study, with an average of 1.6 $m^2$ $m^{-2}$. The average LAI for the measurement trees, over the trial period, was 3.3 $m^2$ $m^{-2}$.

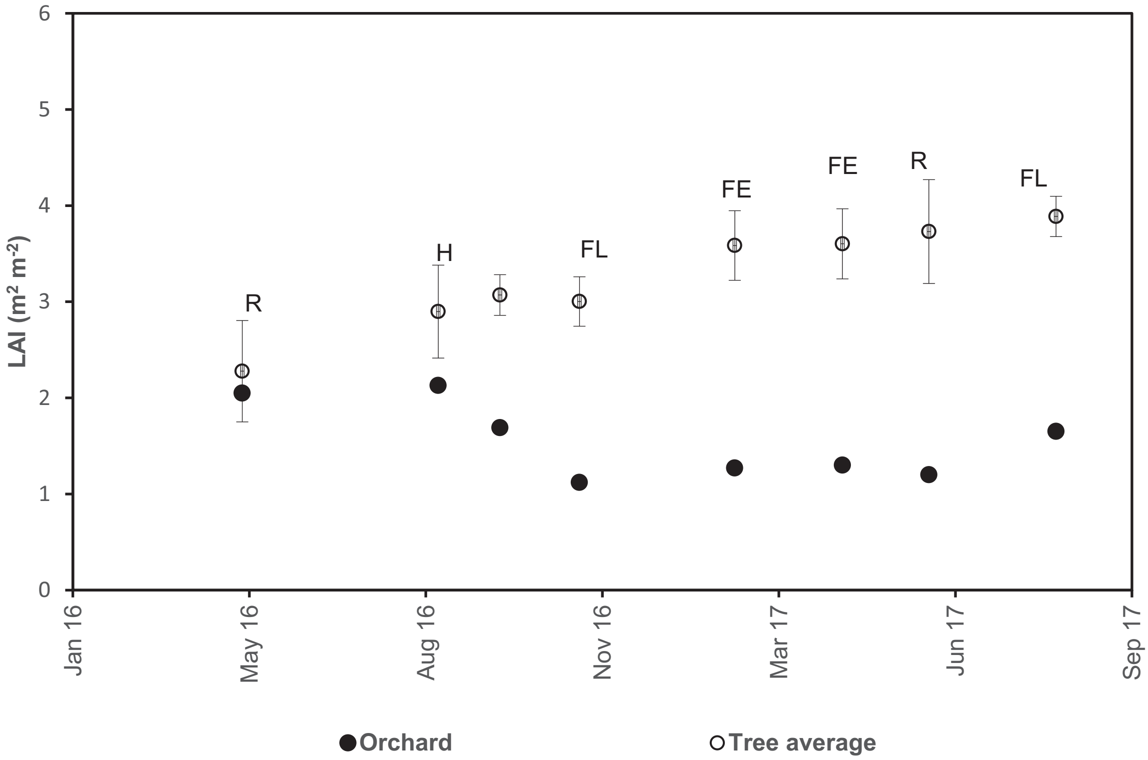


**Figure 5.18 2013 'Valley Gold' mandarin orchard leaf area index (LAI) and the average LAI of the four experimental trees, with error bars indicating the standard deviation. Letters give phenological stages: FE (fruit enlargement) R (ripening period), FL (flowering period), FR (fruitlets) and H (harvesting)**

The LAI of the measurement trees in the 2015 'Valley Gold' mandarin orchard remained fairly constant for the first 9 months of measurements (average of 2.5 $m^2\ m^{-2}$) and following a slight decrease in February 2017, there was a steady increase in LAI up until the end of the data collection period, when a LAI of 4.1 $m^2\ m^{-2}$ was recorded (Figure 5.19). A very similar trend was observed for the orchard LAI, with a more pronounced decrease in LAI from February to May 2017, which could have been related to the bending of the trees with crop load. The average tree LAI over the data collection period was 2.9 $m^2\ m^{-2}$ and the average orchard LAI was 2.1 $m^2\ m^{-2}$.

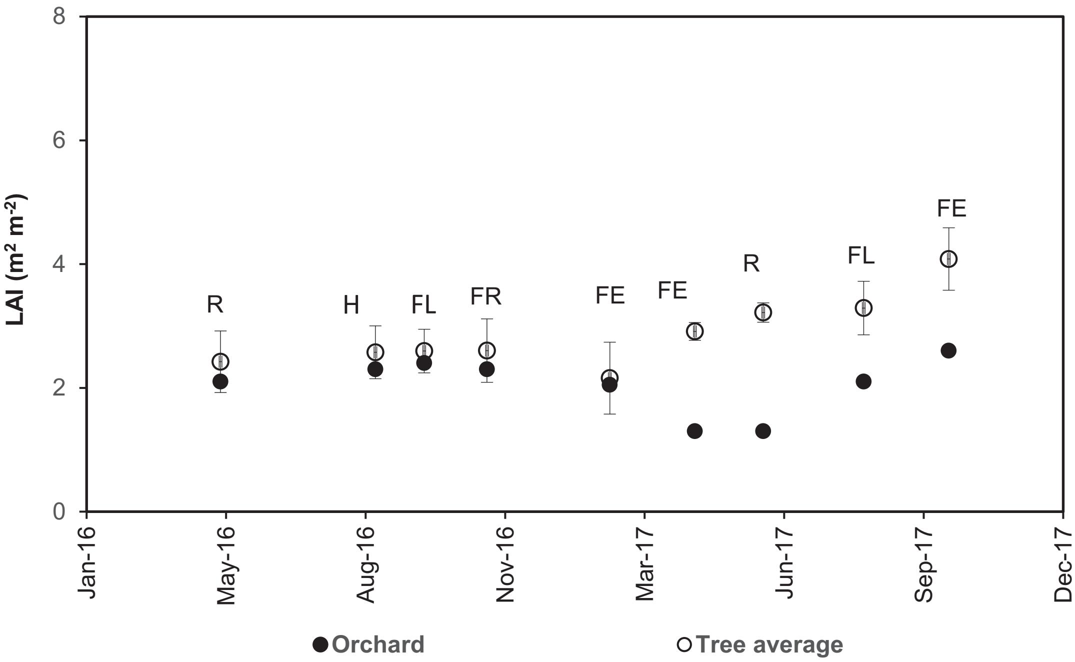


**Figure 5.19 2015 'Valley Gold' mandarin orchard leaf area index (LAI) and the average LAI of the four experimental trees, with error bars indicating the standard deviation. Letters give phenological stages: FE (fruit enlargement) R (ripening period), FL (flowering period), FR (fruitlets) and H (harvesting)**

### 5.4.2 Transpiration

Transpiration data was collected from February 2017-March 2018 for the 2013 and 2015 'Valley Gold' mandarin orchards. Generally daily T was very similar for the 2013 and 2015 'Valley Gold' mandarin orchards, especially during the winter months (Figure 5.20). However, during the summer months T in the 2013 'Valley Gold' mandarin orchard was marginally higher than the 2013 'Valley Gold' mandarin orchard, which could reflect the slightly bigger canopy in the older trees. For the measuring period, $ET_o$ ranged between 0.93 mm day$^{-1}$ and 6.72 mm day$^{-1}$. Transpiration (average of the four measured trees) on the day when the maximum $ET_o$ was recorded, was 0.76 and 0.73 mm respectively for the 2013 and 2015 'Valley Gold' mandarin orchards. The T on the day when the minimum $ET_o$ was recorded was 0.03 mm for the 2013 and 0.02 mm for the 2015 'Valley Gold' mandarin orchards.

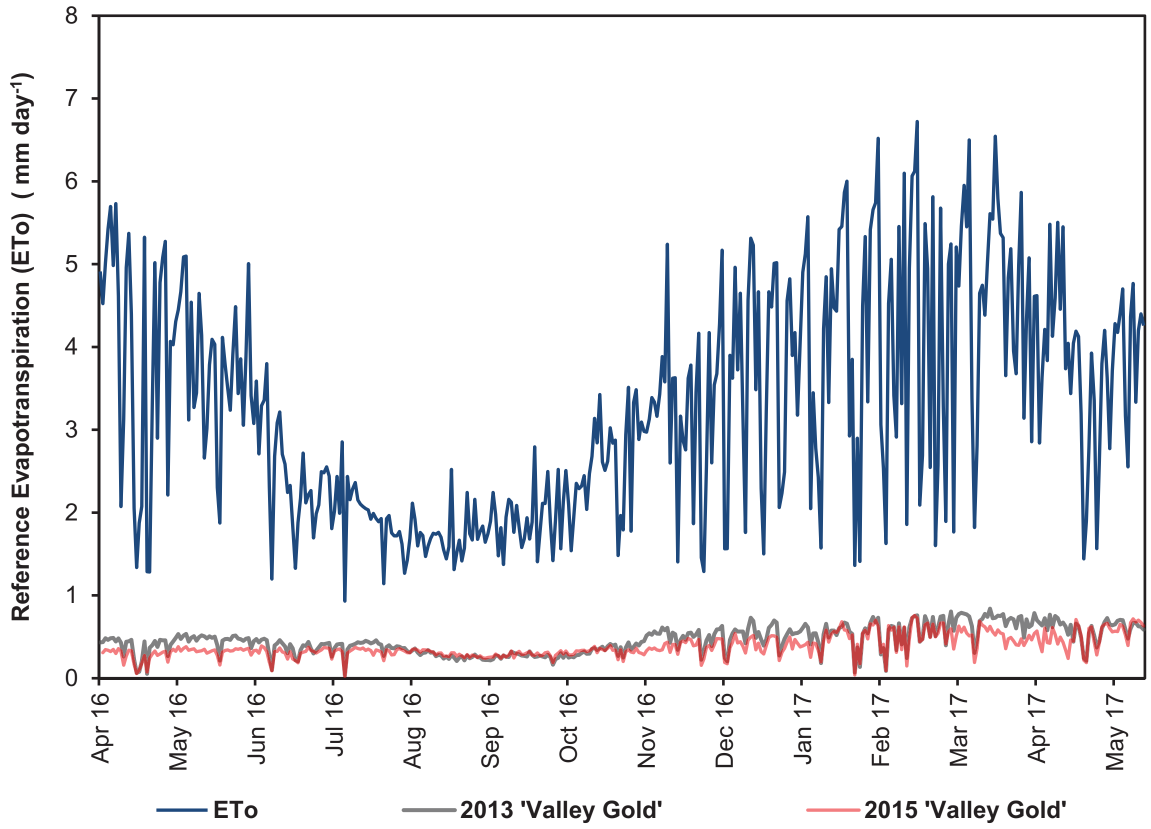


**Figure 5.20 Daily transpiration (mm day$^{-1}$) and reference evapotranspiration ($ET_o$, mm day$^{-1}$) for the 'Valley Gold' mandarin orchards planted in 2013 and 2015**

The daily $K_t$ values, presented in Figure 5.21, ranged from 0.04-0.32 for the 2013 and 2015 'Valley Gold' mandarin orchards. As with the other orchards, $K_t$ values tended to be higher in winter and declined as summer approached and $ET_o$ increased. Monthly $K_t$ values were very similar for both orchards, with only slight differences noted during the summer months (Figure 5.22).

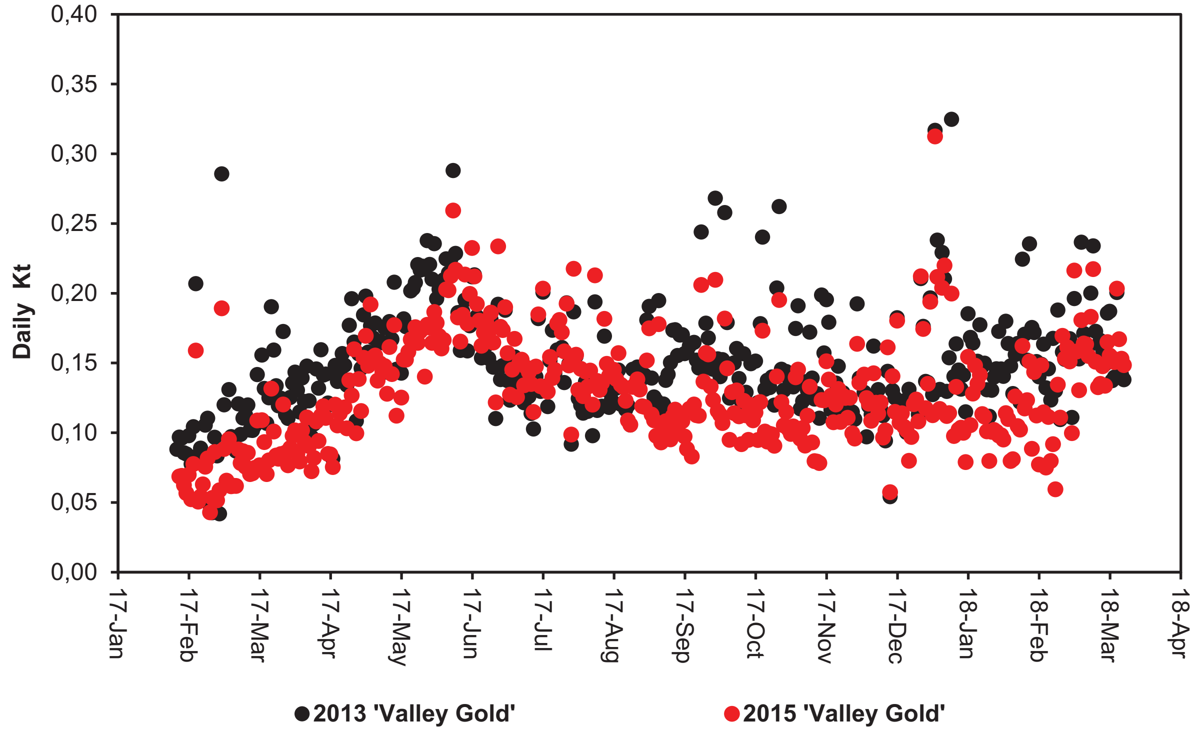


**Figure 5.21 Daily transpiration crop coefficients ($K_t$) for the 'Valley Gold' mandarin orchards planted in 2013 and 2015**

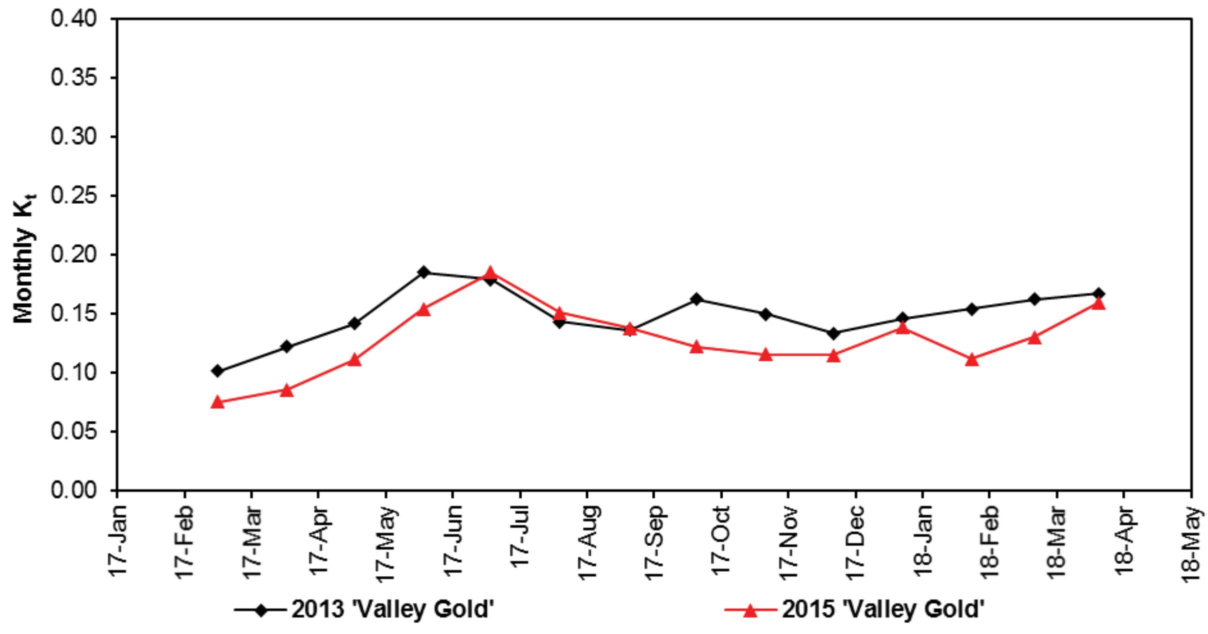


**Figure 5.22 Monthly transpiration crop coefficients ($K_t$) for the 'Valley Gold' mandarins planted in 2013 and 2015**

Transpiration was measured for 295 and 294 days in the 2013 and 2015 'Valley Gold' orchards. Total T (average of four measurement trees) for the measurement periods were 185 and 154 mm with an average of 0.46 and 0.38 mm of water being transpired per day in

2013 and 2015 'Valley Gold' orchards respectively. The annual water use of the four measurement trees in the 2013 'Valley Gold orchard was 167 mm and 139 mm in the 2015 'Valley Gold orchard for the period 1 March 2017-28 February 2018. (Table 5.3).

**Table 5.3 Average tree water use for the four measured trees in the 'Valley Gold' mandarin orchards planted in 2013 and 2015**

| Transpiration | 2013 'Valley Gold' | | 2015 'Valley Gold' | |
|---|---|---|---|---|
| | mm | L $tree^{-1}$ | mm | L $tree^{-1}$ |
| **Total** | 185 | 3 881 | 154 | 3 233 |
| **Maximum per day** | 0.8 | 17.6 | 0.8 | 15.9 |
| **Minimum per day** | 0.03 | 0.6 | 0.02 | 0.5 |
| **Average per day** | 0.5 | 9.7 | 0.4 | 8.1 |
| **Annual water use** | 167 | 3 506 | 139 | 2 917 |
| **Measurement period (days)** | 402 | | 401 | |

## 5.5 Evapotranspiration of the orchards

Evapotranspiration measurements in the summer rainfall region were conducted in the mature 10-year-old 'Star Ruby' grapefruit orchard for more than 5 months, in the immature 3-year-old 'Midknight' Valencia orchard for approximately a month and a half and in an intermediate 'Valley Gold' mandarin orchard for nearly 3 weeks (Table 5.4). Data collection periods therefore ranged from 19 days in the 'Valley Gold' mandarin orchard to 164 days in the 'Star Ruby' grapefruit orchard (Table 5.4). Whilst data collected in the 'Star Ruby' grapefruit and 'Valley Gold' mandarin orchard was generally very good, problems were encountered in the 'Midknight' Valencia orchard with net radiation measurements and power issues. This limited the number of useable measurements in this orchard. Energy balance closure was poor in the 'Valley Gold' orchard (slope = 0.52) and corrections were made to the final ET data using the Bowen ratio adjustment according to Twine et al. (2000). As seen in Citrusdal, ET varied with canopy size and environmental conditions (Table 5.4). Generally, fairly good relationships were found between $ET_o$ and ET in the three orchards, which were particularly noticeable under low atmospheric evaporative demand conditions (Figure 5.23). Measurements in the two smaller orchards were carried out in autumn, winter and spring and ET was therefore also lower in these orchards due to cooler conditions. Measurements in the mature 'Star Ruby' grapefruit orchard were carried out over the hot summer period. The different slopes of the relationships for each orchard also indicate different $K_c$ for each orchard, which reflects the differences in canopy sizes between the three orchards. The proportion of ET consisting of T varied between the three orchards (19-45%), with T making up a greater proportion of ET in the 'Star Ruby' grapefruit orchard which had the largest canopy (71% canopy cover). The sparse canopy and microsprinkler irrigation in the smaller two orchards resulted in T being only between 19 and 24% of ET in these orchards (27-42% canopy cover). This indicates that non-beneficial consumptive water use makes up a considerable proportion of water use in orchards in Letsitele, due to the greater area wet by the irrigation.

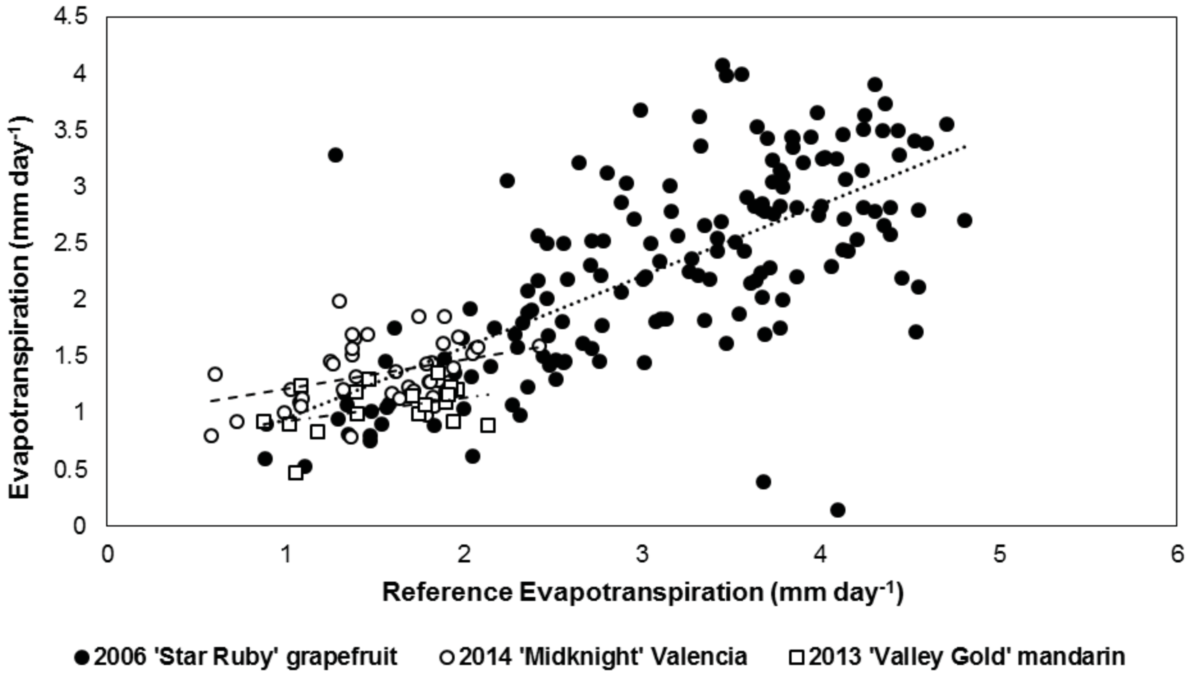


**Figure 5.23 Comparison of evapotranspiration determined using the eddy covariance technique in citrus orchards in Letsitele**

**Table 5.4 Summary of evapotranspiration (ET), reference evapotranspiration ($ET_o$) and transpiration (T) measurements in the orchards in Letsitele**

| Orchard | Measurement duration (no. of days) | Variable | Maximum (mm $day^{-1}$) | Minimum (mm $day^{-1}$) | Average (mm $day^{-1}$) | Average T fraction of ET |
|---|---|---|---|---|---|---|
| 'Star Ruby' grapefruit 2006 | 18/10/2016-09/04/2017 (164) | $ET_o$ | 4.07 | 0.14 | 2.28 | 45% |
| | | ET | 4.80 | 0.88 | 3.11 | |
| | | T | 1.97 | 0.16 | 1.33 | |
| 'Midknight' Valencia 2014 | 11/04/2017-22/05/2017 (42) | $ET_o$ | 2.42 | 0.07 | 1.53 | 24% |
| | | ET | 1.99 | 0.79 | 1.35 | |
| | | T | 0.42 | 0.01 | 0.31 | |
| 'Valley Gold' mandarin 2013 | 29/07/2017-16/08/2017 (19) | $ET_o$ | 2.13 | 0.88 | 1.57 | 19% |
| | | ET | 1.35 | 0.47 | 1.05 | |
| | | T | 0.37 | 0.17 | 0.28 | |

## 5.6 Transpiration response to environmental variables

The responses of all eight different citrus orchards in the summer rainfall region (i.e. three 'Star Ruby' grapefruit orchards, three 'Midknight' Valencia orchards and two 'Valley Gold' mandarin orchards) to $ET_o$, average daily temperature, $R_s$ and average daily VPD are given in Figure 5.24, Figure 5.25 and Figure 5.26. Poor relationships were generally found between T and the various environmental variables for most of the orchards, which probably resulted from the weather stations not being in close proximity to the trial sites. Another factor to consider is that although these weather stations were equipped with the necessary instruments to measure the environmental variables for $ET_o$ calculations, the main purpose of these stations is for disease modelling, which may have influenced the quality of the weather data, as they were not ideally situated for the determination of $ET_o$. Generally they were located to close to large trees and water bodies. A poor linear relationship between T and $R_s$ and T and temperature and a poor second order polynomial relationship between T and $ET_o$ and T and VPD was found for most orchards. However, generally it was observed that T increased with VPD up to a certain point, with little increase in T once VPD had exceeded 2.0 kPa. A similar response was observed for $ET_o$, with no further increase in T observed once atmospheric demand exceeded approximately 6 mm.

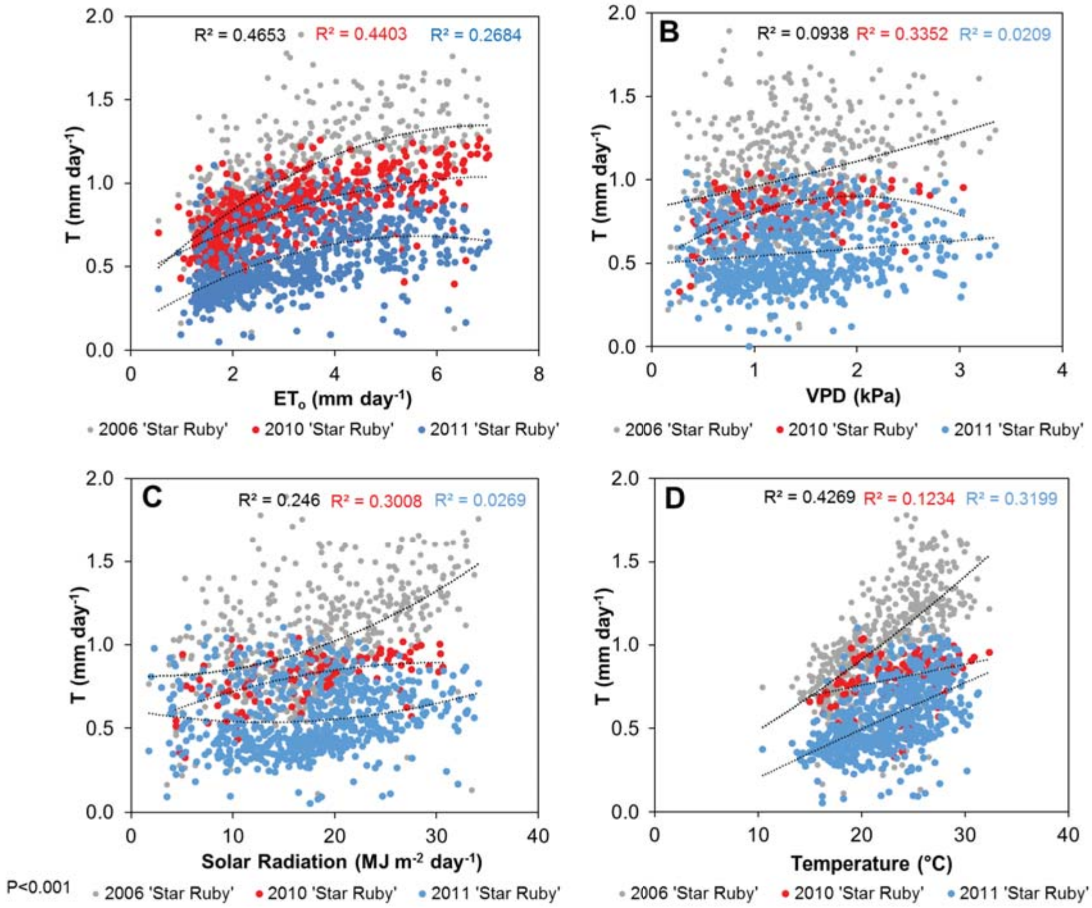


**Figure 5.24 Typical response of daily transpiration (T) of the different 'Star Ruby' grapefruit orchards in a summer rainfall region to daily A) total reference evapotranspiration ($ET_o$), B) average vapour pressure deficit (VPD), C) total solar radiation and D) average temperature**

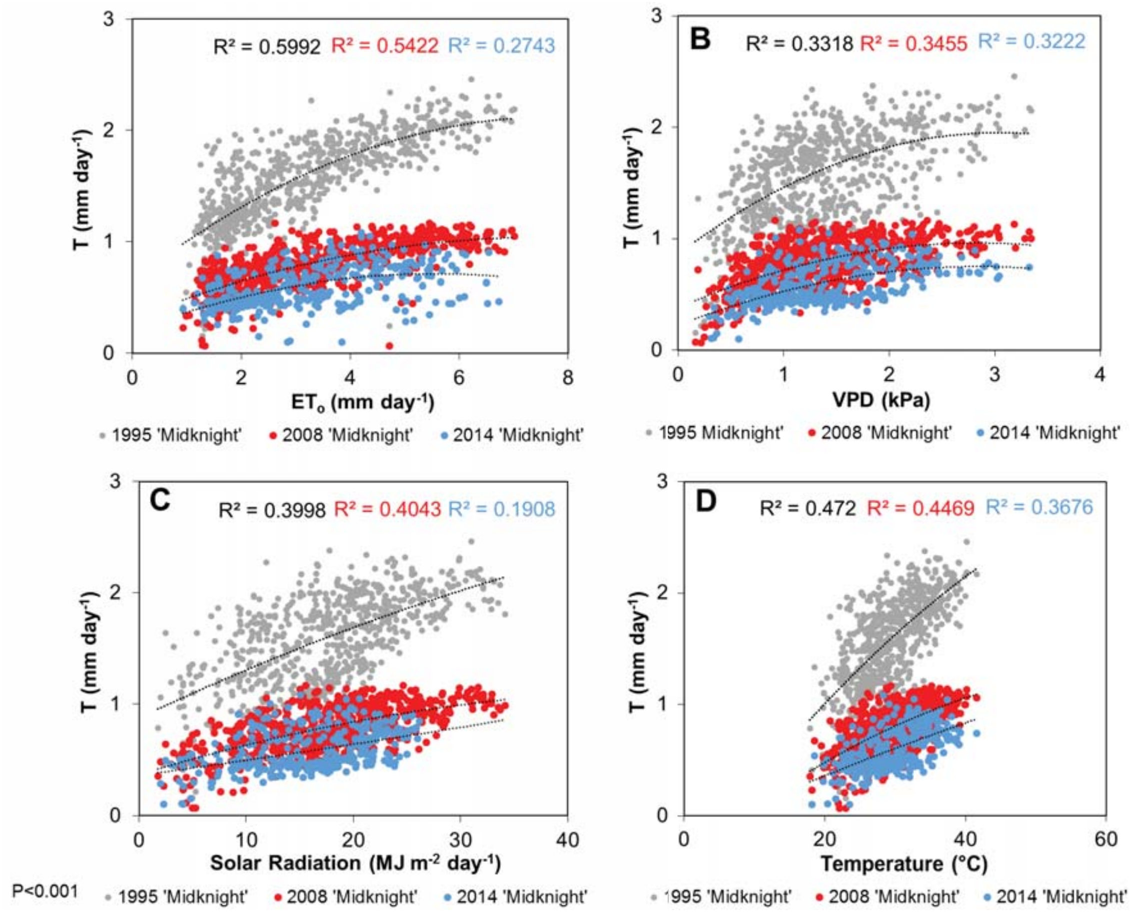


**Figure 5.25 Typical response of daily transpiration (T) different Valencia orchards in a summer rainfall region to daily A) total reference evapotranspiration ($ET_o$), B) average vapour pressure deficit (VPD), C) total solar radiation and D) average temperature**

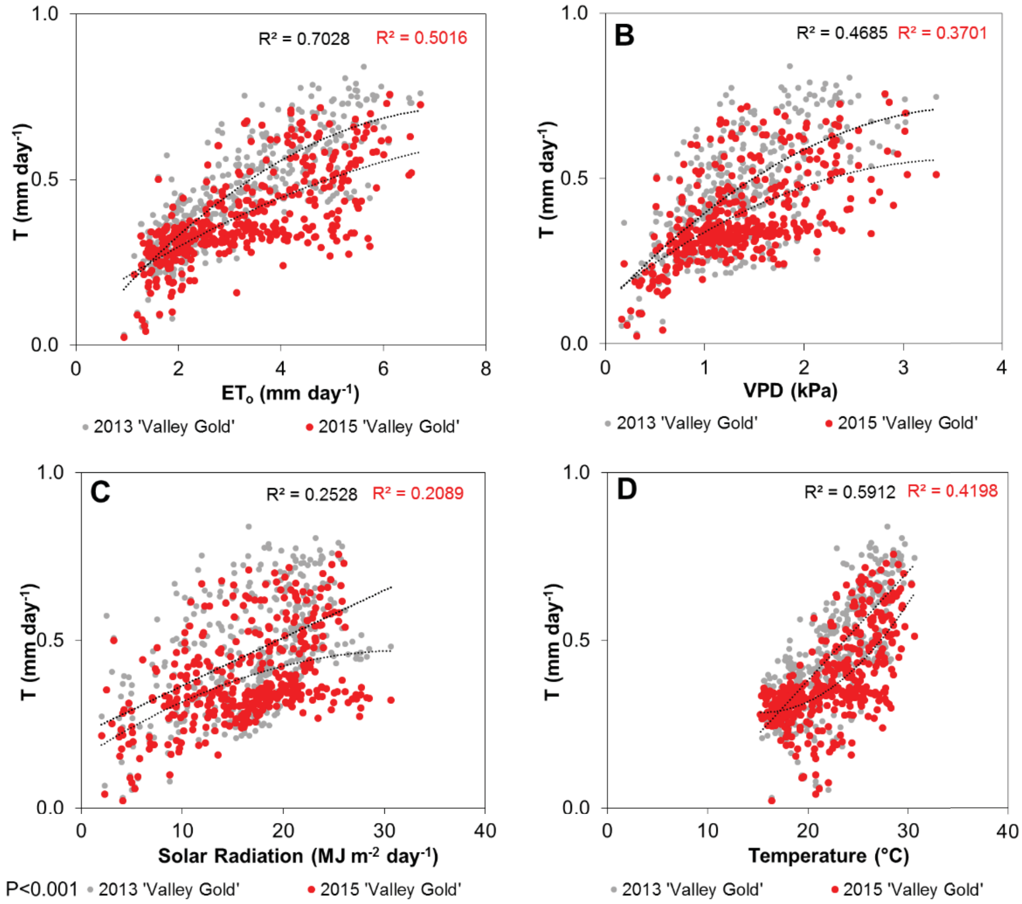


**Figure 5.26 Typical response of daily transpiration (T) of different mandarin orchards in a summer rainfall region to daily A) total reference evapotranspiration ($ET_o$), B) average vapour pressure deficit (VPD), C) total solar radiation and D) average temperature**

## 5.7 Ecophysiology of the citrus trees

In order to select the correct model and model citrus water use mechanistically, it is important to have a thorough understanding of the mechanisms controlling citrusT. Whilst a fair amount has been published on citrus water use (Fares et al., 2008; Villalobos et al., 2009), little work has been done on a range of citrus species, in contrasting climates. This study has provided an opportunity to increase our understanding of the way T is regulated in various citrus trees. In this section we will focus on mature 'Midknight' Valencia trees, as we have data from both a summer and winter rainfall region.

In previous sections on the environmental regulation of T, it was evident that as atmospheric evaporative demand ($ET_o$) or VPD passed a certain threshold, T no longer increased at the same rate as either $ET_o$ or VPD. A maximum T rate was soon reached after this threshold. The question therefore is, why does this happen and what is happening in the tree?

Firstly, stomata tend to close with increasing VPD (Figure 5.27), as demonstrated in the two 'Midknight' Valencia orchards in both the summer and winter rainfall regions. Stomatal conductance increased initially with increasing VPD up to approximately 1 kPa and then began to decline. This seems to be a typical response for citrus and is possibly related to the maintenance of whole plant hydraulic safety, to avoid cavitation in desiccating environments (Tyree and Sperry, 1989; Sperry, 2000). The manner in which leaf water potential is controlled is important for understanding the regulation of T, with plants typically being divided into "water savers" with an isohydric strategy or "water spenders" with an anisohydric strategy (Tardieu and Simonneau, 1998).

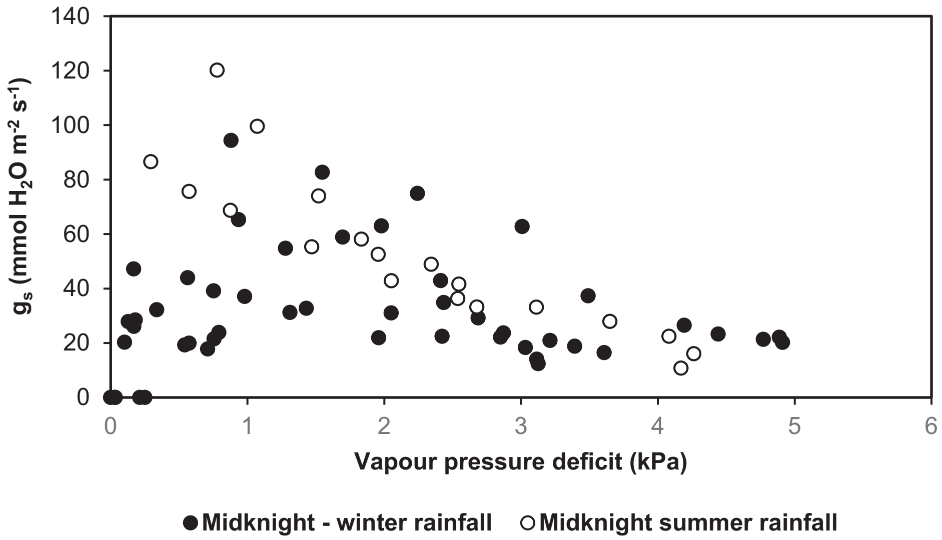


**Figure 5.27 The relationship between vapour pressure deficit and stomatal conductance ($g_s$) in a mature 'Midknight' Valencia orchard in Citrusdal and a mature 'Midknight' Valencia orchard in Letsitele**

In citrus $g_s$ have been observed to decline rapidly when midday $\Psi_{leaf}$ fall below -1.0 MPa for 30 month old 'Pera' orange trees (Gomes et al., 2004), whilst the closure of stomata occurred at a midday $\Psi_{leaf}$ lower than -2.2 MPa for 'Washington' navels (Cohen and Cohen, 1983). Syvertsen (1982) found that stomatal closure occurs over a relative narrow range of $\Psi_{leaf}$ 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 (1982) also noted stable maximum T rates, regardless of environmental conditions, suggesting strong stomatal control over T. However, due to an increase in evaporative demand, an increase in VPD can cause an increase in T, even if $g_s$ decreases. An increase in T usually results in more negative $\Psi_{leaf}$ and low $\Psi_{leaf}$ can reduce $g_s$. Decreases in $g_s$ in citrus with increasing VPD are generaly not great enough to decrease T under conditions of non-limiting soil water, which was often the case in our orchards.  Thus, in healthy well-watered trees $\Psi_{leaf}$ does not directly modulate stomatal behaviour and this is possibly why we do not see a clear relationship between $g_s$ and $\Psi_{leaf}$ in our orchards (Figure 5.28A). This unclear relationship can also be attributed to hysteresis in the data, where at the same $\Psi_{sun\ leaf}$ two distinct values for $g_s$ are found in the morning and the afternoon (Figure 5.28B). Stomata open in the morning in response to increasing $R_s$ and as transpiration begins, $\Psi_{leaf}$ starts to drop. However, as VPD increases passed a certain limit, $g_s$ starts to decrease to protect the hydraulic integrity of the plant and prevent $\Psi_{leaf}$ from falling further (KoÈrner and Cochrane, 1985). As a result $\Psi_{leaf}$ stabilises. Finally, $\Psi_{leaf}$ starts to recover in the afternoon as transpiration rate decreases due to a lowering of the VPD gradient out the leaf. It appears that stomatal responses to varying VPD may result in a reasonably constant T (the concept of a maximum transpiration rate suggested by Sinclair and Allen (1982)).

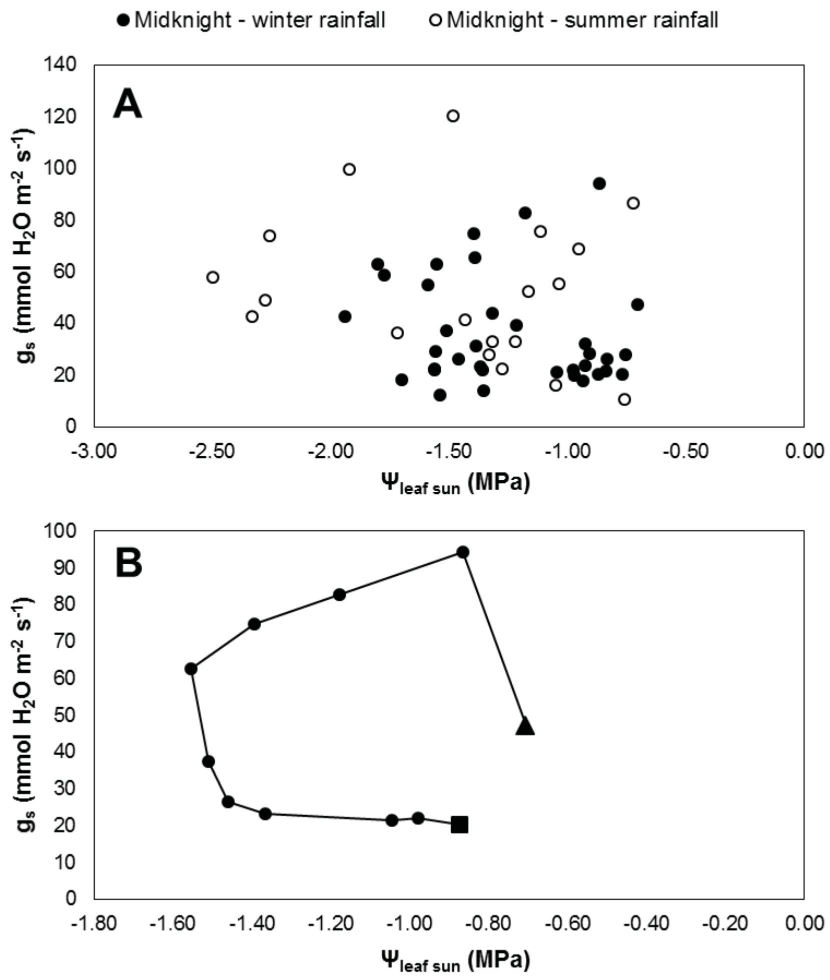


**Figure 5.28 A) The relationship between sun leaf water potential ($\Psi_{sun\ leaf}$) and stomatal conductance ($g_s$) in mature 'Midknight' Valencia orchards in the summer and winter rainfall regions. B) Hysteresis in the diurnal relationship between sun leaf water potential ($\Psi_{sun\ leaf}$) and $g_s$ in the Midknight Valencia orchard in Citrusdal. The data progresses chronologically from 8:00 (▲) to 18:00 (■)**

Upon examination of the diurnal course of $\Psi_{leaf}$ in 'Midknight' Valencia trees in the two rainfall regions and under different conditions, it is evident that the prevailing environmental conditions significantly impacted the minimum water potential of sunlit leaves ($\psi_{sun\ leaf}$) (Figure 5.29). On hotter and drier days (February in both regions) $\Psi_{leaf}$ reached lower levels than in the cooler winter (July – winter rainfall) and spring days (September – summer rainfall). The potential for control over $\Psi_{leaf}$ is evident in the data from the summer rainfall region in September when VPD reached close to 4.5 kPa in the middle of the day, yet $\Psi_{sun\ leaf}$ did not fall below -2 MPa. In contrast in February $\Psi_{sun\ leaf}$ fell below -2 MPa when maximum VPD was 2.7 kPa. The considerable drop in $\Psi_{shade\ leaf}$ indicates that these leaves were actively transpiring, as observed by Moreshet et al. (1990).

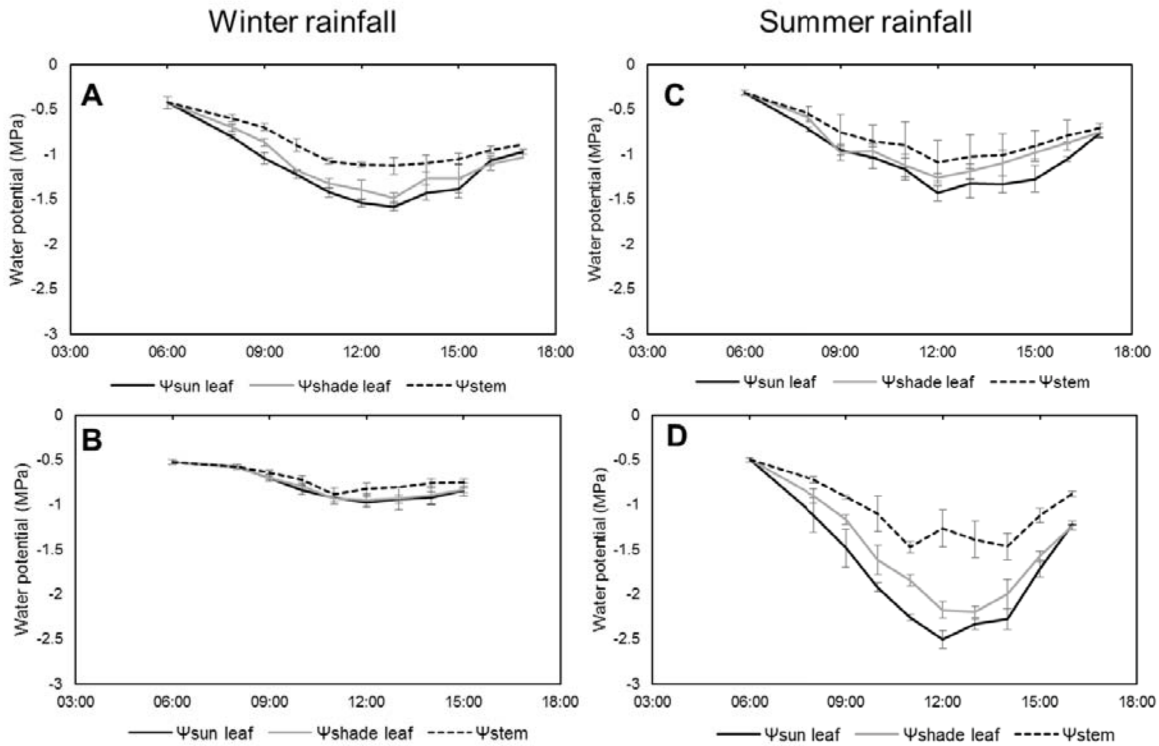


**Figure 5.29 Diurnal sun leaf water potential, shade leaf water potential and stem water potential for "Midknight' Valencia orchards in the summer and winter rainfall regions. A) February 2016, B) July 2016, C) September 2016 and D) February 2017**

Typical isohydric plants display very similar minimum midday sun $\Psi_{leaf}$ irrespective of environmental conditions or soil water content. However, in the 'Midknight' Valencia orchard in Citrusdal, very different minimum $\Psi_{leaf}$ were noted over the course of the study (Figure 5.30). Appreciable stomatal closure in *Citrus sinensis* was not observed until a $\Psi_{leaf}$ of -2.5 MPa, with full closure below -3.0 MPa. This is usually below the value regularly seen in the diurnal pattern of healthy irrigated trees, i.e. -2.3 MPa (Syvertsen and Albrigo, 1980; Lloyd and Howie, 1989). It is also interesting to note very different diurnal curves for the two rainfall regions during winter. Whilst Citrusdal is characterised by winter days with fairly low VPDs, the opposite is true for Letsitele in the summer rainfall, where winters and springs can be dry and warm.

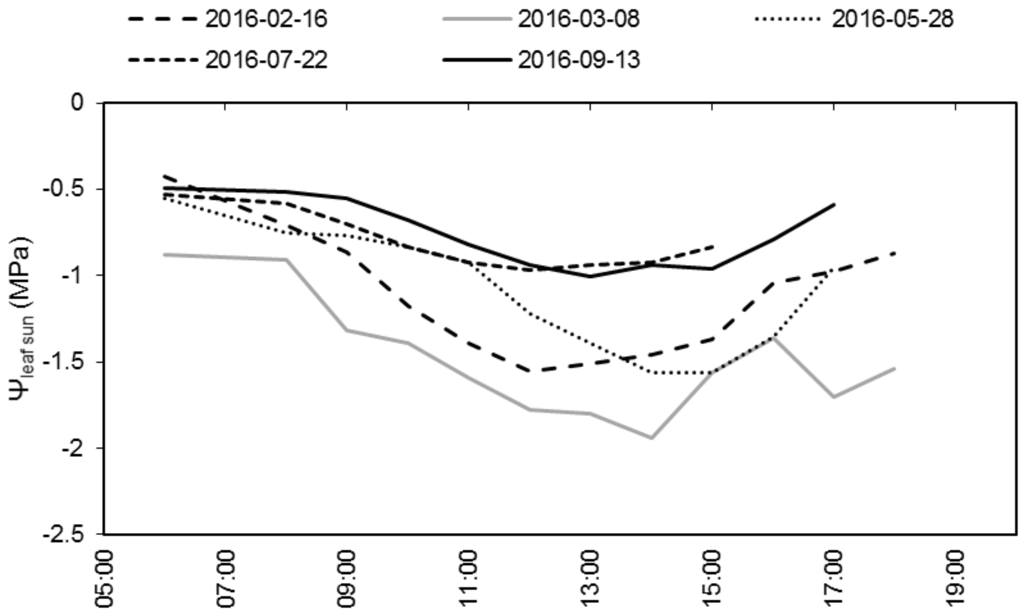


**Figure 5.30 Diurnal sun leaf water potentials for the mature 'Midknight' Valencia orchard in Citrusdal**

The question then arises – why can citrus trees not meet high atmospheric demands? As mentioned above this is largely a mechanism to protect hydraulic integrity. An examination of diurnal (Figure 5.31) and seasonal (Figure 5.32) trends of the partitioning of hydraulic conductances within the mature 'Midknight' Valencia trees revealed that hydraulic conductance is typically lower in the soil to stem pathway than the stem to leaf pathway. This is not surprising as high root resistances have been reported for citrus (Van Bavel et al., 1967; Kriedemann and Barrs, 1981; Sinclair and Allen, 1982). However, Moreshet et al. (1990) found that root conductances and the transpiring canopy conductance were comparable in size. These discrepancies could be a result of rootstocks and the soil type in which the trees are planted. Unfortunately, Moreshet et al. (1990) did not specify the rootstock, but if it was a more vigorous rootstock, the root system could have a higher hydraulic conductivity. Fairly low whole tree hydraulic conductance was noted for 'Midknight' Valencia trees in both rainfall regions. These conductances were typically slightly lower than those reported by Moreshet et al. (1990). However, conductance was lower in the summer than winter rainfall regions which requires further investigation. The accurate estimation of hydraulic conductance depends on knowing which leaves and how many of them are transpiring. Although we took into account both sun and shade leaves in our estimation of hydraulic conductance, the limited number of samples per tree could have resulted in some of the large errors observed in this study. However, by examining three to four trees the accuracy of our measurement would have been improved.

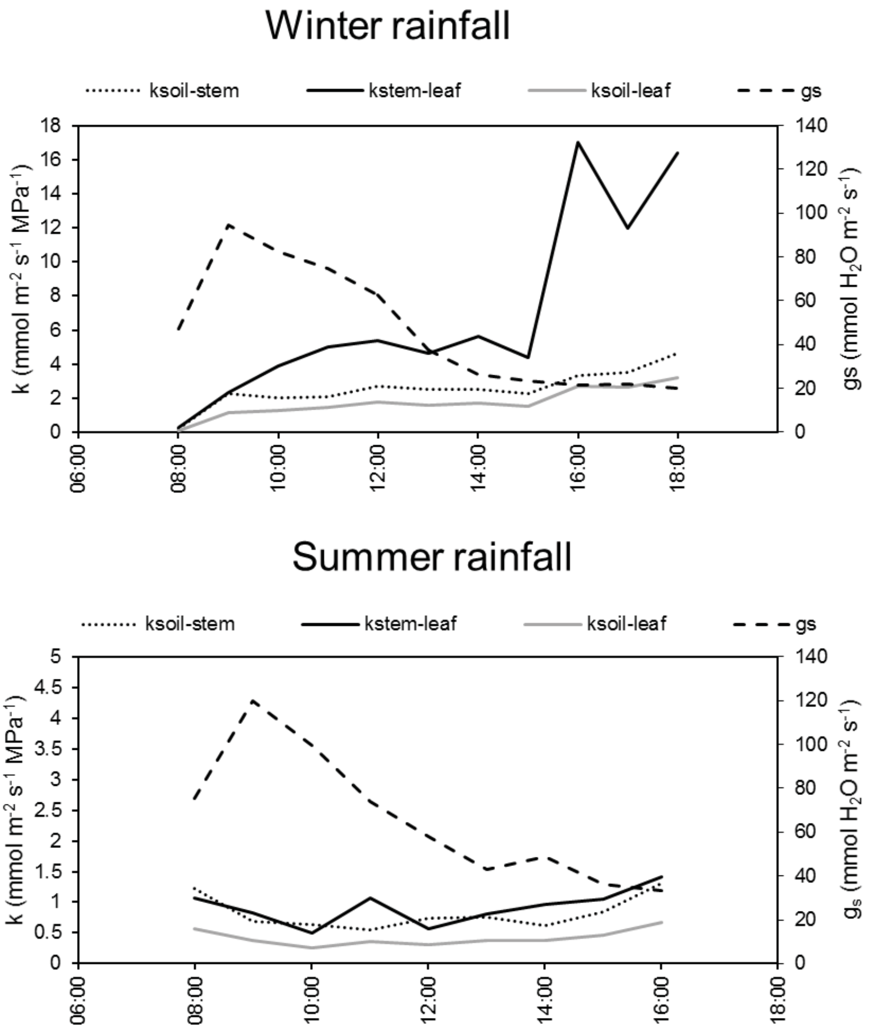


**Figure 5.31 Diurnal course of hydraulic conductances and stomatal conductance for the mature 'Midknight' Valencia orchards in the winter and summer rainfall regions**

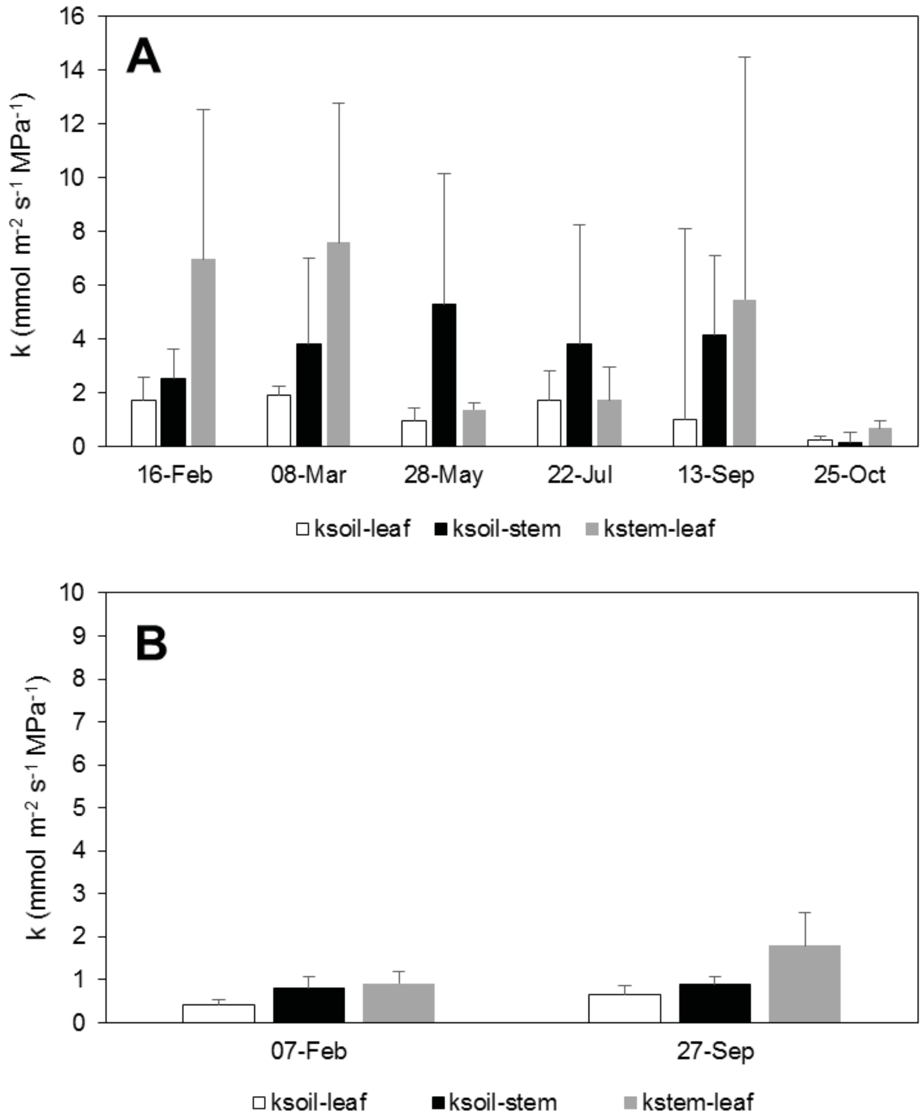


**Figure 5.32 Seasonal progression of average daily hydraulic conductances in mature 'Midknight' Valencia orchards in the A) winter and B) summer rainfall regions**

Whilst a plot of T versus $\psi_{sun\ leaf}$ was similar for mature 'Midknight' and 'Afourer' trees, 'Midknight' trees in the summer rainfall region exhibited a different trend (Figure 5.33). The slope of the relationship in the graph below is an estimation of the resistance to water flow between the soil and the leaf (Camacho-B, 1977) and therefore the 'Midknight' Valencia orchard appears to have higher resistances than the other trees in the winter rainfall region. Whilst this could indicate a change in hydraulic conductance under summer rainfall conditions, it could also be attributed to a smaller data set for this orchard that did not cover a greater period of the growing season.

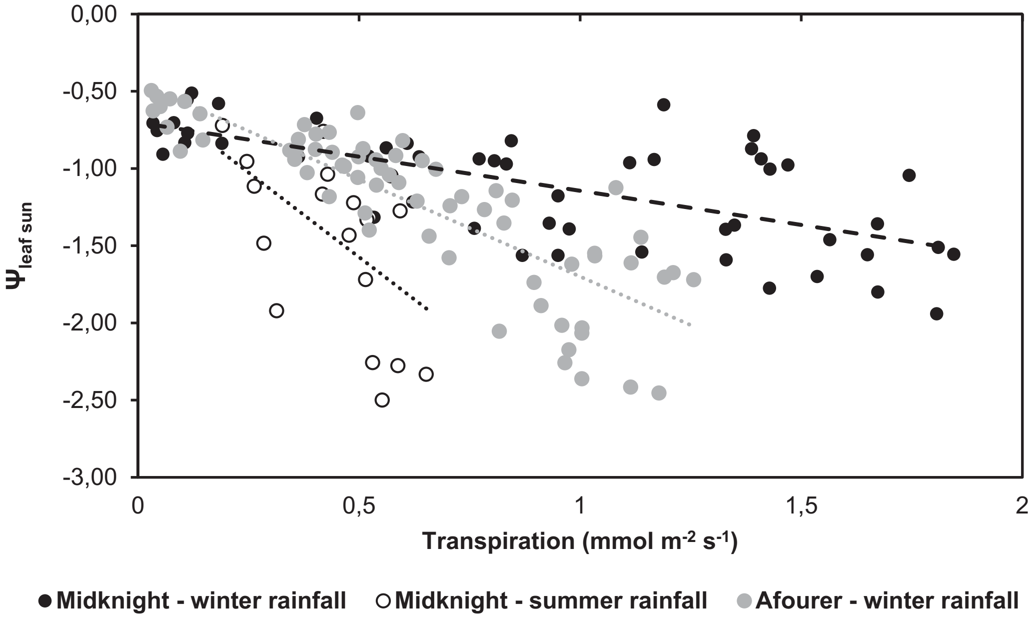


**Figure 5.33 The relationship between transpiration and sun leaf water potential in mature orchards in the summer and winter rainfall areas**

# 6 MODELLING CITRUS WATER USE

## 6.1 Introduction

From the analysis of the T measurements, together with certain ancillary variables, it was apparent that when modelling citrus T, stomatal regulation should be taken into consideration. Therefore, a simple mechanistic model that allows the calculation of T, based on canopy conductance ($g_c$) is of paramount importance. Orgaz et al. (2007), proposed a semi-empirical model that calculates bulk $g_c$ of evergreen trees as a function of tree intercepted radiation (*fI*PAR) and VPD (equation 7). This was based on the earlier works of Leuning (1995), who established the relationship between conductance and carbon dioxide assimilation. Based on the established relationships of Orgaz et al. (2007), a model that calculates $g_c$ for water vapour (mol-m$^{-2}$s$^{-1}$) in different fruit tree and nut species was developed and validated by Villalobos et al. (2013) (equation 7). The model simulates the integrated effects of stomatal control on T over a day. In this approach $g_c$ is modelled from T measurements, which is based on the model of Orgaz et al. (2007) and incorporated into the "imposed" evaporation equation (Tan et al., 1978; McNaughton and Jarvis, 1983) to allow the calculation of the average T rate during the daytime ($E_p$, mol m$^{-2}$ s$^{-1}$; equation 8).

$$g_c = 1.6c \frac{\alpha Q R_{sp}}{\left(1+\left(\frac{D}{D_o}\right)\right)C_s} \tag{7}$$

where, c is an empirical coefficient (dimensionless), α is the radiation use efficiency (μmol $CO_2$ μmol$^{-1}$), Q is the fraction of PAR intercepted by the canopy (dimensionless), $R_{sp}$ is the average incident daily PAR (μmol m$^{-2}$ s$^{-1}$), D the VPD (kPa), $D_o$ (kPa) is an empirical coefficient related to the response of stomatal closure to D, $C_s$ is the $CO_2$ concentration in the leaf boundary layer (μmol mol$^{-1}$) and the coefficient 1.6 converts conductance for $CO_2$ to that of water vapour, where, $P_a$ is atmospheric pressure.

$$E_p = 1.6c \frac{\alpha Q R_{sp}}{\left(1+\left(\frac{D}{D_o}\right)\right)C_s} \frac{D}{P_a} \tag{8}$$

By rearranging equation 7, Cs, c, α and $D_o$ can be estimated from the slope and intercept of the linear function of intercepted radiation and $g_c$ with D*,* as follows

$$\frac{QR_{sp}}{g_c} = \frac{C_s}{1.6c \propto D_0}(D + D_0) = a + bD \tag{9}$$

Following the determination of a and b, based on actual measurements, daily T ($E_{pd}$, in mm day$^{-1}$) can be expressed as a function of total daily $R_{sp}$ (J m$^{-2}$ d$^{-1}$).

$$E_{pd} = 37.08 \times 10^{-3} \frac{QR_{sd}}{a+bD} \frac{D}{P} \quad (10)$$

where, $R_{sd}$ is total daily solar radiation and the coefficient 37.08 x 10$^{-3}$ incorporates the conversion of units for Joules of $R_s$ to μmol quanta and from mol to kg water.

For the calibration of the model daytime mean values of $g_c$ were calculated by inversion of the imposed evaporation equation as follows

$$g_c = \frac{E_p P_a}{D} \quad (11)$$

where, mean daytime values of T were obtained by dividing total T by daylength and D was averaged for the daytime period.

The fraction of intercepted radiation by the canopy was determined using the model of Oyarzun et al. (2007), which computes the fraction of intercepted radiation in row crops based on the fraction of the orchard ground that is shaded by the trees at any given time (FGs). The trees are considered as prismatic-shaped porous bodies. Intercepted radiation by the trees is calculated based on geometric relationships between the canopy structure, the sun position and the length of the shadow cast by the trees. Inputs for the model include tree dimensions (height of the trees, height of insertion of the lower branches and canopy width, both perpendicular and parallel to rows), orchard configuration (planting distances, direction of rows, slope and aspect), daily global $R_s$ and a correction factor which accounts for gaps in the canopy (i.e. canopy porosity). Canopy porosity ($C_p$) is estimated from the proportion of sunfleck within the shaded area cast by the trees on the ground (Figure 6.1).

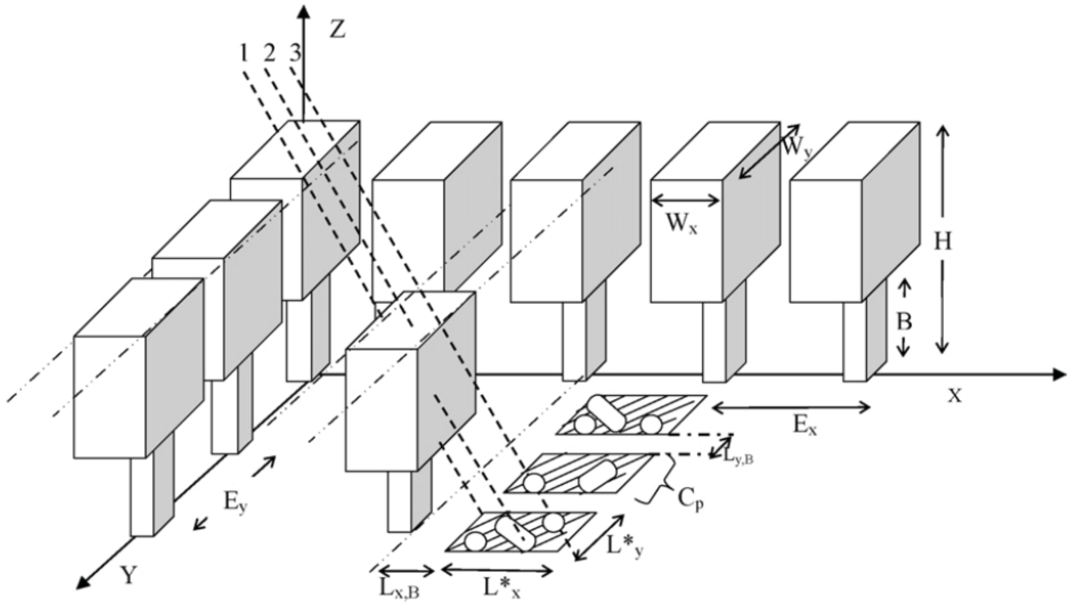


**Figure 6.1 Schematic representation of a fruit tree orchard showing model input parameters used in radiation interception modelling related to orchard configuration, canopy dimensions, and canopy porosity. The dotted lines show the interaction between solar rays (---) and the trees when: (1) the direct rays of the sun pass unobstructed below the canopy; (2) the direct rays of the sun pass unobstructed through gaps in the canopy, observed as a sunfleck on the shaded ground area ($C_P$); and (3) the beam passes by the edge of the canopy, thus casting a shadow**

The model was calibrated and validated with data that was collected during the 2015/2016 and 2016/2017 seasons in the winter and summer rainfall regions. The model was tested across different species/varieties with different canopy sizes. This comparison did not only provide an opportunity to assess the effect of leaf area variation on the fraction of $R_s$ intercepted by the canopies, but it also provided a platform to test the proposed model in a wide range of citrus species/varieties to ascertain if radiation interception in citrus can be modelled generically or if species/variety calibration is required.

## 6.2 Hourly and daily simulation of PAR interception in the winter rainfall region

A summary of all the input parameters used for simulation is shown in Table 6.1.

**Table 6.1 Input parameters used to model hourly and daily values of fractional interception of photosynthetically active radiation by different citrus species/varieties in the winter rainfall region. The year indicates the planting date for each orchard**

| Input parameters | 'Afourer' mandarin | | 'Midknight 'Valencia | | 'McLean' Valencia |
|---|---|---|---|---|---|
| | 2002 | 2013 | 2000 | 2008 | 2010 |
| Altitude (m) | 200 | 184 | 160 | 184 | 185 |
| Latitude (°) | -32.50 | -32.54 | -32.45 | -32.50 | -32.50 |
| Longitude (°) | 18.99 | 19.00 | 18.96 | 18.98 | 18.98 |
| Xstd (°) | 30 | 30 | 30 | 30 | 30 |
| $E_x$,$E_y$ (m) | 5.5 x 3.0 | 5.0 x 3.0 | 5.0 x 2.5 | 5.0 x 3.0 | 5.0 x 3.0 |
| H (m) | 3.2-6.0 | 1.9-3.0 | 3.5-4.8 | 3.2-4.0 | 2.-3.0 |
| $W_y$ (m) | 2.3-4.0 | 1.0-2.2 | 5.2-4.8 | 2-3.5 | 2-3.5 |
| $W_x$ (m) | 3.2-6.0 | 1.3-2.9 | 3.4-5.0 | 3-4.0 | 2-3.0 |
| B (m) | 0.35-0.40 | 0.39-1.0 | 0.3-0.40 | 0.3-0.28 | 0.4-0.30 |
| $C_p$ | 0.06-0.01 | 0.5-0.4 | 0.14-0.04 | 0.6-0.4 | 0.05-0.01 |
| ϕ (°) | 159 | 16 | 86 | 8 | 8 NS |
| ρ ( °) | 0.2 | 0 | 0.4 | 0 | 0 |

Abbreviations – Xstd – standard meridian, $E_x$ – spacing between rows, $E_y$ – distance between trees in a row, H – canopy height, $W_y$ – canopy width along the row direction, $W_x$ – canopy width perpendicular to the row direction, B – height of insertion of lower branches, $C_p$ – field-observed canopy porosity, ϕ – row azimuth, ρ – terrain slope

The diurnal measured and simulated hourly fractional interception of PAR (*f*IPAR) for the different orchards in the winter rainfall is shown Figure 6.2 and Figure 6.3. Although simulations were done in all the study orchards, selected orchards are presented to show the diurnal pattern of *f*IPAR. The selected orchards were representative of the study orchards (i.e.; different species/variety, orchard configuration, slope and canopy size). In addition, simulations excluded data sets under variable sky conditions. As observed by Oyarzun et al. (2007), the model is incapable of simulating variable sky conditions, which only contributed 23% of the whole data set in the winter rainfall region. Comparisons of hourly estimates of *f*IPAR in the winter rainfall region indicated acceptable results. The model simulated diurnal trends of hourly *f*IPAR fairly well (Figure 6.2 and Figure 6.3). The diurnal patterns were similar for all measurements, which can be represented by a bell-shaped, i.e. high interception in the morning and in the afternoon, with the lowest interception at midday.

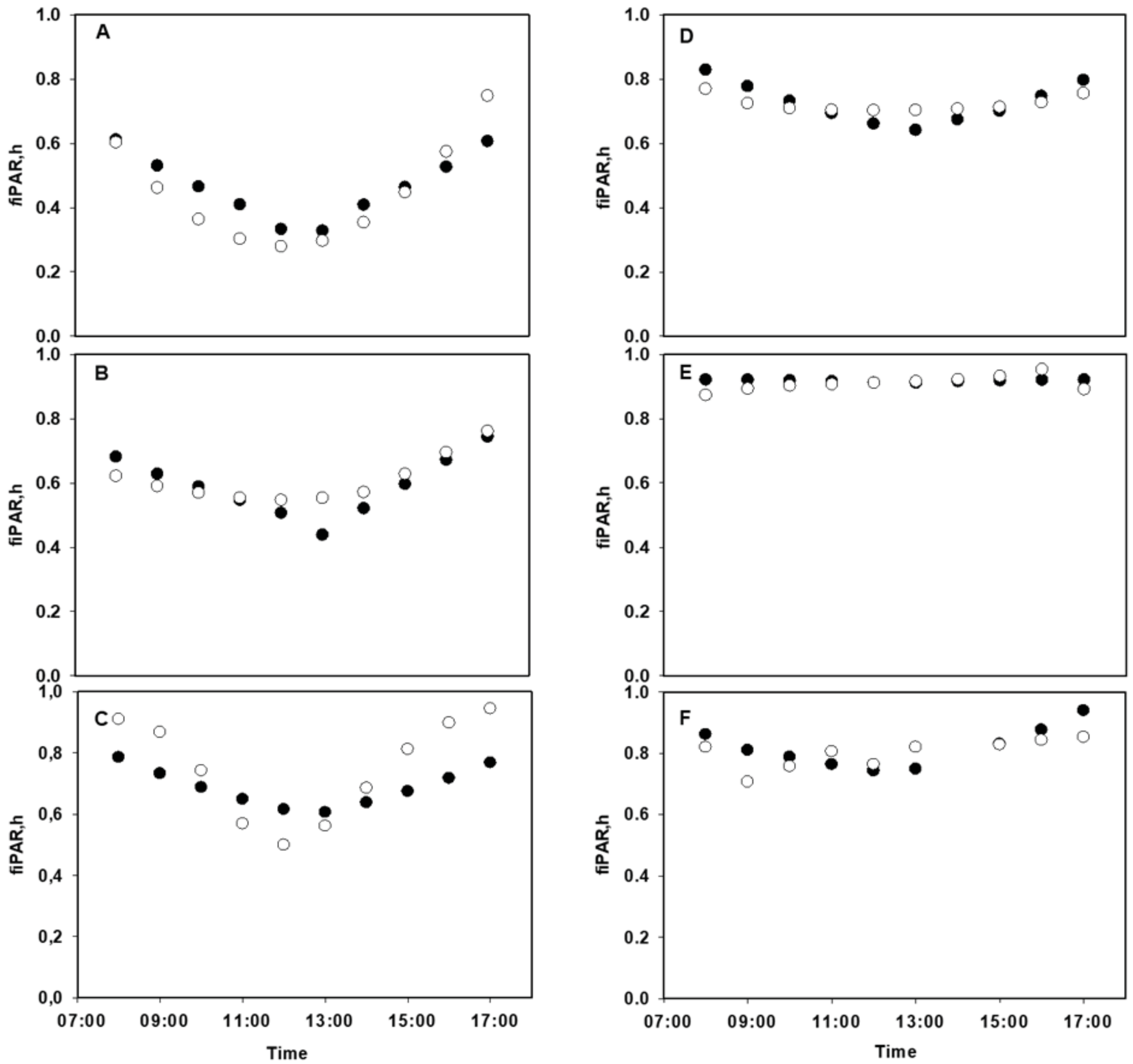


**Figure 6.2 Diurnal variation of hourly fractional interception of PAR (*fI*PAR,h) for 'Afourer' mandarin orchards planted in 2013 (A,B and C) and 2002 (D E, and F). PAR data was collected in October 2015 (A and D), February 2016 (B and E), and October 2016 (C and F) Solid circles represent simulated *fI*PAR, h and open triangles represent measured fIPAR, h**

However, discrepancies were observed in the diurnal trend. This was largely due to the asymmetrical shape of the canopy. For simplicity, the model assumes a prismatic shape of the tree canopies, however, this geometric shape causes inaccurate estimates of the canopy light interception as the canopy develops (Pereira et al., 2017). This was also observed in the current study; the model estimated radiation interception with high accuracy in the small sized canopies. Some studies have assumed more complex geometric shapes such as ellipsoids, truncated ellipsoids (Annandale et al., 2004) and spheres (Morse and Robertson, 1987). As stated by Oyarzun et al. (2007), the use of such complex geometric shapes may result in a better representation of the canopy shape, but it may lead to a complicated model and complex mathematics. Despite the discrepancies, the statistical parameters for hourly simulation indicated that the model can be used to successfully simulate hourly intercepted radiation by citrus canopies (Table 6.2).

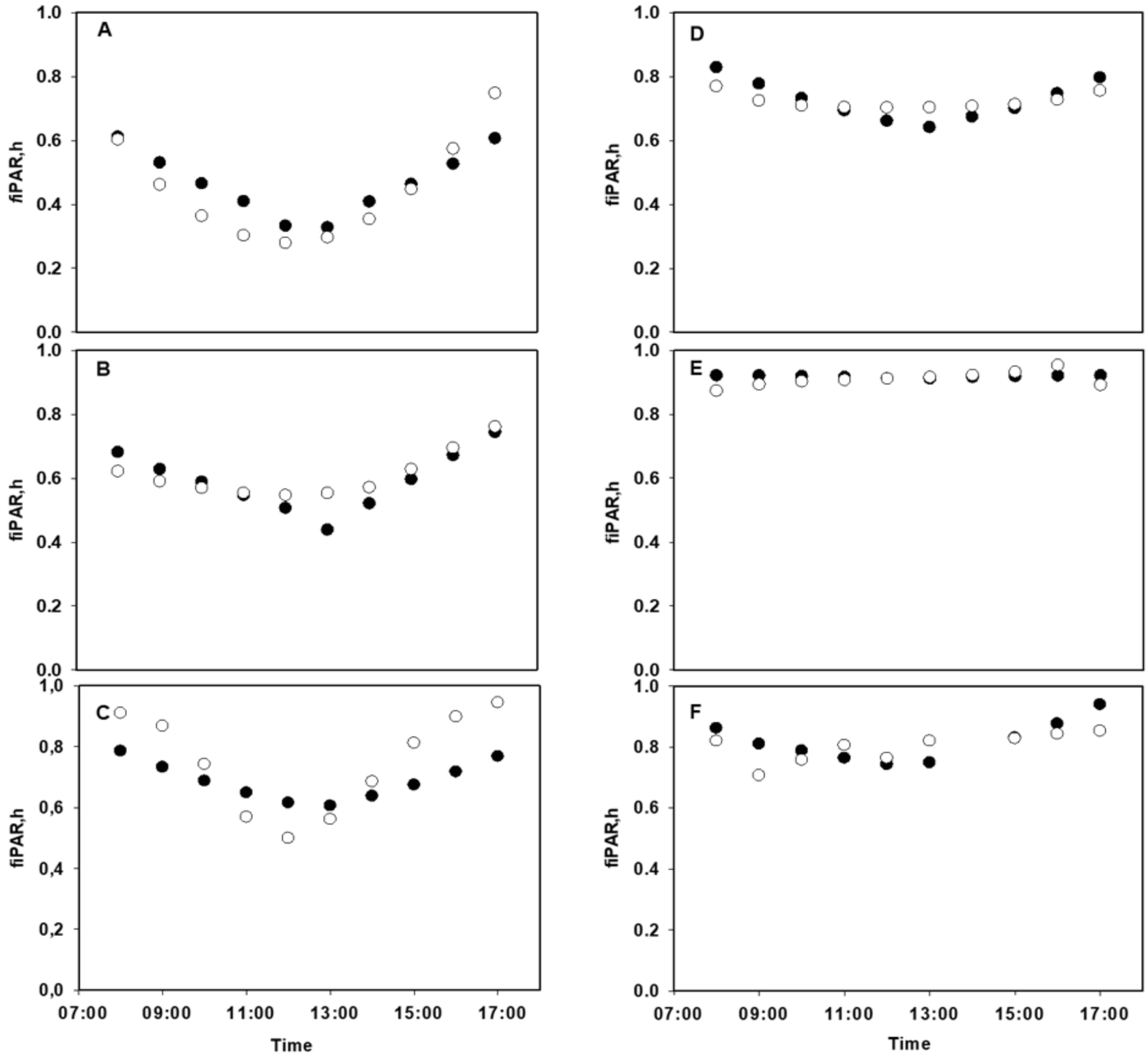


**Figure 6.3 Diurnal variation of hourly fractional interception of PAR (*fI*PAR, h) for 'Midknight' Valencia orchards planted in 2008 (A, B and C) and 2000 (D, E and F). PAR data was collected in October 2015 (A and D), February 2016 (B and E) and October 2016 (C and D). Solid circles represent simulated *fI*PAR, h and open triangles represent measured *fI*PAR, h**

**Table 6.2 Model performance for the hourly estimations of *f*IPAR for the winter rainfall region. $R^2$ is the coefficient of determination, RMSE is the root mean square error, MAE is the mean absolute error, CRM is the coefficient of residual mass and D is the Wilmott's index of agreement**

| Species | Planting date | $R^2$ | RMSE | MAE (%) | CRM | D |
|---|---|---|---|---|---|---|
| 'Afourer' mandarins | 2013 | 0.81 | 0.06 | 5.3 | 0.00 | 0.96 |
| | 2002 | 0.82 | 0.05 | 3.6 | 0.01 | 0.93 |
| 'MIdknight' Valencia | 2008 | 0.69 | 0.09 | 5.3 | 0.01 | 0.90 |
| | 2000 | 0.63 | 0.06 | 5.8 | 0.06 | 0.85 |
| | 2010 | 0.54 | 0.15 | 8 | 0.06 | 0.78 |

The performance of the model for daily measured and simulated values is shown in Figure 6.4 and Table 6.3. As expected, the model performed better with daily estimations of *f*IPAR or *f*DIPAR than hourly values. The overall performance of the model, as indicted by statistical parameters, was good ($R^2$=0.93 and D=0.98). Errors, quantified as RMSE, MAE and CRM were within acceptable range of 0.17, 0.4 and 0.03 respectively.

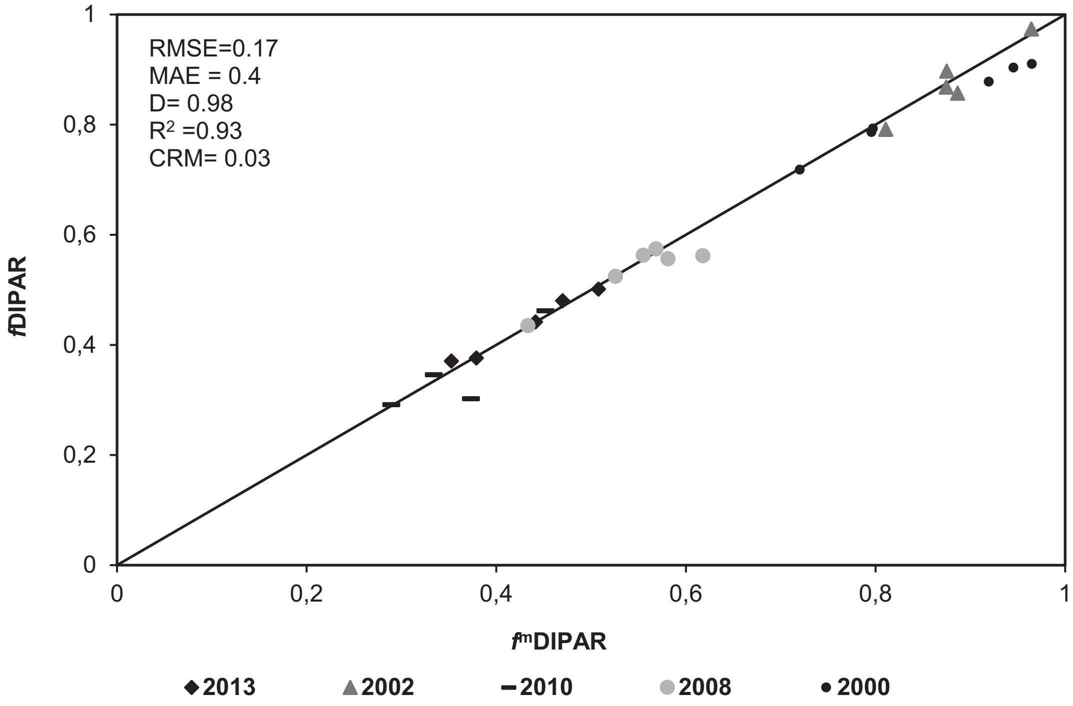


**Figure 6.4 Comparison of the measured ($f^m$DIPAR) and estimated ($f$DIPAR) daily fractional interception of PAR for all the species and/or cultivar considered in the winter rainfall region: 'Afourer' mandarin orchard planted in 2002 and 2013, 'Midknight' Valencia orchards planted in 2008 and 2000 and McLean Valencia orchard planted in 2010. The solid line is the 1:1 line**

**Table 6.3 Model performance for the daily estimation of $f$IPAR in the winter rainfall region. $R^2$ is the coefficient of determination, RMSE is the root mean square error, MAE is the mean absolute error, CRM is the coefficient of residual mass and D is the Wilmott's index of agreement**

| Species | Orchard | $R^2$ | RMSE | MAE (%) | CRM | D |
|---|---|---|---|---|---|---|
| 'Afourer' mandarins | 2013 | 0.86 | 0.001 | 4.0 | 0.00 | 0.80 |
| | 2002 | 0.70 | 0.02 | 1.7 | -0.00 | 0.85 |
| 'Midknight' Valencia | 2010 | 0.80 | 0.04 | 2.8 | -0.02 | 0.91 |
| | 2008 | 0.81 | 0.08 | 2.0 | 0.00 | 0.92 |
| | 2000 | 0.75 | 0.03 | 2.6 | 0.02 | 0.80 |

## 6.3 Hourly and daily simulation of PAR interception in the summer rainfall region

The input parameters used in model parametrisation are shown in Table 6.4 for all the study orchards in the summer rainfall region.

**Table 6.4 Input parameters used to model hourly and daily values of fractional interception of photosynthetically active radiation by different citrus species/varieties in the summer rainfall region. The year indicates the planting date for each orchard**

| Input parameters | 'Star Ruby' grapefruit | | | 'Midknight' Valencia | | | 'Valley Gold' mandarin | |
|---|---|---|---|---|---|---|---|---|
| | **2006** | **2010** | **2011** | **1995** | **2008** | **2014** | **2013** | **2015** |
| Altitude (m) | 491 | 492 | 496 | 439 | 455 | 456 | 550 | 579 |
| Latitude (°) | -23.80 | -23.80 | -23.80 | -23.70 | -23.69 | -32.47 | -23.85 | -23.86 |
| Longitude (°) | 30.40 | 30.46 | 30.42 | 30.58 | 30.57 | 30.27 | 30.35 | 30.35 |
| Xstd (°) | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| $E_x$, $E_y$(m) | 7 x 3 | 7 x 3 | 7 x 3 | 7 x 3 | 7 x 3 | 7 x 3 | 7 x 3 | 7 x 3 |
| H (m) | 3.2-6.0 | 2-5.0 | 2.0-4.0 | 3.2-4.0 | 2.6-3.0 | 4.0-5.2 | 3.2-6.0 | 1.9-3.0 |
| $W_y$ (m) | 3.0-4.2 | 1.2-3.0 | 1.5-3.0 | 2.0-3.5 | 2.7-3.0 | 1.5-3.0 | 2.3-4.0 | 1.0-2.2 |
| $W_x$ (m) | 3.2-6.0 | 1.3-2.9 | 3.0-5.0 | 3.0-4.1 | 2.0-2.6 | 1.8-3.0 | 3.2-6.0 | 1.3-2.9 |
| B (m) | 0.40 | 0.39 | 0.30-0.40 | 0.30 | 0.40 | 0.30-0.40 | 0.35-0.40 | 0.39-1.00 |
| $C_p$ | 0.05-0.01 | 0.36-0.20 | 0.70-0.50 | 0.01-0.13 | 0.54-0.51 | 0.75-0.54 | 0.80-0.50 | 0.80-0.66 |
| $\phi$ (°) | 65 NE | 65 NE | 42 NE | 90 E | 90 E | 0 N | 116 | 30 NE |
| $\rho$ (°) | 0 | 0 | 0 | 0.4 | 0 | 0 | 0 | 0.3 |

Abbreviations – Xstd – standard meridian, $E_x$ – spacing between rows, $E_y$ – distance between trees in a row, H – canopy height, $W_y$ – canopy width along the row direction, $W_x$ – canopy width perpendicular to the row direction, B – height of insertion of lower branches, $C_p$ – field-observed canopy porosity, $\phi$ – row azimuth, $\rho$ – terrain slope

Modelled hourly radiation interception in the summer rainfall region was consistent with the results obtained in the winter rainfall region. Hourly simulations followed the same pattern, which reflected the impact of row orientation or slope of terrain on intercepted radiation (Figure 6.5 and Figure 6.6), as both regions had orchards that had a nearly N-S and/or E-W orientation with a negligible slope (1.5-3$^{o}$). As in the winter rainfall region, the model simulated hourly *f*IPAR well. However, as also seen in the winter rainfall region, the ability of the model to simulate hourly interception declined with an increase in canopy size (Table 6.5). This was a result of either: 1) An error in the input parameter's acquisition; as the $C_p$ was measured using a grid method, although this presented a simple and practical way of estimating the parameter, accuracy is hugely compromised in trees with big canopies (Castillo-Ruiz et al., 2016) or 2) the inherent heterogeneity of the canopy of mature citrus trees results in an irregular shape which is better represented by an ellipsoid and not a prism.

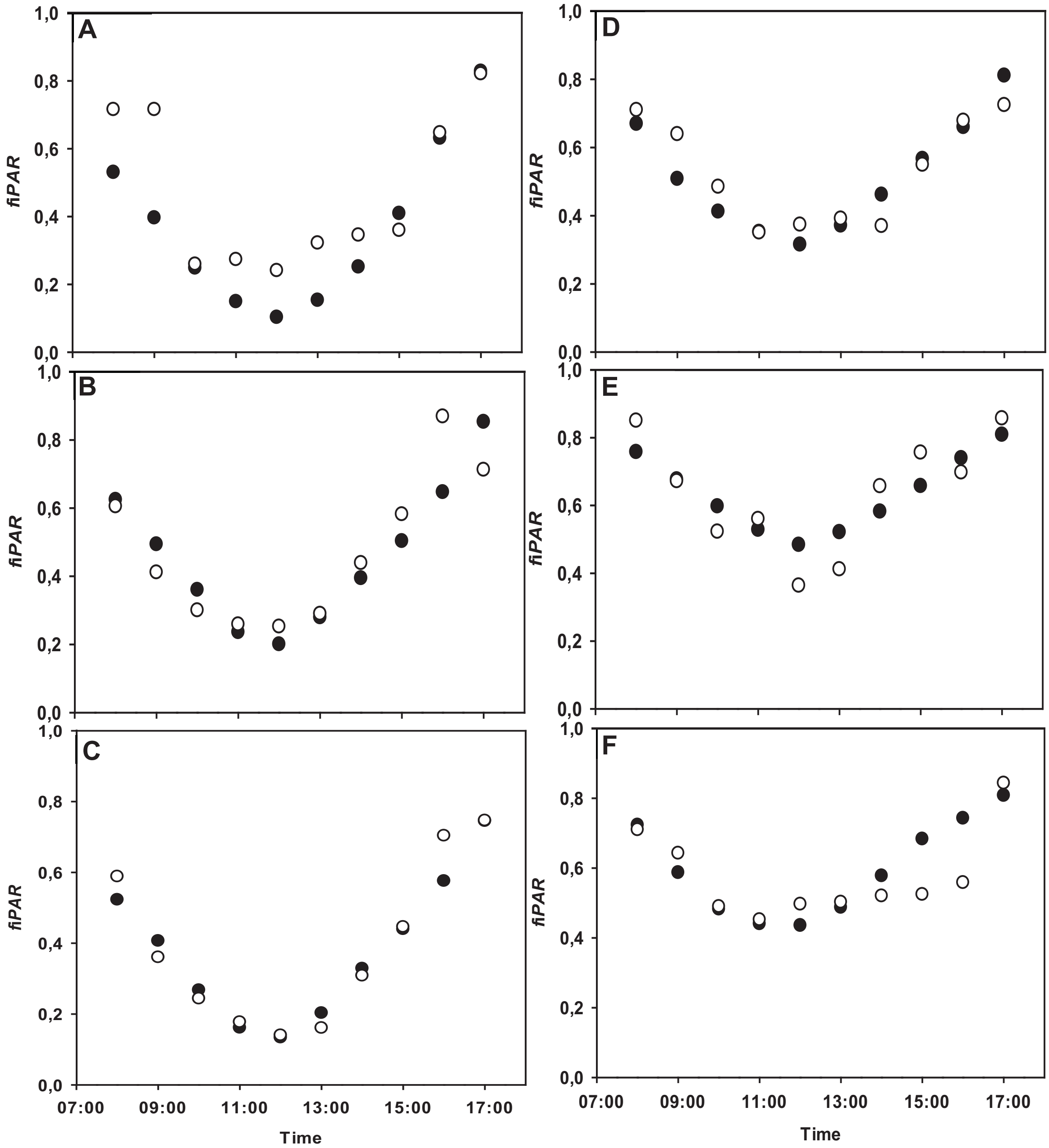


**Figure 6.5 Diurnal variation of hourly fractional interception of PAR (*fI*PAR, h) for 'Valley Gold' mandarin orchards planted in 2015 (A, B and C) and 'Valley Gold' mandarin orchards planted in 2013 (D, E, and F). PAR interception data was collected in April (A and D), February 2017 (B and E) and October 2017 (C and F). Solid circles represent simulated *fI*PAR, h and open triangles represent measured *fI*PAR, h**

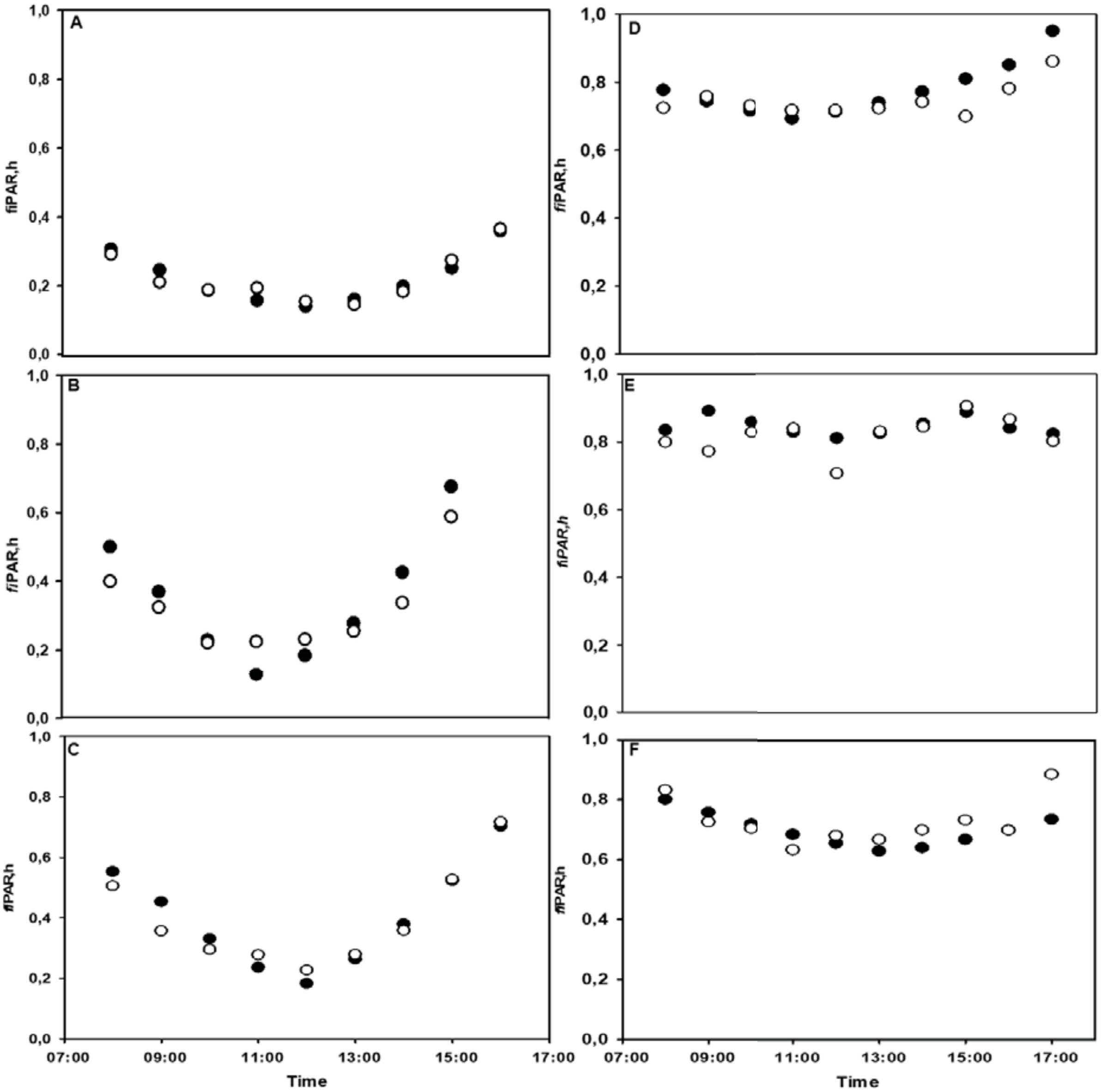


**Figure 6.6 Diurnal variation of hourly fractional interception of PAR (*f*IPAR, h) for the 'Midknight' Valencia orchard planted in 2014 (A, B and C) and the 'Midknight' Valencia orchard planted in 1995 (D, E, and F). The data set for the Midknight' Valencia orchard planted in 2014 was collected August 2016, and February and May 2017 (A, B, and C respectively). PAR interception data was collected in May, September 2016 and February 2017 for 'Midknight' Valencia orchard planted in 1995 (D, E, F respectively). Solid circles represent simulated *f*IPAR, h and open triangles represent measured *f*IPAR**

**Table 6.5 Model performance for the hourly estimations of *f*IPAR in the summer rainfall region. $R^2$ is the coefficient of determination, RMSE is the root mean square error, MAE is the mean absolute error, CRM is the coefficient of residual mass and D is the Wilmott's index of agreement**

| Species | Planting date | $R^2$ | RMSE | MAE (%) | CRM | D |
|---|---|---|---|---|---|---|
| **'Midknight' Valencia** | 2014 | 0.91 | 0.07 | 5.3 | 0.00 | 0.95 |
| | 2008 | 0.78 | 0.11 | 6.7 | 0.01 | 0.91 |
| | 1995 | 0.69 | 0.12 | 9.7 | 0.03 | 0.78 |
| **'Valley Gold' mandarins** | 2015 | 0.80 | 0.09 | 6.7 | 0.01 | 0.94 |
| | 2013 | 0.74 | 0.08 | 7.6 | 0.02 | 0.90 |
| **'Star Ruby' grapefruit** | 2006 | 0.60 | 0.24 | 17.0 | -0.50 | 0.75 |
| | 2010 | 0.62 | 0.20 | 16.0 | -0.60 | 0.76 |
| | 2011 | 0.65 | 0.19 | 12.0 | -0.56 | 0.80 |

On a daily timescale, the model provided good simulations of the fraction of intercepted radiation, as the model statistics were within an acceptable range (Figure 6.7 and Table 6.6). In most orchards, the agreement between observed and predicted daily interception (D) was close to 1 (Table 6.6). Therefore, the model by Oyarzun et al. (2007) can be successfully used to estimate daily radiation interception. In addition, errors between modelled and measured data (RMSE and MAE) were minimal when compared to hourly estimates.

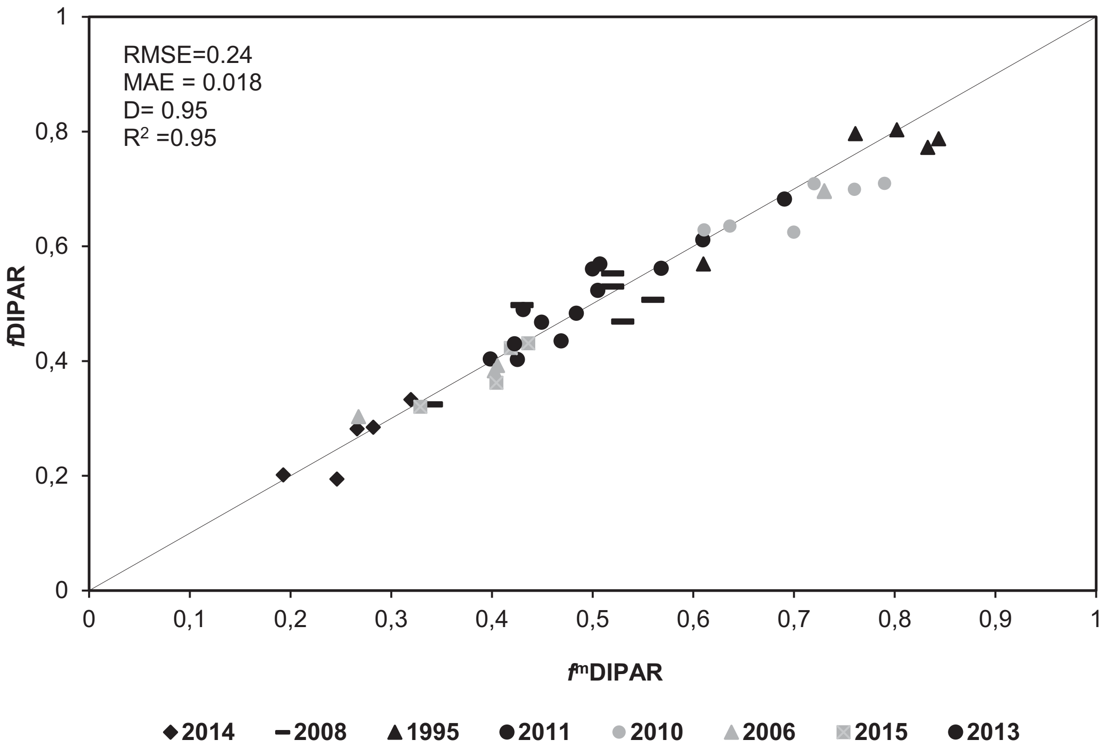


**Figure 6.7 Comparison of the measured ($f^m$DIPAR) and estimated ($f$DIPAR) daily fractional interception of PAR for all the species and/or cultivar considered in the summer rainfall region: 'Midknight' Valencia orchards planted in 1995, 2008 and 2014, 'Star Ruby' grapefruit orchards planted in 2006, 2010 and 2011 and 'Valley Gold' mandarin orchards planted in 2013 and 2015. The solid line is the 1:1 line**

**Table 6.6 Model performance for the daily estimation of *f*IPAR in the summer rainfall region. $R^2$ is the coefficient of determination, RMSE is the root mean square error, MAE is the mean absolute error, CRM is the coefficient of residual mass and D is the Wilmott's index of agreement**

| Species | Planting date | $R^2$ | RMSE | MAE (%) | CRM | D |
|---|---|---|---|---|---|---|
| 'Midknight' Valencia | 2014 | 0.84 | 0.08 | 1.8 | 0.00 | 0.94 |
| | 2008 | 0.65 | 0.05 | 1.6 | 0.04 | 0.75 |
| | 1995 | 0.83 | 0.03 | 3.2 | 0.01 | 0.83 |
| 'Valley Gold' mandarins | 2015 | 0.93 | 0.03 | 2.1 | 0.05 | 0.92 |
| | 2013 | 0.94 | 0.03 | 2.3 | 0.03 | 0.91 |
| 'Star Ruby' grapefruit | 2006 | 0.63 | 0.9.0 | 11.0 | -0.50 | 0.76 |
| | 2010 | 0.68 | 0.50 | 8.0 | -0.40 | 0.78 |
| | 2011 | 0.64 | | 12.0 | -0.60 | 0.76 |

## 6.4 Modelling of daily canopy conductance and transpiration in the winter rainfall region

### 6.4.1 Canopy conductance

The bulk $g_c$ of the orchards in the winter rainfall region (calculated using equation 10) showed a seasonal pattern of variation (Figure 6.8). Very low values were observed in spring and summer and higher values during autumn and winter. Canopy conductance values reached maximum in winter (June/July). The mature orchards (2002 'Afourer' mandarin orchard and 2000 'Midknight' Valencia orchard) exhibited higher $g_c$ values varying between 0.05 and 1.18 mol $m^{-2}$ $s^{-1}$, whilst in the 2008 'Midknight' Valencia orchard $g_c$ varied between 0.02 and 0.88 mol $m^{-2}$ $s^{-1}$. The trend in the data was comparable to those found by Testi et al. (2006) in olives and Villalobos et al. (2013) in citrus, as these authors also found an increase in $g_c$ in winter and autumn.

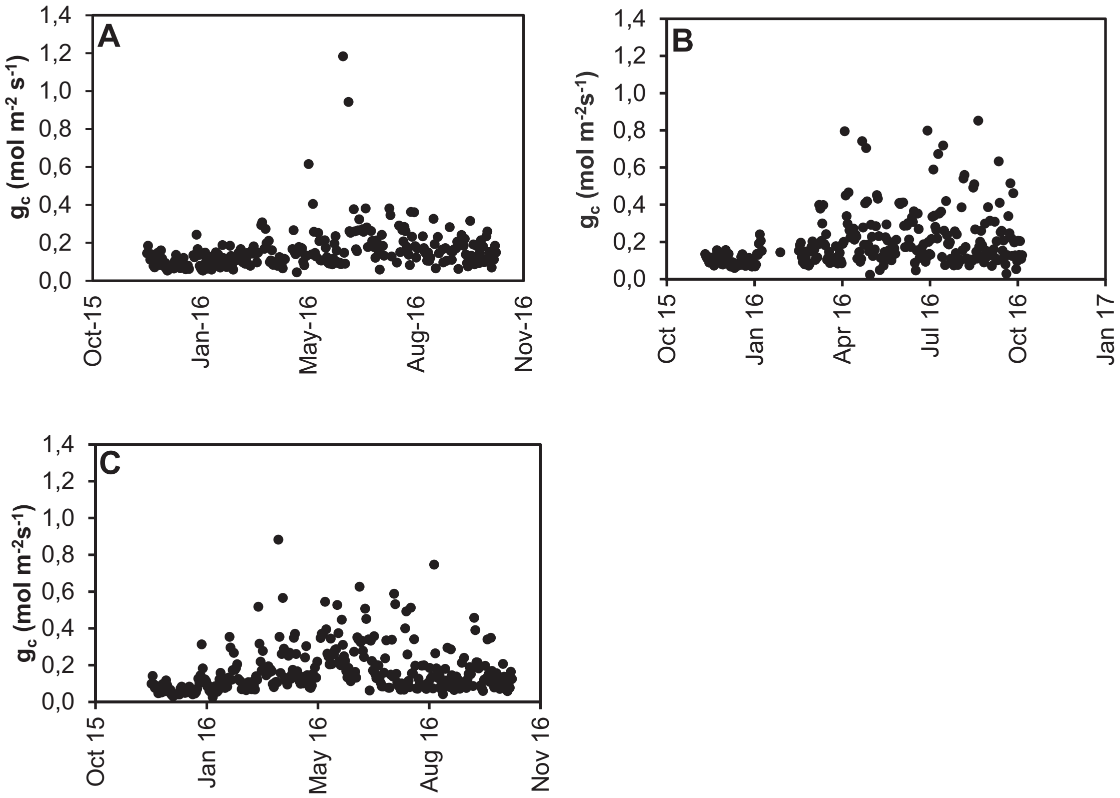


**Figure 6.8 Time series of bulk canopy conductance ($g_c$) in the winter rainfall orchards calculated by inverting the imposed evaporation equation. A) 'Afourer' mandarin orchard planted in 2002, B) 'Midknight' Valencia orchard planted in 2000 and C) 'Midknight' Valencia orchard planted in 2008**

However, the absolute values were slightly different from those obtained by Villalobos et al. (2013) for citrus. The maximum $g_c$ values observed in the study were significantly higher (average range between 0.02 mol m$^{-2}$ s$^{-1}$ and 0.96 mol m$^{-2}$ s$^{-1}$) than those obtained by Villalobos et al. (2013) (0.074-0.100 mol m$^{-2}$ s$^{-1}$). This could be attributed to the differences in canopy size, as illustrated by the difference in LAI values for the two studies. The orchards in Villalobos et al. (2013) had an LAI ranging between 1.1 and 1.7 m$^2$ m$^{-2}$, whilst in the current study LAI ranged from 2.5-4.6 m$^2$ m$^{-2}$. The plot $QR_{sp}/g_c$ against D, to determine the coefficients a (intercept) and b (slope) of the linear function (equation 9), is shown in Figure 6.9. The slopes of the linear functions ranged between 43 434 ('Afourer' mandarin) and 3 632 (2000 'Midknight' Valencia) μEmol$^{-1}$ kPa$^{-1}$ in the three orchards. The slopes of the linear function for $QR_{sp}/g_c$ versus D for the 2008 'Midknight Valencia' orchard was 3 759 μEmol$^{-1}$ kPa$^{-1}$, while the intercept values ranged between 307 and 881 μEmol$^{-1}$ kPa$^{-1}$ (Table 6.7). Although these values did not vary between the study orchards, they were significantly higher than those found by Villalobos et al. (2013) (a=1 070, 1002; b=1 566, 1 666). This is of some concern, as it would be preferable to have very similar coefficients for citrus, which could be applied to orchards in which T has not been measured. These parameters are expected to be consistent for a species as they represent the radiation use efficiency (α; μmol $CO_2$ μmol$^{-1}$), an empirical coefficient related to the response of stomatal closure to D ($D_o$), and the $CO_2$ concentration in the leaf boundary layer ($C_s$).

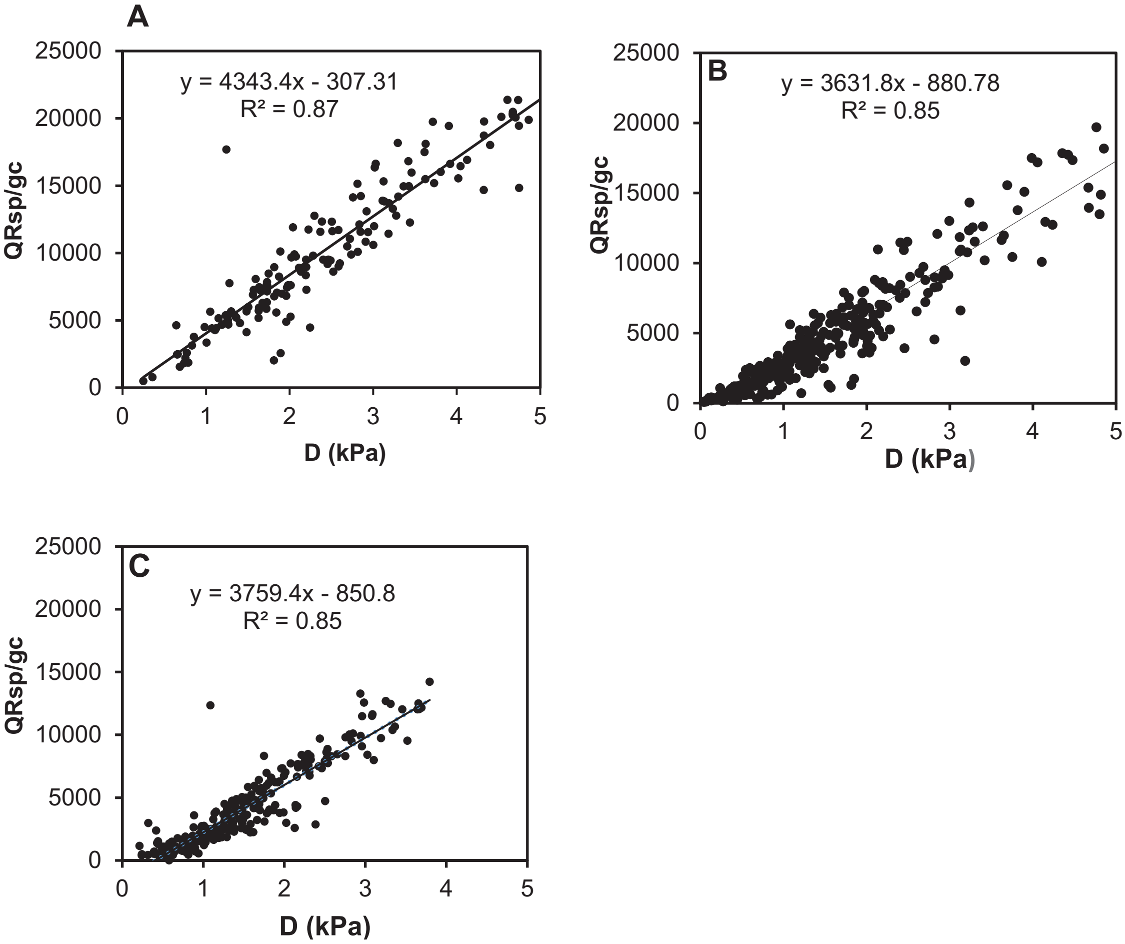


**Figure 6.9 Model calibration for the winter rainfall orchards. A) 'Afourer' mandarin orchard planted in 2002 B) 'Midknight' Valencia orchard planted in 2000 and C) Midknight' Valencia orchard planted in 2008**

**Table 6.7 Regression coefficients of the ratio of intercepted radiation and canopy conductance versus vapour pressure deficit in the two citrus orchards. The parameter *$D_o$* is calculated as the ration of a/b. Statistical parameters indicating model performance for daily estimates of transpiration are also presented. $R^2$ is the coefficient of determination, RMSE is the root mean square error, MAE is the mean absolute error and D is the Wilmott's index of agreement**

| Species | Planting date | b ($\mu$E $mol^{-1}$) | a ($\mu$E $mol^{-1}$) | $D_o$ | $R^2$ | RMSE (mm $day^{-1}$) | MAE | D |
|---|---|---|---|---|---|---|---|---|
| 'Midknight' Valencia | 2000 | 3472 | 880.8 | 0.25 | 0.52 | 0.50 | 19 | 0.81 |
| | 2008 | 3631 | 850.0 | 0.24 | 0.69 | 0.36 | 21 | 0.85 |
| 'Afourer' mandarin | 2002 | 4343 | 209.0 | 0.07 | 0.70 | 0.39 | 18 | 0.90 |

### 6.4.2 Daily estimation of transpiration

The output of the calibrated model is shown in Figure 6.10. In all orchards the simulation matched the seasonal T pattern well. However, there were periods of discrepancies in the daily simulation, where T was underestimated at the start of the year (mid-January), especially in the Valencia orchards. The daily simulation of T, however, improved towards the end of the year (Figure 6.10). Better estimates of T were observed in the 'Afourer' mandarin and mature 'Midknight' Valencia orchards and over the entire measurement period, the model performance was relative good. The statistical parameters for the different orchards were in an acceptable range, with the MAE below 20% for the 2000 'Midknigh' Valencia and 2002 'Afourer' mandarin orchards (Table 6.7). A slight difference was noted in the 'Midknight' Valencia orchard planted in 2008, where an MAE of 21% was observed.

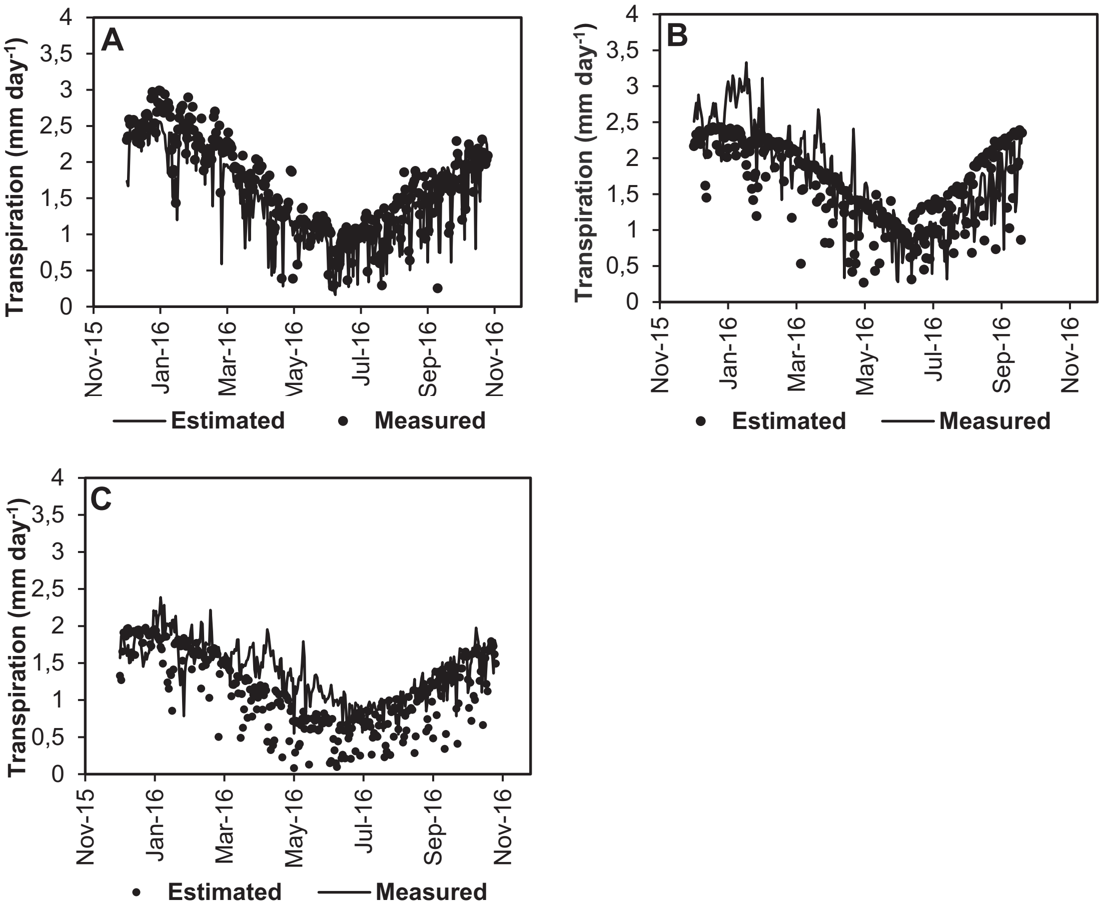


**Figure 6.10 Time series of daily transpiration rates estimated from sap flow measurements and transpiration estimated from the Villalobos et al. (2013) model. A) 'Afourer' mandarin orchard planted in 2002, B) 'Midknight' Valencia orchard planted in 2000 and C) 'Midknight' Valencia orchard planted in 2008**

### 6.4.3 Monthly estimation

Model performance improved slightly when monthly estimates of T were compared with monthly measured T (Figure 6.11), as indicated by the modelling statistics in Table 6.8. As with daily estimations, monthly T was still underestimated in spring and summer, but improved estimates were obtained in autumn and winter. Contrasting results were observed between orchards when the overall performance of the model was evaluated (Table 6.8). The model underestimated T in the 2000 'Midknight' Valencia orchard (CRM = 0.10), whilst T was overestimated in the 2002 'Afourer' mandarin orchard (CRM = -0.06) and the 'Midknight' Valencia orchard planted in 2008 (CRM = -0.05).

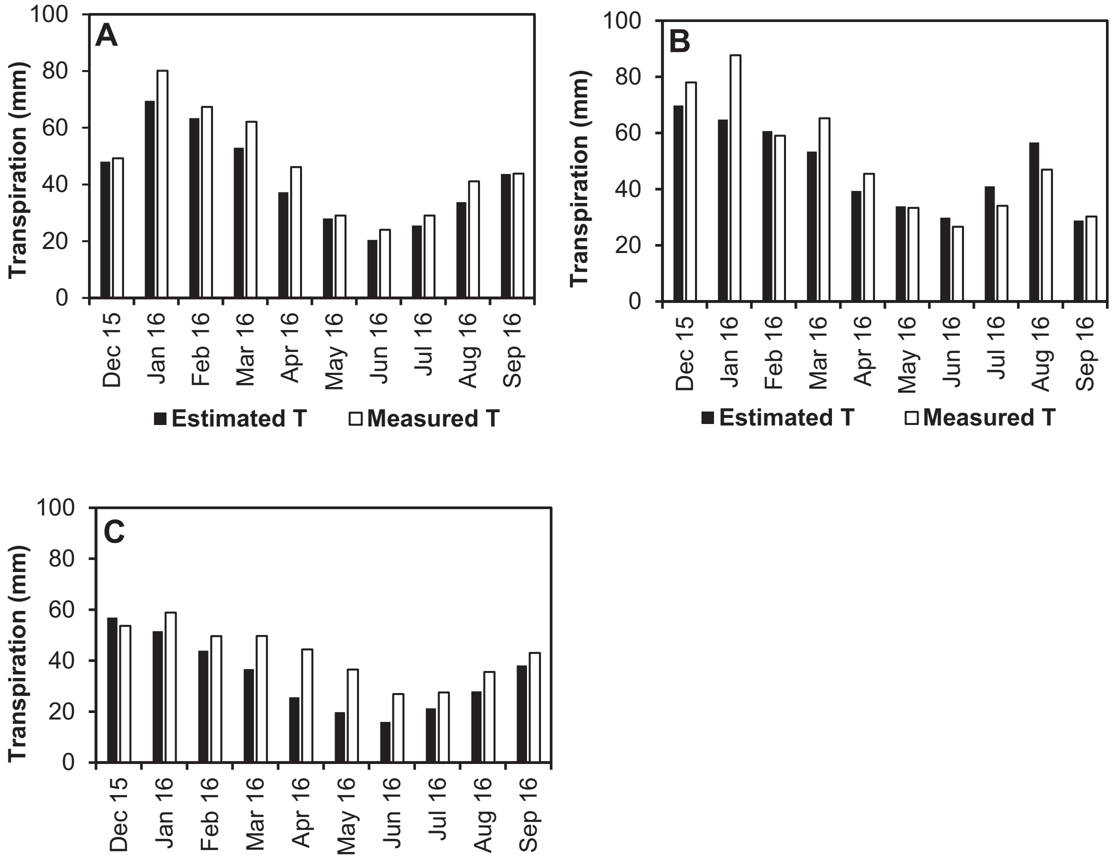


**Figure 6.11 Monthly measured and estimated transpiration in the winter rainfall region. A) 'Afourer' mandarin orchard planted in 2002, B) 'Midknight' Valencia orchard planted in 2000 and C) 'Midknight' Valencia orchard planted in 2008**

**Table 6.8 Model performance for the monthly transpiration estimates in the winter rainfall region. Monthly transpiration estimates we calculated by summing daily estimated values. $R^2$ is the coefficient of determination, RMSE is the root mean square error, MAE is the mean absolute error, CRM is the coefficient of residual mass and D is the Wilmott's index of agreement**

| Species | Planting date | $R^2$ | RMSE | MAE (%) | CRM | D |
|---|---|---|---|---|---|---|
| 'Midknight' Valencia | 2000 | 0.82 | 0.71 | 9.2 | 0.10 | 0.92 |
| | 2008 | 0.77 | 0.52 | 11.0 | -0.06 | 0.85 |
| 'Afourer' mandarin | 2002 | 0.95 | 0.59 | 6.2 | -0.05 | 0.96 |

## 6.5 Daily modelling of canopy conductance and transpiration in the summer rainfall region

### 6.5.1 Canopy conductance

The $g_c$ for the 'Midknight' Valencia and 'Valley Gold' mandarin orchards are shown in Figure 6.12. Considerable difference in $g_c$ between the 'Midknight' Valencia orchard planted in 1995 (Figure 6.12 A) and the other three orchards measured (Figure 6.12 B, C and D) was observed, with higher $g_c$ values measured in orchards with bigger trees and canopies. For the 1995 'Midknight' Valencia orchard, $g_c$ increased rapidly in winter (May/June in 2016 season and April/May in 2017 season) and in spring towards summer (November/December). The highest $g_c$ measured for this orchard was 0.68 mol $m^{-2}$ $s^{-1}$. The three smaller canopy size orchards (2014 'Midknight' Valencia and 2013 and 215 'Valley Gold' mandarin orchards) displayed little variation throughout the season and had very similar $g_c$ values (0.02-0.25 mol $m^{-2}$ $s^{-1}$). However, a small increase in bulk conductance occurred at the end of autumn (April/May) and a more pronounced increase in $g_c$ was observed in summer (January and again at the end of February) for the 2013 'Valley Gold' mandarin (0.25 mol $m^{-2}$ $s^{-1}$), 2015 'Valley Gold' mandarin (0.25 mol $m^{-2}$ $s^{-1}$) 2014 'Midknight' Valencia (0.25 mol $m^{-2}$ $s^{-1}$). These values were very similar to those obtained by Villalobos et al. (2013).

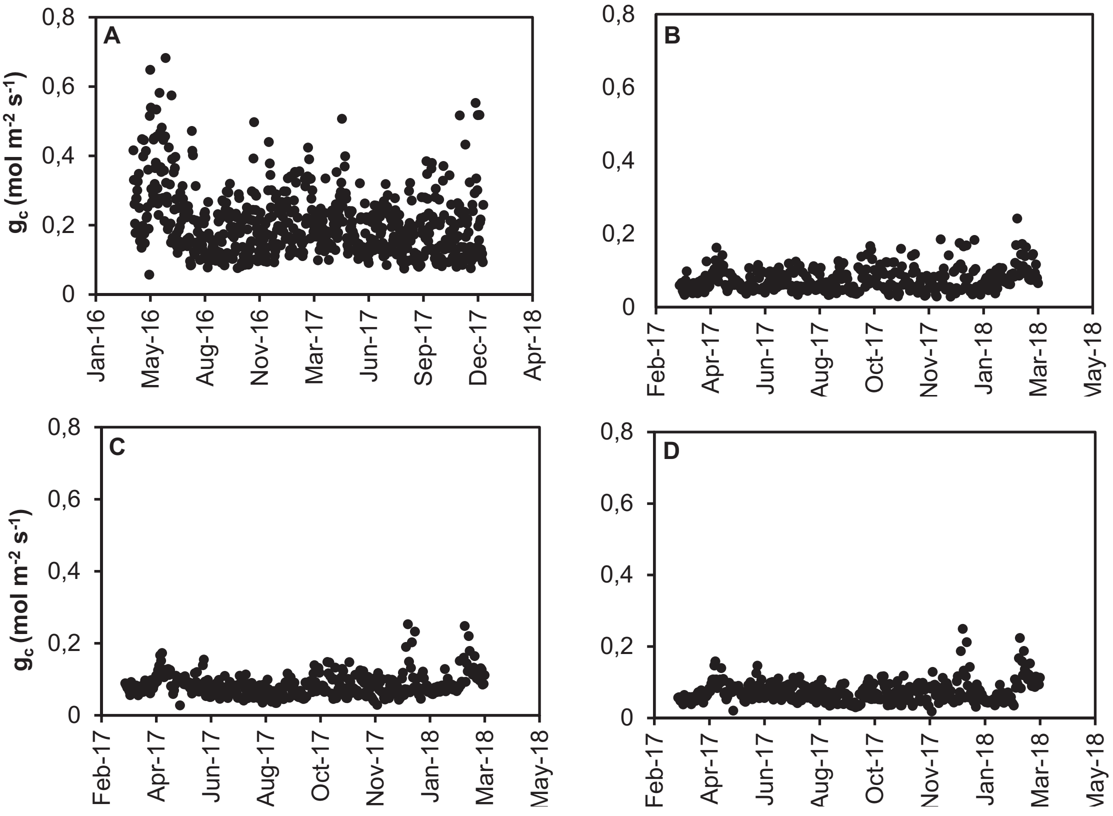


**Figure 6.12 Time series of observed bulk canopy conductance ($g_c$) in the summer rainfall orchards. 'Midknight' Valencia orchards planted in A) 1995 and B) 2014, and 'Valley Gold' orchard planted C) 2013 and D) 2015. Canopy conductance was calculated by inverting the imposed evaporation equation**

For the summer rainfall region the plot of $QR_{sp}/g_c$ against D is given in Figure 6.13. The coefficients a (intercept) and b (slope) from the linear function (equation 9), for the summer rainfall region, were similar to those obtained in the winter rainfall and ranged between 3 314 and 5 264 µEmol$^{-1}$ kPa$^{-1}$ (Figure 6.13 and Table 6.9). For the 1995 'Midknight' Valencia orchard (Figure 6.13 A), b was 3 759 µEmol$^{-1}$ kPa$^{-1}$ with an intercept of 851 µEmol$^{-1}$ kPa$^{-1}$ and for the 'Midknight' Valencia orchard planted in 2014, b was 3 314 µEmol$^{-1}$ kPa$^{-1}$ and a 864 µEmol$^{-1}$ kPa$^{-1}$ (Figure 6.13 B). In the 'Valley Gold' mandarin orchards larger differences in the slopes of the linear functions were observed between the 'Valley Gold' mandarin orchard planted in 2013 and the orchard planted in 2015. For the larger canopy size orchard (2013 'Valley Gold' mandarin), b was 3 665 µEmol$^{-1}$ kPa$^{-1}$ and a 1 411 µEmol$^{-1}$ kPa$^{-1}$ (Figure 6.13 C), while for the smaller size canopy orchard (2015 'Valley Gold' mandarin), b was 5 264 µEmol$^{-1}$ kPa$^{-1}$ and a 142 µEmol$^{-1}$ kPa$^{-1}$ (Figure 6.13 D). However, these values were significantly higher than those found by Villalobos et al. (2013). Importantly, the intercepts, did not vary from the values observed in the winter rainfall region (range between 209-1 502 μEmol$^{-1}$ kPa$^{-1}$).

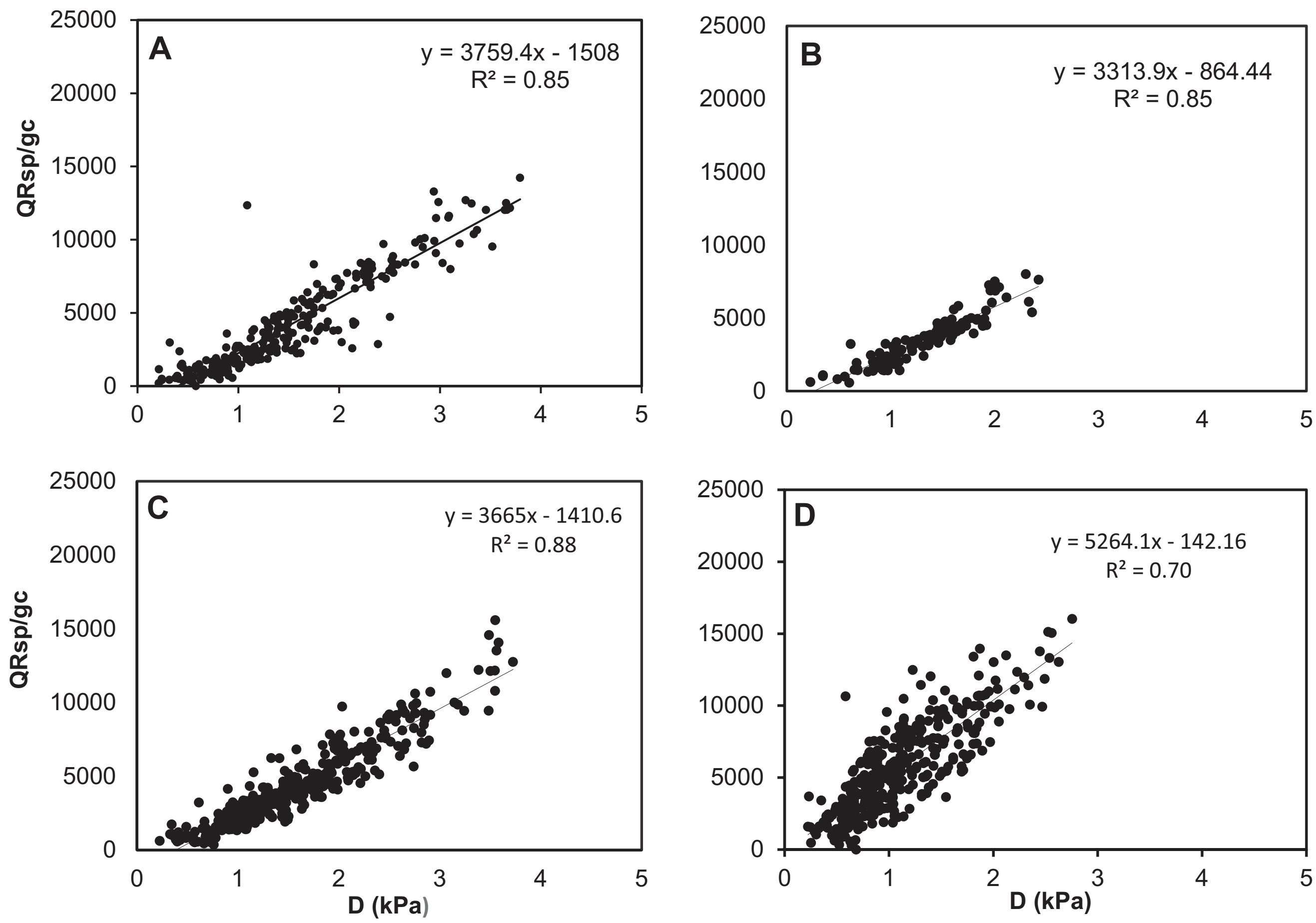


**Figure 6.13 Model calibration for the summer rainfall orchards. 'Midknight' Valencia orchards planted in A) 1995 B) Midknight Valencia planted in 2014, C) 'Valley Gold' orchard planted 2013 and D) 'Valley Gold' orchard planted 2015**

**Table 6.9 Regression coefficients of the ratio of intercepted radiation and canopy conductance versus vapour pressure deficit in the four citrus orchards. The parameter $D_o$ is calculated as the ratio of a/b. Statistical parameters indicating model performance for daily estimates of transpiration are also presented. $R^2$ is the coefficient of determination, RMSE is the root mean square error, MAE is the mean absolute error, CRM is the coefficient of residual mass and D is the Wilmott's index of agreement**

| Species | Planting date | b ($\mu E\ mol^{-1}$) | a ($\mu E\ mol^{-1}$) | $D_o$ | $R^2$ | RMSE ($mm\ day^{-1}$) | MAE | CRM | D |
|---|---|---|---|---|---|---|---|---|---|
| 'Midknight' Valencia | 1995 | 3759 | 850 | 0.22 | 0.85 | 0.33 | 20 | 0.18 | 0.79 |
| | 2014 | 3331 | 864 | 0.25 | 0.85 | 0.30 | 20 | 0.16 | 0.80 |
| 'Valley Gold' mandarin | 2013 | 3665 | 14101 | 0.38 | 0.88 | 0.14 | 5 | 0.04 | 0.99 |
| | 2015 | 5264 | 142.16 | 0.02 | 0.70 | 0.16 | 3 | 0.02 | 0.99 |

### 6.5.2 Daily estimation of transpiration

The output of the calibrated model is shown in Figure 6.14. In contrast to the winter rainfall region, better estimates of T were observed for the orchards in the summer rainfall region, as indicated by the statistical parameters, where the MAE was less than 20% (Table 6.9). Good estimates of daily T were observed in the smaller orchards (both the 'Midknight' Valencias and 'Valley Gold' mandarins), which agrees with the PAR interception modelling results, where better estimates were found for orchards with smaller trees. When considering the overall performance of the model across these study orchards, a positive CRM was observed indicating that the model underestimated T throughout the study period (Table 6.9).

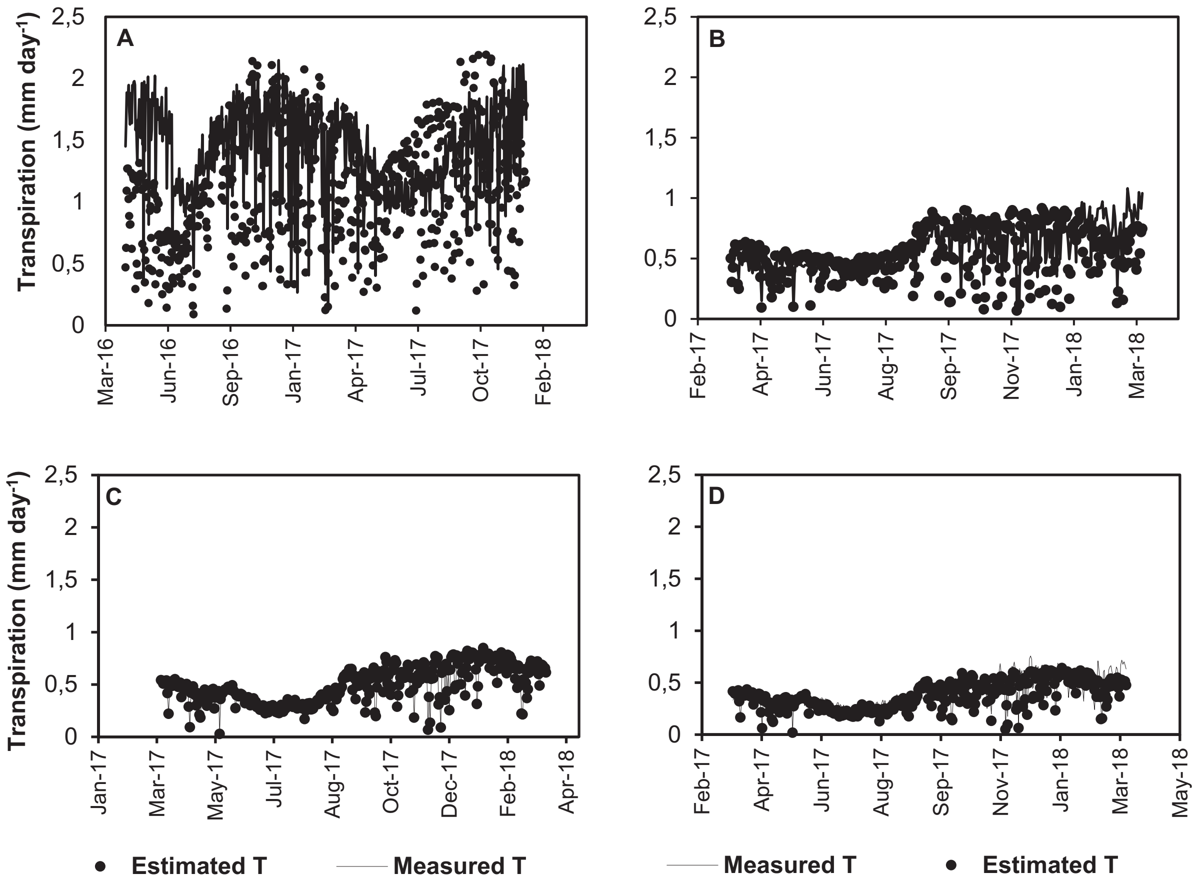


**Figure 6.14 Time series of daily transpiration rate estimated from sap flow measurements and the transpiration estimated from the Villalobos et al. (2013) model for the 'Midknight' Valencia orchards planted in A) 1995 and B) 2014 and 'Valley Gold' mandarin orchards planted in C) 2013 and D) 2015**

### 6.5.3 Monthly transpiration

As observed in the winter rainfall region, estimations of T s were better on a monthly basis than a daily basis in the summer rainfall region (Figure 6.15). The model statistics indicate that provided the initial calibration is accurate, the model can predict monthly T with minimal errors (Table 6.10). Differences between measured and estimated T on a monthly basis were consistent with daily estimates, as T was estimated better in orchards with smaller trees than orchards with bigger trees. Once again this possibly reflects the accuracy with which radiation interception was modelled for the orchards.

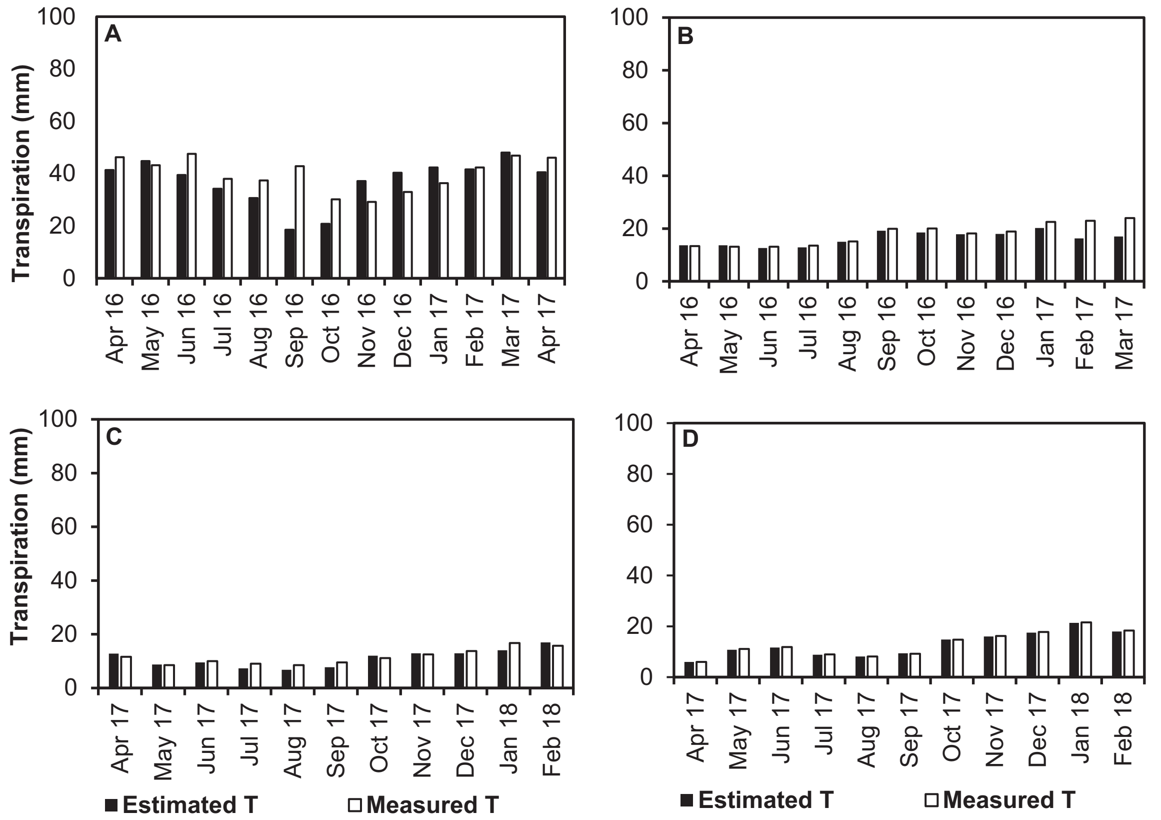


**Figure 6.15 Monthly measured and estimated transpiration in the summer rainfall region. 'Midknight' Valencia orchards planted in A) 1995 and B) 2014, and 'Valley Gold' mandarin orchards planted in C) 2013 and D) 2015**

**Table 6.10 Model performance for the monthly transpiration estimates in the summer rainfall region. Monthly transpiration estimates we calculated by summing daily estimated values. RMSE is the root mean square error, MAE is the mean absolute error and D is the Wilmott's index of agreement**

| Species | Planting date | $R^2$ | RMSE | MAE (%) | CRM | D |
|---|---|---|---|---|---|---|
| Valencia oranges | 1995 | 0.58 | 1.30 | 18 | 0.07 | 0.70 |
| | 2014 | 0.54 | 0.98 | 2 | 0.20 | 0.80 |
| Mandarins | 2013 | 0.99 | 0.16 | 4 | 0.03 | 0.99 |
| | 2015 | 0.93 | 1.10 | 9 | 0.04 | 0.99 |

## 6.6 Conclusion

The examination of water relations and the response of T to environmental variables, indicated the importance of including $g_c$ in models which estimate T of citrus orchards. This is due to the strong stomatal control of T in citrus orchards in response to increasing VPD. These studies therefore also suggested that PAR and VPD should be included in a $g_c$ model. A simplified $g_c$ and T approach of Villalobos et al. (2013) was therefore evaluated in seven orchards in both the summer and winter rainfall regions of South Africa. The results indicated that, provided the model is calibrated accurately, accurate predictions of both daily and monthly T can be achieved. However, more errors were noted with daily estimations as compared to monthly estimates. This is possibly the result of the large variation in daily weather conditions found in both regions, which had a significant impact on the day to day variation in T. In addition, the model uses a radiation interception model to account for canopy size of trees in an orchard and the carry over effects from errors in the radiation interception model cannot be ignored in the ability of the model to predict T. This was evident for orchards with smaller canopies, where better estimates of fractional interception of PAR resulted in better estimates of T. Currently, the model can be used to predict monthly estimates of T and will therefore be very useful for planning purposes, such as irrigation system design and water resource planning. Improvements in the modelling of radiation interception by citrus canopies could potentially assist in improving daily estimates of T. It might also be necessary to evaluate the manner in which $g_c$ is calculated for model calibration as the imposed evaporation equation assumes that canopy temperature equals $T_a$ and this is not always the case when stomata start to close at the hottest times for the day.

# 7 INFLUENCE OF WATER STRESS ON YIELD AND FRUIT QUALITY

## 7.1 Introduction

A field trial was designed to determine the effect of water stress at three different fruit phenological stages of 'Delta' Valencias, as categorised by Carr (2012), viz. fruit set (phase I cell division), fruit enlargement (phase II, cell enlargement) and fruit maturity (phase III), on final yield and quality. The length of the first phase, called the cell division phase, can be anything between four and nine weeks depending on the onset date of blossoming (Bain, 1958). For navels, in the southern hemisphere, this normally starts in September and ends in November. The increase in fruit size during phase I is mainly because of the increase in peel thickness due to cell division (Bain, 1958). The second phase is the cell enlargement phase, which is a four- to six-month period of very rapid fruit growth and occurs from mid-November to mid-April (this could vary according to cultivar and climate). Rapid morphological and physiological changes occur as the cells enlarge and accumulate water in the absence of cell division. The growth of the pulp is responsible for most of the increase in fruit size (Bain, 1958). The last phase is the maturation phase (a non-climacteric process in citrus) when fruit growth slows down and external and internal ripening processes occur. These ripening processes include colour change, a decline in acidity and an increase in sugars (Iglesias et al., 2007). The parameters which were measured in the field trial constituted fruit size, fruit yield, fruit quality, $g_s$ and predawn leaf and $\Psi_{stem}$, including a detailed analysis of water stress in relation to yield and fruit quality.

## 7.2 Pre-harvest

Daily soil tensiometer readings at 30 cm and 60 cm depths for phase (I), (II) and (III) of water stress are presented in Figure 7.1, Figure 7.2 and Figure 7.3 respectively. The soil water potentials registered at 30 and 60 cm depths for the water stress treatments during phase I and II of fruit development were lower than the control block (Figure 7.1 and Figure 7.2). In general, the soil matric potential of the control block (block 6) was kept between 0 and -20 kPa at 30 cm and 60 cm depth. This was significantly higher than the tensiometer readings during the water stressed treatments, where the aim was to keep the tensiometer readings at -50 kPa. Periodic watering of the trees was conducted when the trees showed physical signs of water stress, such as severe leaf rolling. During phase II, dry hot conditions (23-30 January 2017) resulted in a sharp decrease in the 30 cm tensiometer readings of all treatments. However, it was challenging to maintain soil water tensions close to -50 kPa due to heavy rainfall in the area, even with the plastic sheeting added to reduce the impact of rainfall, during the latter period of the trial. During phase III the rain season was coming to an end and it was fairly easy to maintain tensiometer readings below -50 kPa for the 30 and 60 cm depth (Figure 7.3).

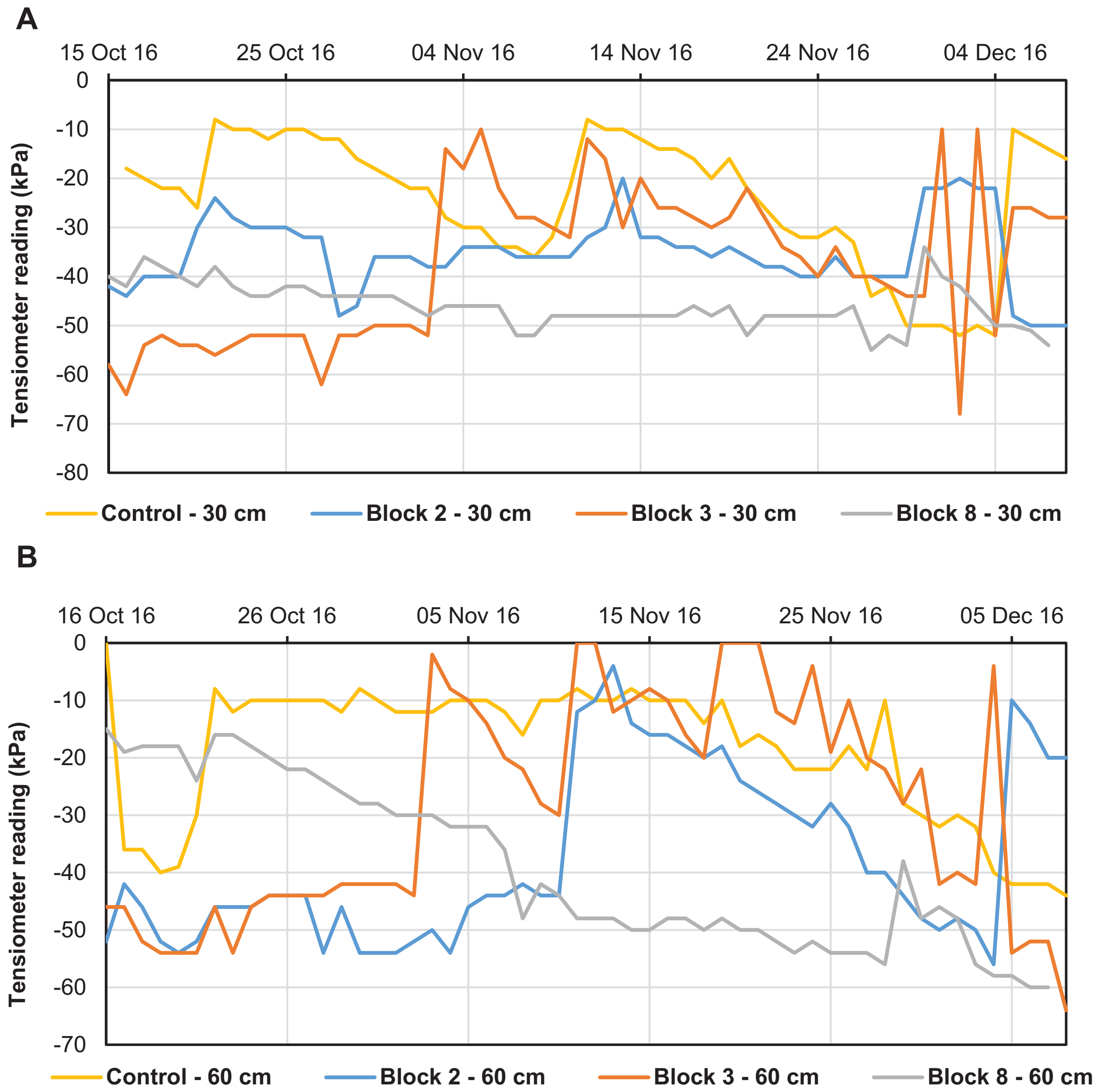


**Figure 7.1 Tensiometer readings for the control (irrigated according to local farming practices) and water stress treatments (Block 2, 3 and 8) at A) 30 cm and B) 60 cm depth during phase I of fruit development**

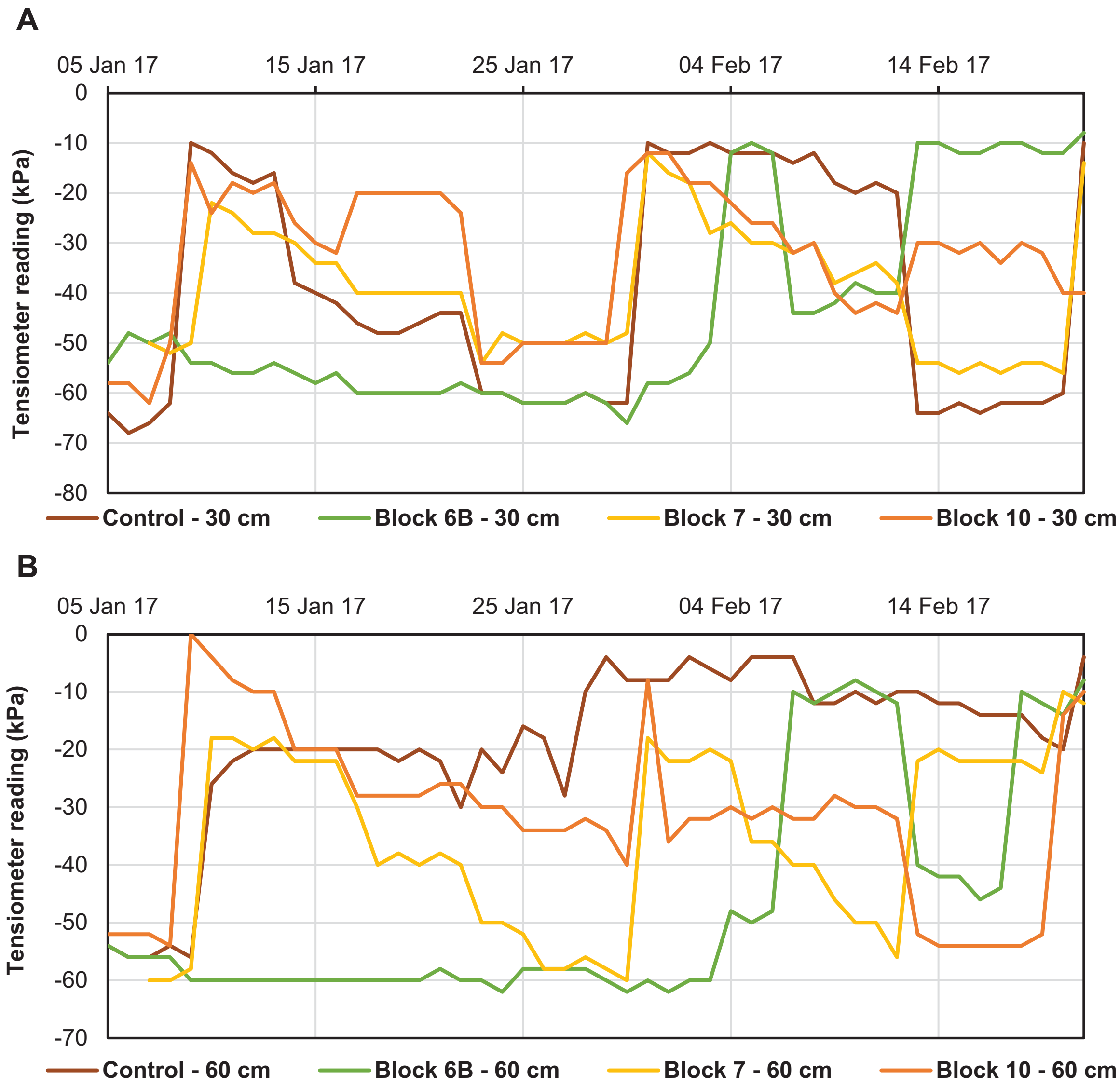


**Figure 7.2** **Tensiometer readings for the control (irrigated according to local farming practices) and water stress treatments (Block 7, 10 and 6B) at A) 30 cm and B) 60 cm depth during phase II of fruit development**

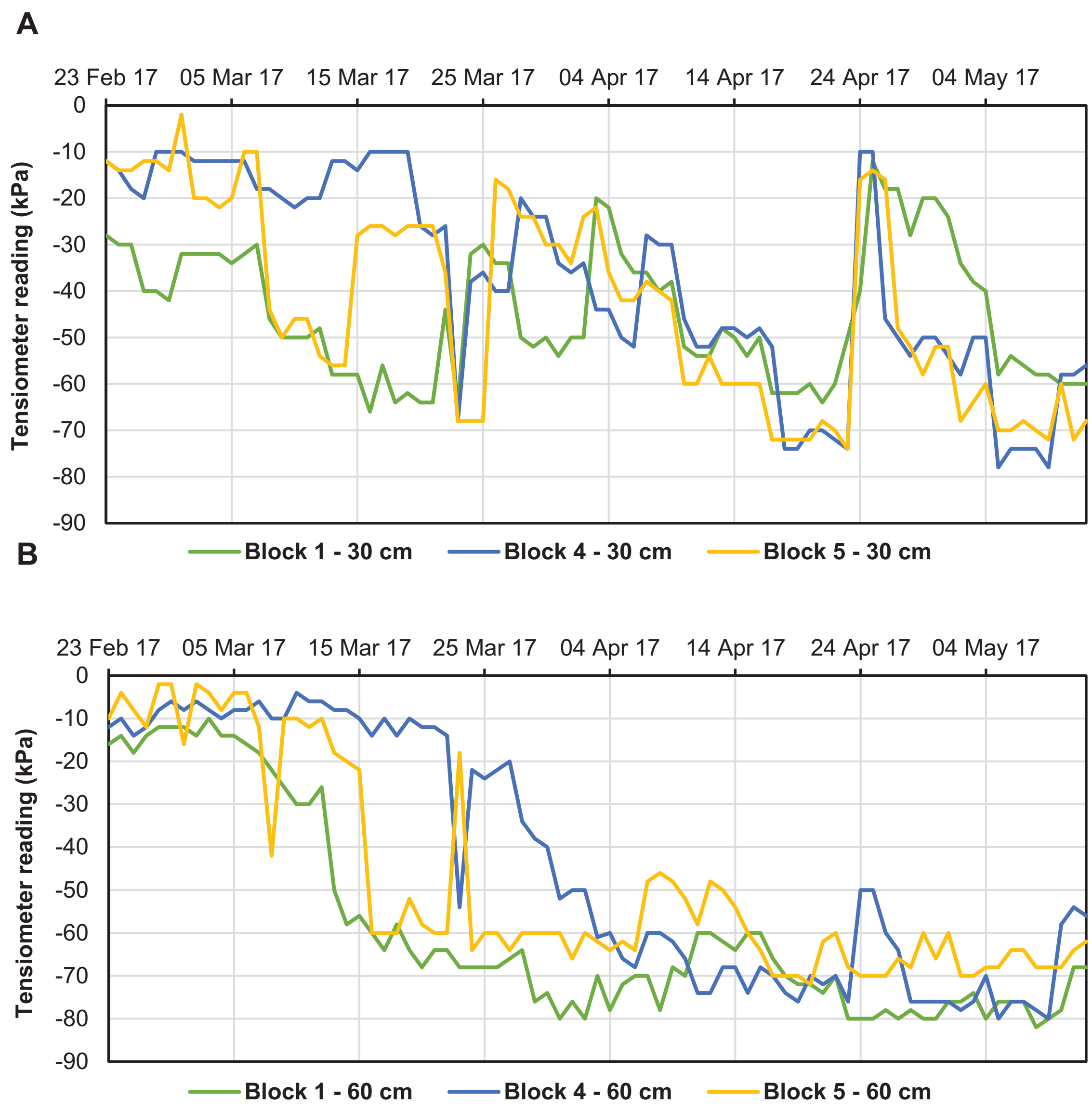


**Figure 7.3 Tensiometer readings for the water stress treatments (Block 1, 4 and 5) at A) 30 cm and B) 60 cm depth during phase III of fruit development**

As a result of water stress, relatively low $\Psi_{pd}$ and midday $\Psi_{stem}$ were measured from the water stressed blocks. The $\Psi_{pd}$ of the control trees indicated that these trees were not experiencing water stress (Figure 7.4 A, Figure 7.5 A and Figure 7.6 A), as the predawn values were higher than -0.5 MPa (Kriedemann and Barrs, 1981). Similarly a midday $\Psi_{stem}$ higher than -0.8 MPa (García-Tejero et al., 2011), except for the measurements made on 2 and 16 November, also showed that the control orchard was not stressed (Figure 7.4 B, Figure 7.5 B and Figure 7.6 B). The $\Psi_{pd}$, for the water stressed treatment blocks, were significantly lower than -0.5 MPa (except for phase I measured on 16 November and block 8 measured on 7 December) when water stress was induced (Figure 7.4 A, Figure 7.5 A and Figure 7.6 A), indicating that the trees were stressed. This was in synchrony with the readings from the tensiometers. Similarly the midday $\Psi_{stem}$ were significantly lower than -0.8 MPa (Figure 7.4 B, Figure 7.5 B and Figure

7.6 B). The lowest $\Psi_{pd}$ (-2.2 MPa), in Block 1, and lowest midday $\Psi_{stem}$ (-2.5 MPa), in Block 5, was recorded during the water stress treatment of phase III of fruit development (Figure 7.6 A and B), which were corroborated by the low tensiometer readings (Figure 7.3). For Block 1 the 30 cm tensiometer reading recorded was -64 kPa (Figure 7.3 A) and -72 kPa for the 60 cm tensiometer (Figure 7.3 B). For Block 5 the 30 cm tensiometer reading was -68 kPa (Figure 7.3 A) and -62 kPa for the 60 cm tensiometer (Figure 7.3 B).

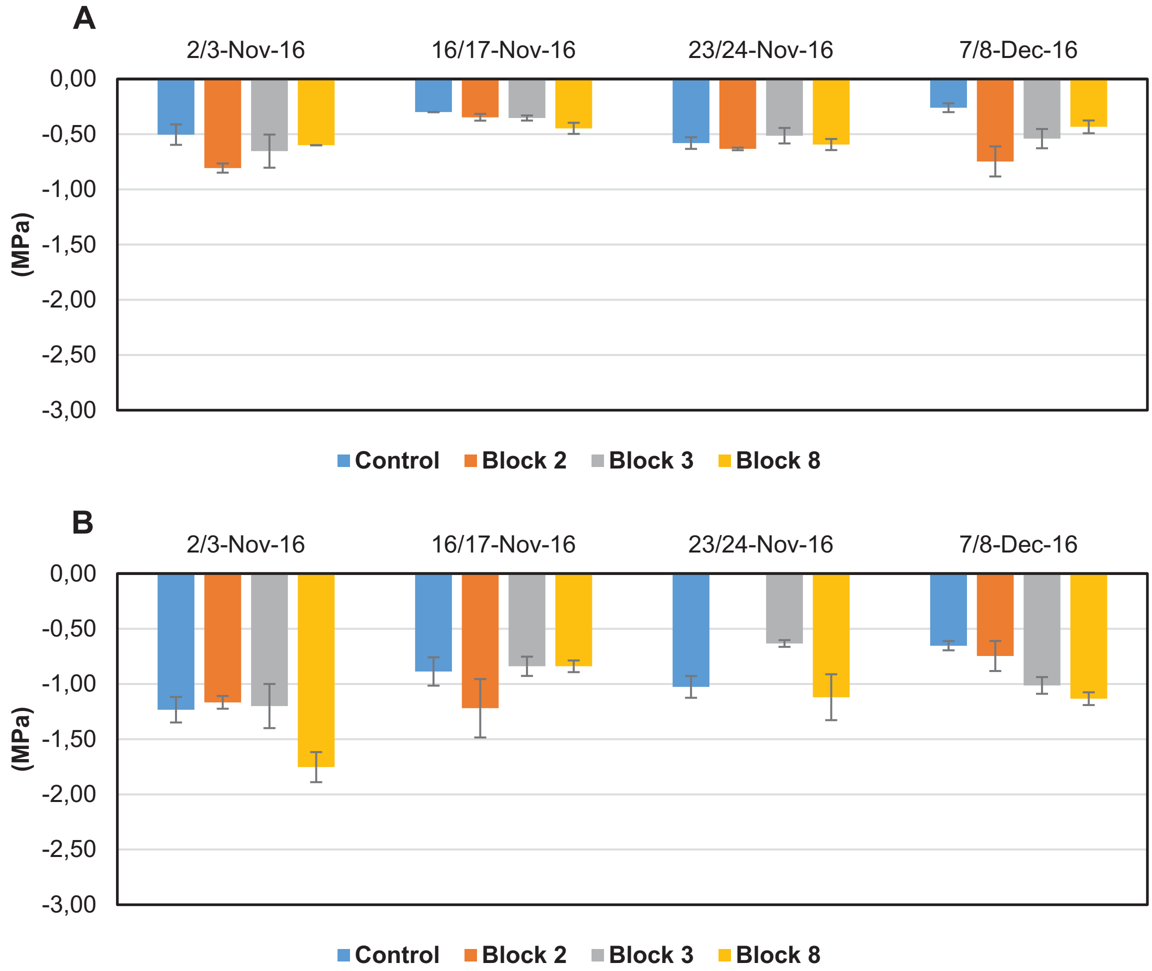


**Figure 7.4 A) Predawn and B) midday stem water potential during phase I of water stress. Error bars indicate standard deviation**

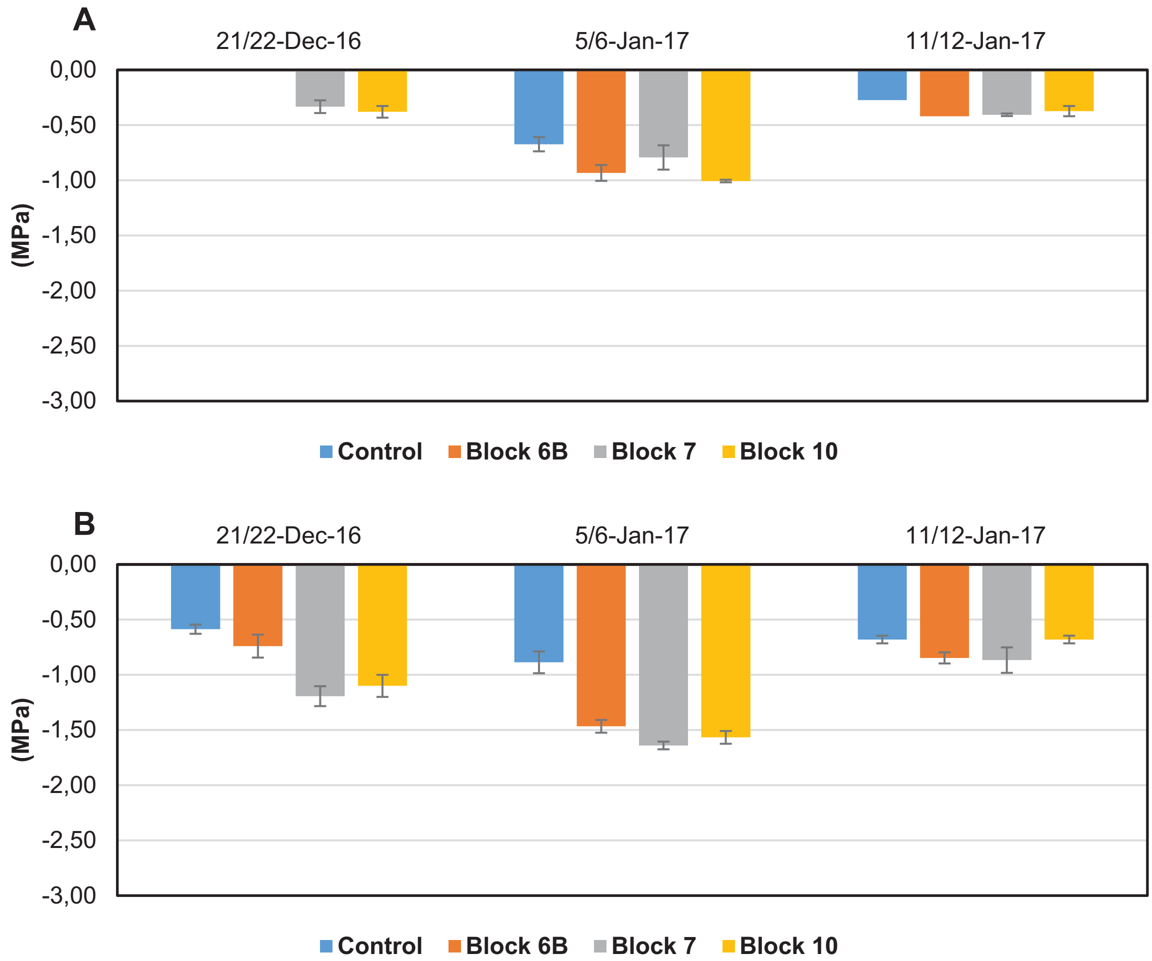


**Figure 7.5 A) Predawn and B) midday stem water potential during phase II of water stress. Error bars indicate standard deviation**

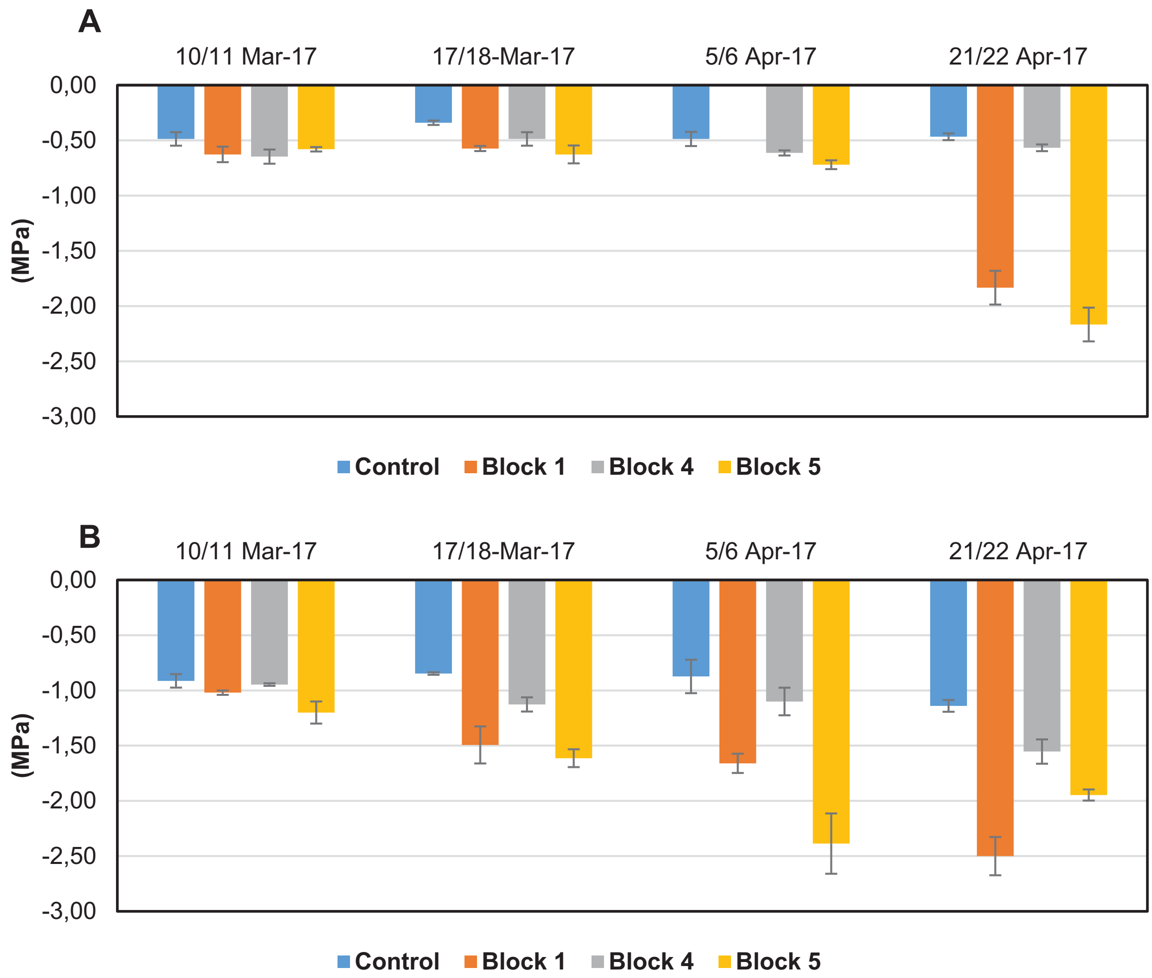


**Figure 7.6 A) Predawn and B) midday stem water potential during phase III of water stress. Error bars indicate standard deviation**

In Figure 7.7 the average $g_s$ of the selected leaves of the measuring trees for phase I, II and III of fruit development are given. Stomatal conductance followed a typical diurnal trend. Generally the maximum daily $g_s$ was lower for all water stress treatments than the maximum daily $g_s$ of the control (Figure 7.7). The main cause of reduced $g_s$, when citrus trees are water stressed, is believed to be due to an increase in abscisic acid ABA in the leaves (Gomes et al., 2004). These results indicate that the trees under investigation were water stressed, as the physiological activity of the trees was reduced.

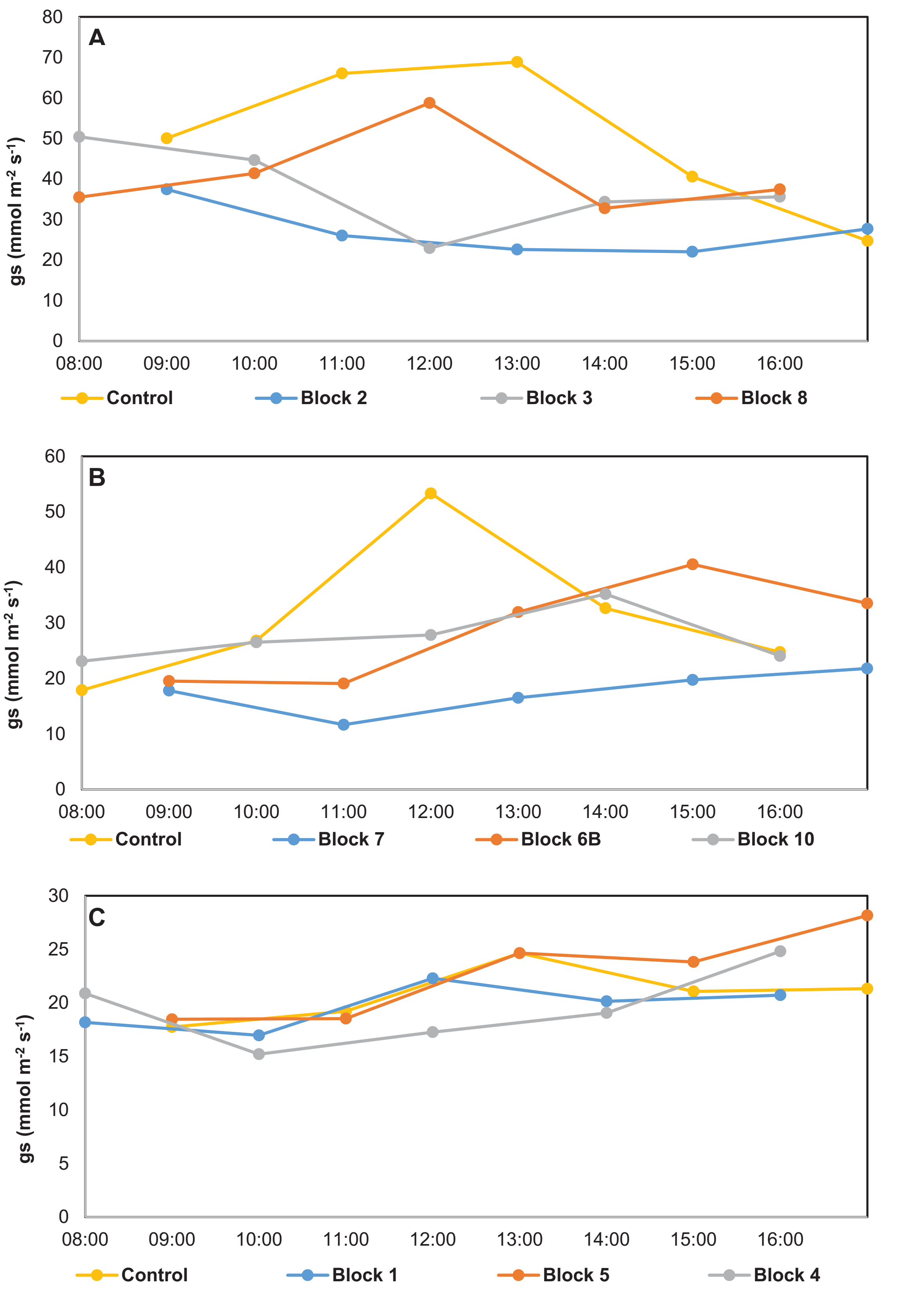


**Figure 7.7** **A typical diurnal trend of the stomatal conductance of water stressed trees during A) phase I, B) phase II and C) phase III of fruit development**

In Table 7.1 the percentage differences in fruit mass and fruit yield is given and in Figure 7.8 the average fruit mass and yield is given. Withholding irrigation during phase I and II of fruit development led to a significant (P < 0.05) decrease (32%) in harvestable yield and an increase in fruit mass compared to the control (Table 7.1). Fruit yield between the water stress treatments during phase I (455 kg) and II (455 kg) of fruit development did not differ significantly (P < 0.05), while the yield from the trees subjected to water stress in phase III (637 kg) was significantly (P < 0.05) higher than the yield from the treatment trees in phase I and II (455 kg). No significant (P < 0.05) difference in yield was found between the water stress treatment in phase III and the control (672 kg). Decreased yields in phase I and II are attributed to excessive fruit drop, while in phase III the fruit was well-established on the trees and unlikely to drop and therefore the yield was not severely affected (Doorenbos and Kassam, 1979). Yield reductions during phase I of fruit growth have been noted in a number of studies and have been attributed to increased fruit drop (Ginestar and Castel, 1996; González-Altozano and Castel, 1999; González-Altozano and Castel, 2000). Yield reductions during phase II are typically associated with reduced fruit size (Carr, 2012). However, in this trial the decrease in yield, for the stress treatment during phase II, was also associated with larger fruit (Figure 7.8A) and, therefore, the yield reduction was most probably due to fewer fruit on the tree.

**Table 7.1 Percentage change in fruit mass and harvestable yield compared to the control during each phase of fruit growth**

| | % increase in fruit mass | % increase in fruit yield |
|---|---|---|
| Phase I | 7 | -32 |
| Phase II | 13 | -32 |
| Phase III | -0.7 | -5 |

Competition between fruit occurs in citrus. When fruit drop occurs, the same leaf area supports less fruit, thus making more photosynthates available for each fruit that results in larger fruits. This phenomenon is evident in Figure 7.8 A. Increased fruit size was observed in the treatments (phase I and II) with the largest decrease in yield. This inverse relationship observed, is consistent with results from Goldschmidt and Monselise (1977) who conducted a study in the relationship between fruit size and available leaf area in ‘Shamouti’ oranges and ‘Wilking’ mandarin.

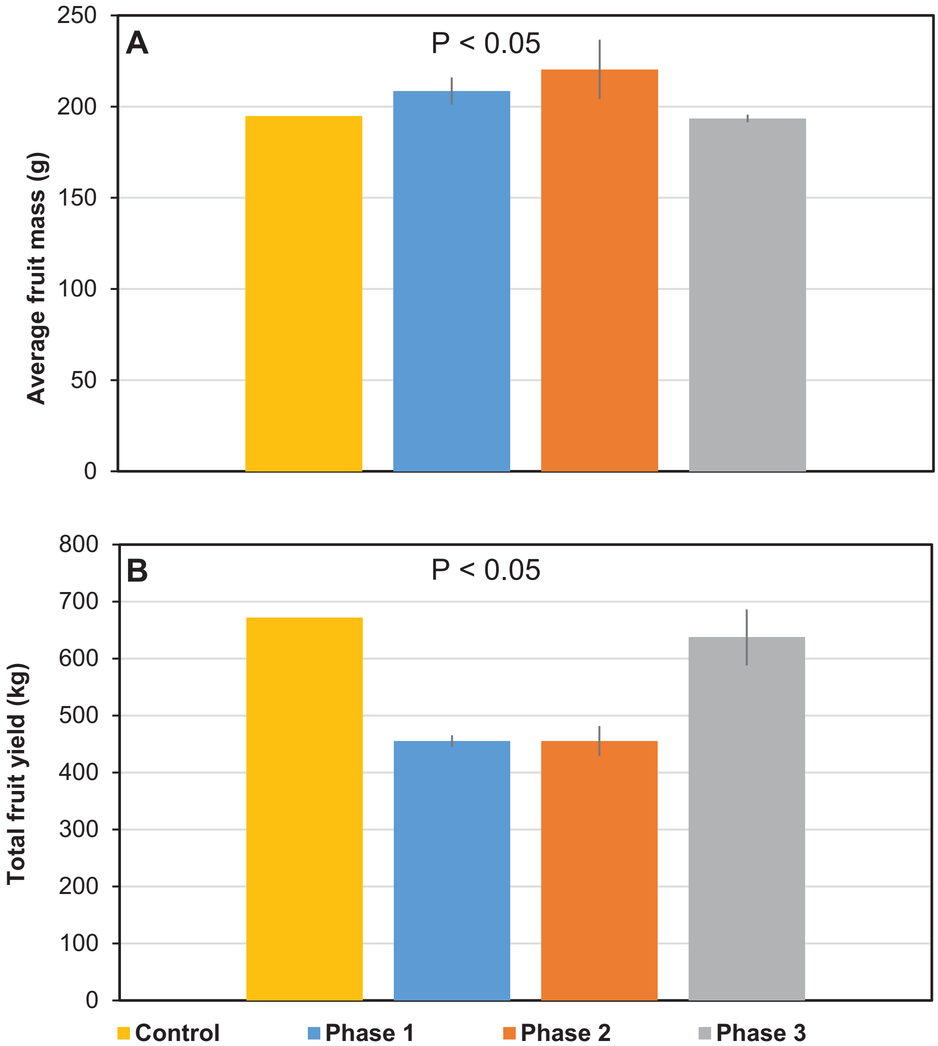


**Figure 7.8 A) Average fruit mass and B) average fruit yield of the trees subjected to water stress during phase I, II and III of fruit development. Error bars indicate standard deviation**

## 7.3 Post-harvest

No significant differences ($P < 0.05$) in colour development for the different water stress treatments and post-harvest storage (storage at 4°C and -0.6°C) were found. However, numerous studies conducted on water stress in citrus showed that water stress affects the internal properties of fruit, such as the titratable acids (TA), brix and juice content (Bielorai, 1982; García-Tejero et al., 2010). In Figure 7.9 results on the internal fruit properties for the different water stress treatments are shown. No significant differences ($P < 0.05$) in the percentage fruit juice for the different water stress treatments were found. However, the fruit stored at 4°C had a significantly ($P < 0.05$) lower juice content than the fruit stored at -0.6°C (Figure 7.9 A). Although not significant, the TSS, measured as Brix, for the control was lower than the TSS measured for water stress treatments for the fruit stored at both 4°C and -0.6°C (Figure 7.9 B). The acid percentage in the fruit (Figure 7.9 C) was slightly lower in the fruit of the control (except phase II stored at 4°C) than the water stress treatments, which complies with the export requirements (acid level 0.65% to 1.8%). These results are consistent to what was observed by Verreynne et al. (2001), who reported that a conventional deficit irrigation strategy, increased the TSS and TA in 'Marisol' Clementines without affecting the juice content or reducing the fruit size.

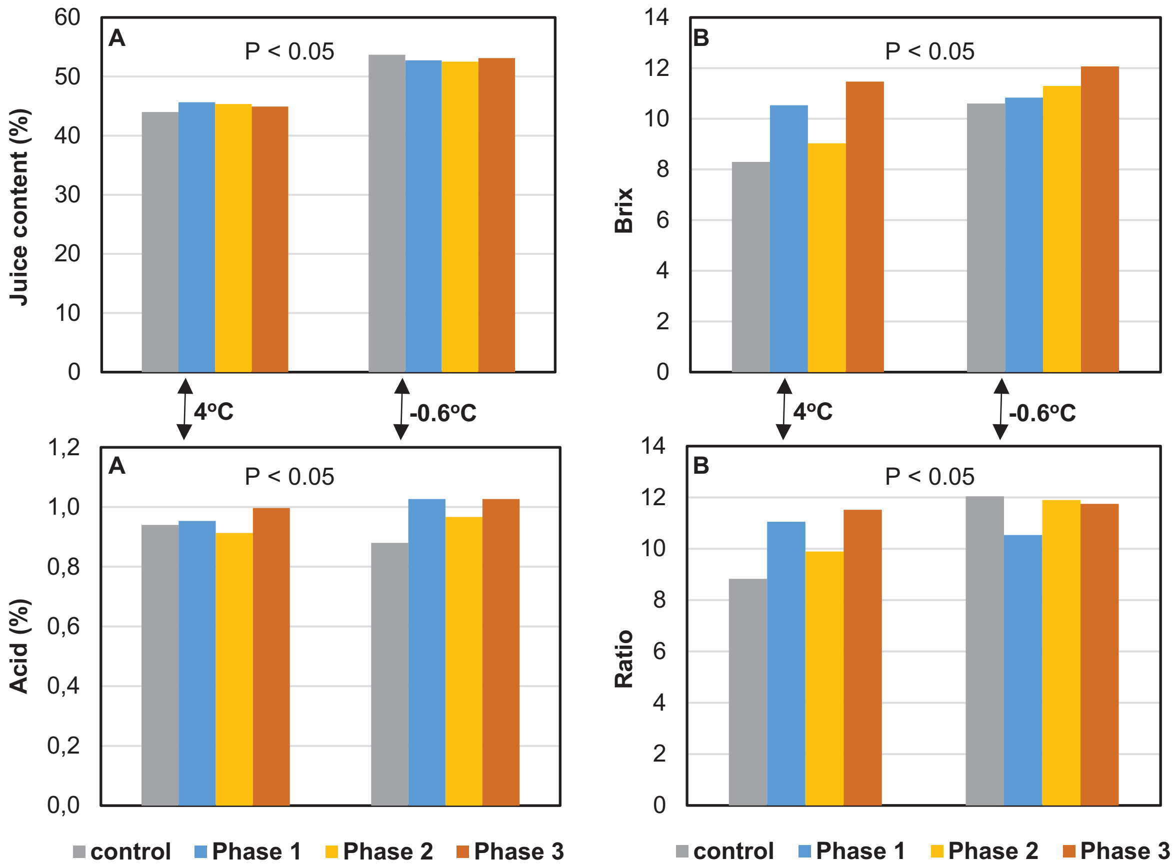


**Figure 7.9 Influence of water stress, during the different phases of fruit development, on the postharvest quality of 'Delta' Valencia fruit determined at two temperatures (4°C and -0.6°C)**

## 7.4 Conclusions

The impact of water stress on the yield and quality of 'Delta' Valencias was more evident in the pre-harvest than the postharvest assessments. Water stress during phase I (fruit set, cell division) and phase II (cell enlargement) of fruit development had the largest impact, with a 32% reduction in yield. No significant decrease in yield was observed when the water was withhold during phase III (fruit maturity) of fruit development. Excessive fruit drop was also observed during phase I and II of fruit development that resulted in less, but larger fruit on the trees.

Water stress treatments at fruit set (phase I), fruit enlargement (phase II) and fruit maturity (phase III) did not significantly influence colour development, percentage fruit juice, acid percentage and TSS. As a result, the impact of water stress on yield and post-harvest fruit quality during phase III of fruit growth will be less than if water stress occurs during phase I or phase II of fruit growth. Water stress during phase I or phase II of fruit growth will most likely result in a yield penalty, although larger fruit may develop due to less fruit on the tree. Water stress during these stages may also have a limited impact on the post-harvest quality of the fruit.

# 8 DISCUSSION AND CONCLUSIONS

Results from this research showed that in all the orchards measured, both winter and summer rainfall regions, T followed clear diurnal and seasonal trends. Large day-to-day variations were evident, where T varied from less than 1 mm day$^{-1}$ to more than 4 mm day$^{-1}$. The highest daily T (4.5 mm day$^{-1}$) was measured in the 2002 'Afourer' mandarin orchard (Table 8.1). Annual orchard water use also showed significant variation, with an annual water use varying from 139 mm for the 2015 'Valley Gold' mandarin orchard (summer region) to 953 mm for the 2002 'Afourer' mandarin orchard (winter rainfall region). The large variation in daily T measured was driven by environmental conditions and differences in canopy size between orchards. Good correlations between daily T and daily temperature, VPD, $R_s$ and $ET_o$ were found, especially for the winter rainfall region, demonstrating the importance of the environment in supplying the energy to drive T. However, the response of T to $ET_o$ and VPD was not always linear. After an initial strong positive response, T tended towards a plateau value as $ET_o$ and VPD increased passed a certain threshold value. However, despite this response, $ET_o$ still explained a large proportion of the variation in T and therefore $K_t$ values may still be appropriate for estimating the T of orchards from $ET_o$ estimations.

In an attempt to explain the plateau response of T to $ET_o$ and VPD, a number of ecophysiological measurements were performed. Stomata were found to close in 'Midknight' Valencia orchards in both the summer and winter rainfall regions as VPD exceeded approximately 1 kPa. Environmental conditions also significantly influenced the diurnal course of $\Psi_{leaf}$, with $\Psi_{leaf}$ reaching lower values on hot and dry days, as opposed to cooler and more humid days. However, despite hot and dry conditions, values lower than -2.5 MPa were seldom recorded, which again supports some form of physiological control over leaf water status. The reason for this tight physiological control seems to be linked to lower hydraulic conductance in the soil to stem pathway, rather than in the stem to leaf pathway. This agrees with the findings of Kriedemann and Barrs (1981), Sinclair and Allen (1982) and Van Bavel et al. (1967) who suggested that citrus trees have high root resistances.

It was also evident that canopy size was a major determinant of T rates, with larger canopies having higher T both on a daily and annual basis (Table 8.1 and Table 8.2). The drastic increase in water use from planting to maturity should be taken into account when planning irrigation infrastructure (convey to field and on-field delivery) and scheduling irrigation. Whilst newly planted orchards have fairly low water requirements, within 5-6 years this requirement can double and even triple. The cumulative effect over a season must also be considered when planting new orchards, as the initial increase in the size of small trees can be quite dramatic. 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.

An opportunity to evaluate the effect of severe pruning (decreasing canopy size) on water use presented itself, when the farm manager on Patrysberg decided to reduce the size of the 'Midknight' Valencia trees and pruned them aggressively. This resulted in a decrease in the LAI of the trees from 6.9 $m^2 m^{-2}$ in January 2015 to 4.8 $m^2 m^{-2}$ in January 2016 (Figure 8.1). This reduction in LAI influenced tree water use as is evident when the T of the two seasons are compared with each other. The T measured in January 2015 was 52% higher than measured in January 2016.

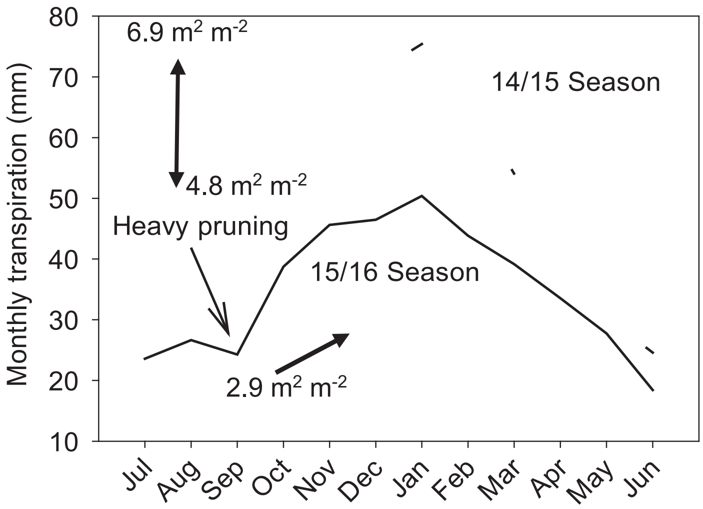


**Figure 8.1 Decrease in transpiration due to pruning**

Importantly water use in citrus orchards does not only consist of T, but also from $E_s$. Whilst extensive measurement and modelling of $E_s$ was not completed in this study, window periods of ET measurements allowed the assessment of the partitioning of ET between T and $E_s$. Understanding the partitioning of ET is important as substantial water savings can be potentially be made by reducing the non-beneficial consumptive water use or $E_s$. This will be of particular importance during periods of drought or when a grower wishes to expand production with his existing water allocation. The fraction of ET partitioned to T was significantly higher in Citrusdal, which is considerably hotter and drier compared to Letsitele. In Citrusdal this value varied between 65% for the 'Washington' navel orchard to 91% in the 'Afourer' Mandarin orchard. However, in Letsitele this value varied from 19% in the 2013 'Valley Gold' mandarin orchard to 45% in the 2006 'Star Ruby' grapefruit orchard. This is most likely a result of the sandier soils and drip irrigation in the Citrusdal orchard, as opposed to the microsprinkler irrigation and more clay soils in Letsitele. A more comprehensive understanding of the dynamics of $E_s$ in orchards will be important to consider in future in order to improve the WUE of a wide range of orchards. It will also assist growers in making better use of a limited resource.

Whilst T values are very useful to understand how much water was required by the orchards of varying sizes during the course of this study, these values are not always easily transferable to different orchards and different regions. This is due to the dependency of T on environmental conditions and canopy size, as demonstrated in this study. One way to try and account for varying environmental conditions is to normalise for local weather conditions using reference evapotranspiration, commonly calculated as $ET_o$. Transpiration crop coefficients ($K_t$) are derived from this process and can be used to try and make the T data determined in this study more applicable to a wider range of regions in South Africa. A fortnightly summary of $K_t$ values for each orchard are provided in Table 8.3 and Table 8.4. In both regions $K_t$ values varied throughout the production season (July to June) according to orchard and to season, however, values were quite similar for orchards in the winter and summer rainfall regions, which had similar canopy sizes or canopy cover. As a result in order to provide reasonable values for irrigation planning purposes, a summary of monthly $K_t$ values for three different canopy sizes is provided in Table 8.5 and Figure 8.2. These can be seen as updated values for citrus to those provided by Allen and Pereira (2009). First of all it was decided to present monthly values, as this reflected the rate of change in $K_t$ values during the spring and autumn months and would therefore allow better estimates of water use during this time. Secondly, what is noticeable is a distinct drop in $K_t$ values in summer, which is more evident in the larger orchards than the smaller orchards. Whilst Allen and Pereira (2009) suggest single values for the citrus for the initial-, mid- and end stages of the $K_c$ curve, this project suggests that a lower value should be considered during the summer months. In addition, these summer values are considerably lower than those suggested by Allen and Pereira (2009), who suggest a value of 0.85 for 70% effective canopy cover ($f_{c\ eff}$), 0.70 for an $f_{c\ eff}$ of 50% and 0.45 for an $f_{c\ eff}$ of 25%.

**Table 8.1 Summary of the tree water use of the orchards on the winter rainfall region**

| | 2000 'Midknight' Valencia | | 2008 'Midknight' Valencia | | 2010 'McLean' Valencia | | 1990 'Bahianinha' navels | | 2006 'Washington' navels | | 2002 'Afourer' mandarin | | 2013 'Afourer' mandarin | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Transpiration** | **mm** | **L** | **mm** | **L** | **mm** | **L** | **mm** | **L** | **mm** | **L** | **mm** | **L** | **mm** | **L** |
| **Total** | 1 601 | 20 014 | 1 064 | 15 959 | 436 | 6 537 | 117 | 1 895 | 201 | 3 009 | 1 325 | 13 248 | 150 | 2 057 |
| **Maximum per day** | 4.0 | 49.9 | 2.8 | 42.0 | 1.3 | 19.4 | 1.7 | 27.9 | 1.2 | 17.3 | 4.5 | 44.9 | 2.5 | 33.8 |
| **Minimum per day** | 0.3 | 4.2 | 0.2 | 3.4 | 0.1 | 1.5 | 0.3 | 5.3 | 0.1 | 0.9 | 0.4 | 3.8 | 0.2 | 2.8 |
| **Average per day** | 2.2 | 27.9 | 1.5 | 22.2 | 0.7 | 11.1 | 1.1 | 17.4 | 0.7 | 10.7 | 2.8 | 27.8 | 1.1 | 15.7 |
| **Annual water use** | 812 | 10 152 | 539 | 8 078 | 251 | 3 765 | 477* | 7 730* | 264* | 3 962* | 953 | 9 533 | 392* | 5 386* |
| **Canopy cover** | 0.83 | | 0.54 | | 0.35 | | 0.58 | | 0.48 | | 0.81 | | 0.19 | |
| **WUE (kg m$^{-3}$)** | - | | 4.7 | | 3.9 | | 8.4* | | 14.4* | | 7.9 | | 5.4* | |
| **Measurement period (days)** | 718 | | 718 | | 588 | | 109 | | 280 | | 476 | | 131 | |

**Table 8.2 Summary of the tree water use of the orchards on the summer rainfall region**

| | 2006 'Star Ruby' grapefruit | | 2010 'Star Ruby' grapefruit | | 2011 'Star Ruby' grapefruit | | 1995 'Midknight' Valencia | | 2008 'Midknight' Valencia | | 2014 'Midknight' Valencia | | 2013 'Valley Gold' mandarin | | 2015 'Valley Gold' mandarin | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Transpiration** | **mm** | **L** | **mm** | **L** | **mm** | **L** | **mm** | **L** | **mm** | **L** | **mm** | **L** | **mm** | **L** | **mm** | **L** |
| **Total** | 576 | 12 096 | 446 | 9 372 | 328 | 6 885 | 1 109 | 23 291 | 547 | 11 497 | 213 | 4 472 | 185 | 3 881 | 154 | 3 233 |
| **Maximum per day** | 1.9 | 39.7 | 1.3 | 26.6 | 1.1 | 23.2 | 2.5 | 51.6 | 1.2 | 24.5 | 1.1 | 22.7 | 0.8 | 17.6 | 0.8 | 15.9 |
| **Minimum per day** | 0.1 | 2.3 | 0.3 | 6.9 | 0.1 | 1.1 | 0.2 | 3.3 | 0.1 | 1.3 | 0.1 | 2.1 | 0.03 | 0.6 | 0.02 | 0.5 |
| **Average per day** | 1.0 | 20.8 | 0.8 | 17.1 | 0.5 | 10.8 | 1.6 | 32.9 | 0.8 | 16.2 | 0.6 | 12.3 | 0.5 | 9.7 | 0.4 | 8.1 |
| **Annual water use** | 387 | 8 135 | 314 | 6 599 | 180 | 3 789 | 560 | 11 751 | 275 | 5 776 | 213 | 4 472 | 167 | 3 506 | 139 | 2 917 |
| **Canopy cover** | 0.71 | | 0.59 | | 0.41 | | 0.74 | | 0.51 | | 0.27 | | 0.42 | | 0.34 | |
| **WUE (kg m$^{-3}$)** | 14.9 | | 19.0 | | 15.4 | | 11.4 | | 13.5 | | 9.6 | | 5.3 | | 2.9 | |
| **Measurement period (days)** | 581 | | 547 | | 636 | | 707 | | 707 | | 363 | | 402 | | 401 | |

**Table 8.3 Fortnightly transpiration crop coefficients ($K_t$) for citrus orchards in the winter rainfall region of South Africa**

| Month | Period within month | 2000 'Midknight' Valencia | 2008 'Midknight' Valencia | 2010 'Mclean' Valencia | 1990 'Bahianinha' navels | 2006 'Washington' navels | 2002 'Afourer' mandarin |
|---|---|---|---|---|---|---|---|
| **Avg. canopy cover** | | 0.83 | 0.54 | 0.35 | 0.54 | 0.48 | 0.81 |
| **July** | **1** | 1.13 | 0.63 | 0.19 | - | 0.32 | 1.19 |
| | **2** | 0.95 | 0.67 | 0.26 | - | 0.25 | 1.07 |
| **August** | **1** | 0.90 | 0.64 | 0.27 | - | 0.24 | 1.03 |
| | **2** | 0.76 | 0.55 | 0.23 | - | - | 0.95 |
| **September** | **1** | 0.66 | 0.49 | 0.23 | - | - | 0.82 |
| | **2** | 0.63 | 0.43 | 0.25 | - | - | 0.71 |
| **October** | **1** | 0.58 | 0.48 | 0.23 | - | - | 0.67 |
| | **2** | 0.58 | 0.44 | 0.21 | - | - | 0.62 |
| **November** | **1** | 0.59 | 0.38 | 0.14 | - | 0.21 | 0.54 |
| | **2** | 0.53 | 0.33 | 0.13 | - | 0.18 | 0.50 |
| **December** | **1** | 0.47 | 0.30 | 0.13 | - | 0.16 | 0.59 |
| | **2** | 0.46 | 0.29 | 0.12 | - | 0.15 | 0.51 |
| **January** | **1** | 0.50 | 0.31 | 0.12 | - | 0.15 | 0.52 |
| | **2** | 0.55 | 0.31 | 0.13 | - | 0.16 | 0.53 |
| **February** | **1** | 0.58 | 0.32 | 0.13 | - | 0.17 | 0.51 |
| | **2** | 0.48 | 0.33 | 0.15 | - | 0.16 | 0.54 |
| **March** | **1** | 0.56 | 0.33 | 0.16 | 0.28 | 0.17 | 0.60 |
| | **2** | 0.69 | 0.33 | 0.19 | 0.32 | 0.22 | 0.64 |
| **April** | **1** | 0.75 | 0.33 | 0.23 | 0.46 | 0.20 | 0.71 |
| | **2** | 0.79 | 0.48 | 0.25 | 0.50 | 0.26 | 0.81 |
| **May** | **1** | 0.80 | 0.59 | 0.28 | 0.59 | 0.29 | 0.84 |
| | **2** | 0.83 | 0.65 | 0.28 | 0.54 | 0.32 | 0.92 |
| **June** | **1** | 0.75 | 0.69 | 0.22 | 0.66 | 0.32 | 1.00 |
| | **2** | 0.97 | 0.74 | 0.19 | 0.83 | 0.33 | 1.10 |

**Table 8.4 Fortnightly transpiration crop coefficients ($K_t$) for citrus orchards in the summer rainfall region of South Africa**

| Month | Period within month | 1995 'Midknight' Valencia | 2008 'Midknight' Valencia | 2014 'Midknight' Valencia | 2006 'Star Ruby' Grapefruit | 2010 'Star Ruby' Grapefruit | 2011 'Star Ruby' Grapefruit | 2013 'Valley Gold' mandarin | 2015 'Valley Gold' mandarin |
|---|---|---|---|---|---|---|---|---|---|
| Avg. canopy cover | | 0.74 | 0.51 | 0.27 | 0.71 | 0.59 | 0.41 | 0.42 | 0.34 |
| July | 1 | 0.71 | 0.36 | 0.24 | 0.42 | 0.34 | 0.18 | 0.14 | 0.15 |
| | 2 | 0.68 | 0.33 | 0.24 | 0.45 | 0.41 | 0.21 | 0.17 | 0.18 |
| August | 1 | 0.60 | 0.31 | 0.23 | 0.35 | 0.33 | 0.19 | 0.13 | 0.15 |
| | 2 | 0.50 | 0.25 | 0.21 | 0.34 | 0.30 | 0.18 | 0.14 | 0.13 |
| September | 1 | 0.45 | 0.22 | 0.20 | 0.29 | 0.26 | 0.17 | 0.15 | 0.10 |
| | 2 | 0.54 | 0.26 | 0.25 | 0.39 | 0.30 | 0.19 | 0.17 | 0.14 |
| October | 1 | 0.46 | 0.23 | 0.19 | 0.27 | 0.25 | 0.18 | 0.15 | 0.12 |
| | 2 | 0.44 | 0.22 | 0.19 | 0.27 | 0.25 | 0.19 | 0.15 | 0.12 |
| November | 1 | 0.46 | 0.22 | 0.18 | 0.31 | 0.30 | 0.18 | 0.15 | 0.11 |
| | 2 | 0.44 | 0.22 | 0.14 | 0.31 | 0.27 | 0.17 | 0.12 | 0.12 |
| December | 1 | 0.45 | 0.21 | 0.16 | 0.32 | 0.26 | 0.18 | 0.12 | 0.11 |
| | 2 | 0.44 | 0.20 | 0.17 | 0.28 | 0.23 | 0.17 | 0.17 | 0.16 |
| January | 1 | 0.44 | 0.21 | 0.17 | 0.33 | 0.25 | 0.19 | 0.16 | 0.12 |
| | 2 | 0.41 | 0.20 | 0.17 | 0.36 | 0.26 | 0.20 | 0.15 | 0.10 |
| February | 1 | 0.43 | 0.21 | 0.20 | 0.29 | 0.20 | 0.19 | 0.14 | 0.10 |
| | 2 | 0.46 | 0.23 | 0.23 | 0.34 | 0.28 | 0.22 | 0.14 | 0.12 |
| March | 1 | 0.45 | 0.23 | 0.24 | 0.30 | 0.23 | 0.21 | 0.14 | 0.12 |
| | 2 | 0.51 | 0.19 | 0.14 | 0.34 | 0.24 | 0.18 | 0.14 | 0.10 |
| April | 1 | 0.54 | 0.27 | 0.14 | 0.37 | 0.28 | 0.19 | 0.13 | 0.09 |
| | 2 | 0.64 | 0.34 | 0.19 | 0.43 | 0.34 | 0.20 | 0.16 | 0.13 |
| May | 1 | 0.71 | 0.37 | 0.20 | 0.45 | 0.40 | 0.21 | 0.16 | 0.14 |
| | 2 | 0.78 | 0.38 | 0.22 | 0.49 | 0.41 | 0.21 | 0.21 | 0.17 |
| June | 1 | 0.82 | 0.40 | 0.27 | 0.43 | 0.40 | 0.22 | 0.20 | 0.20 |
| | 2 | 0.76 | 0.38 | 0.26 | 0.42 | 0.34 | 0.22 | 0.15 | 0.17 |

**Table 8.5 Proposed monthly transpiration crop coefficients (Kt) for citrus orchards with three different canopy sizes**

| Canopy cover | July | August | September | October | November | December | January | February | March | April | May | June |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **70%** | 0.96 | 0.79 | 0.54 | 0.56 | 0.51 | 0.49 | 0.49 | 0.50 | 0.57 | 0.71 | 0.81 | 0.90 |
| **50%** | 0.42 | 0.37 | 0.52 | 0.30 | 0.27 | 0.24 | 0.25 | 0.25 | 0.26 | 0.36 | 0.46 | 0.50 |
| **30%** | 0.20 | 0.19 | 0.56 | 0.17 | 0.14 | 0.15 | 0.15 | 0.16 | 0.16 | 0.17 | 0.21 | 0.21 |

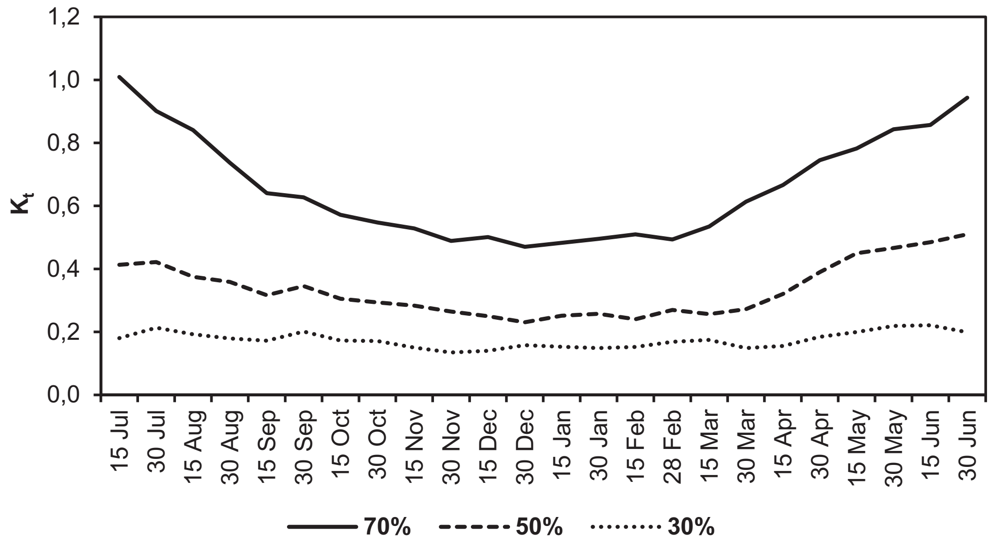


**Figure 8.2 Proposed transpiration crop coefficients (Kt) for high density, medium density and low density citrus orchards**

Not all citrus orchards are classed as having an $f_{c\ eff}$ of 70%, 50% or 30%. The question therefore remains, how would $K_t$ be derived for these orchards in order to provide guidelines on water requirements?

In order to answer this question a number of descriptors of canopy size (volume, LAI and fractional interception of PAR) were regressed against $K_t$ values. Transpiration crop coefficients were used to reduce the variation in the T data caused by variable environmental conditions from day to day. The aim was to determine if there is a single relationship between canopy size and $K_t$ values for the different species and if this relationship is consistent between rainfall regions. For the fractional interception of PAR, data is presented for both field measurements and simulated data (following the parametrized model of Oyarzun et al. (2007)). The equivalent model estimates of PAR interception were run for the times of day that field measurements were taken, but for the monthly estimations the simulation was run throughout the growing season, starting from October 2015 to October 2016 for all the orchards in the winter rainfall. For the summer rainfall region simulations were run from the start of T measurements in each orchard (February 2016 to February 2018). Monthly estimates of PAR interception were obtained by averaging the daily simulated values and then a regression analysis was carried out against monthly $K_t$ values. In order to determine if there is a single relationship between canopy size and $K_t$ values that can be used for all citrus, data from orchards and rainfall regions was combined. As measurements were made in mandarin and Valencia orchards in both region, these orchards were chosen for such comparison. For the daily values of canopy volume and LAI, the $K_t$ values corresponding to the measurement dates were used to determine the relationship between the $K_t$ values and the specific canopy size descriptor.

The relationship between $K_t$ values and canopy size variables are presented in Figure 8.4. From the measured canopy size variables, the fraction of intercepted PAR by the canopy gave the best fit. Both measured and simulated daily *f*IPAR indicated a strong positive correlation, with satisfactory coefficient of determination $R^2$ of > 0.7. However, both LAI and canopy volume resulted in rather poor relationships with $K_t$ values. These results demonstrate that the amount of light intercepted by citrus canopy is important in determining T under non-water-limiting condition. The good relationship with *f*IPAR and $K_t$ is not surprising as this has been found in a number of fruit tree species, including peaches (Ayars et al., 2003) and grapevines (Williams and Ayars, 2005) and it is assumed that the relationship between absorbed energy and T does not change over a season (Pereira et al., 2007).

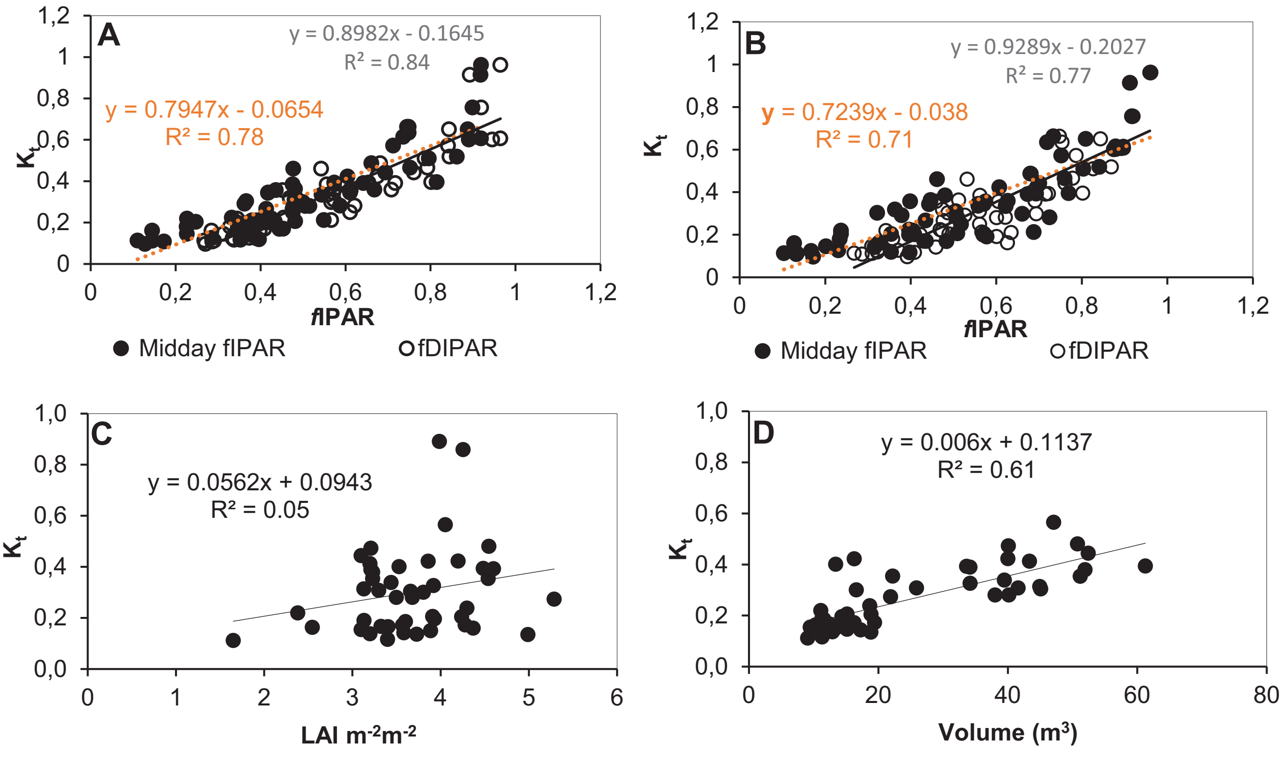


**Figure 8.3 Relationship between transpiration crop coefficients ($K_t$) and canopy size descriptors (*f*IPAR, LAI and canopy volume) for all the species considered in the study, viz: 'Midknight' Valencia, 'Afourer' mandarin, 'Valley Gold' mandarin and 'Star Ruby' grapefruit in both the summer and winter rainfall regions. A) Measured *f*IPAR at midday and throughout the day, B) simulated *f*IPAR at midday and throughout the day, C) measured leaf area index and D) measured canopy volume. Each point represents the daily $K_t$ determined on the particular day of measurement of the canopy size descriptor**

Two aspects of the relationships presented in Figure 8.3 A and B were particularly pleasing. Firstly the strong correlation between *f*IPAR and $K_t$ suggests that $K_t$ could be predicted from measured *f*IPAR for different orchards in which T measurements are not available and secondly, the relationship seemed to be consistent for all the orchards in which measurements were made. This latter aspect was particularly important as it means that perhaps one relationship exists for citrus. Therefore, T coefficients of citrus can be estimated from the fraction of intercepted radiation of the canopy. Girona et al. (2011) suggested that the use of midday fractional interception of PAR can present some problems. In their 3-year study, the authors found non-linearity relationship between different years between midday interception and crop relative water consumption, which the authors attributed, in part, to the shape of the canopies in the studied fruit trees. They concluded that radiation interception at noon may not be a representative of the canopy size when comparing canopies of different structures. They argued that differences in canopy properties such as porosity may have a huge impact in determining light interception. Although, our results demonstrated a strong correlation between T coefficient ($K_t$) and measured and simulated midday *f*IPAR in different citrus species, it was decided to evaluate daily *f*IPAR average over a month with the corresponding monthly $K_t$ value. On a monthly basis a reasonably good relationship between $K_t$ values and *f*IPAR for a number of orchards in both regions was found, with a slope of 0.99 and an intercept of 0.228 (Figure 8.4 A). Although a comparison of regression lines between mandarins and Valencias in both rainfall regions revealed some differences in the regression equations for the two species (Figure 8.4 B), the relationship presented in Figure 8.4 A could potentially be used to adjust monthly $K_t$ values for different orchards in order to provide reasonably T estimates on a monthly basis for strategic decision making in orchards. The one factor limiting the widespread use of this approach would be accurate estimates of *f*IPAR.

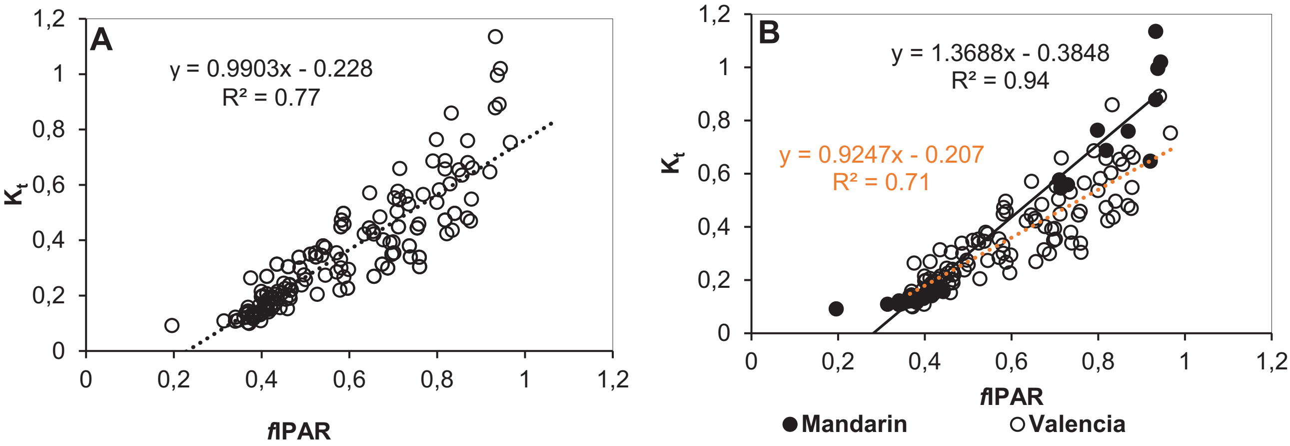


**Figure 8.4 The relationship between monthly transpiration crop coefficients ($K_t$) and estimated average daily *f*IPAR on a monthly basis. A) All three of the different citrus species (Valencia oranges, mandarins and grapefruit) under study in the winter and summer rainfall regions, B) Comparison of the two species (mandarins and Valencia) in which measurements were made in both rainfall regions. The mandarin orchards were planted in 2002, 2013 and 2015, whilst the Valencia planted in 1995, 2000, 2008 and 2014. Solid line represents the regression equation for the Valencia orchards whilst dotted line represents the regression equation for the mandarin orchards**

Whilst monthly estimates of water use are useful for strategic decisions, tactical decisions require estimates on a shorter time scale. As a result the simplified $g_c$ modelling approach of Villalobos et al. (2013) was parameterised in the Valencia and mandarin orchards in the winter and summer rainfall regions. A $g_c$ approach was used as both the ecophysiological studies and changes in $K_t$ values over a season suggested strong stomatal control over T under hot and dry conditions. Initial results seem very promising and fairly 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. As the model requires estimates of fractional interception of $R_s$, the accuracy of this parameter will determine the accuracy of T estimates. Difficulties of estimating *f*IPAR in larger canopies meant that at times T estimates were not as accurate for large trees as smaller trees. This shortcoming could be rectified by better accounting for the shape of mature citrus trees or by improving the method for estimating $C_p$. However, this approach has provided very good monthly estimates of T in a wide range of orchards. The conservative nature of some of the parameters between orchards also suggests that the model can be used for citrus in general, rather than having to derive a specific set of parameters for each citrus type.

As both the simple $K_t$ adjustment using fIPAR and the $g_c$ approach require good estimates of radiation interception by canopies, future work should focus on improving the models of radiation interception for citrus that would allow for estimation of this parameter from fairly simple measurements in an orchard. Remote sensing technology could perhaps prove very useful in this regard. This could potentially facilitate the transfer of results from this study to growers in a very meaningful way and contribute to the improvement of water management in citrus orchards.

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