Water Use of Avocado Orchards

Volume I

Report to the

Water Research Commission

and

South African Avocado Growers' Association

by

NJ Taylor[1], E Mazhawu[2], A Clulow[2], N Roets[3], SJE Midgley[4], T Smit[1], JG Annandale[1]

[1]University of Pretoria, [2]University of KwaZulu-Natal, [3]Agricultural Research Council, [4]Independent Researcher

WRC Report No. 2552/1/21

ISBN 978-0-6392-0272-3

September 2021

Obtainable from

Water Research Commission
Private Bag X03
Gezina, 0031

orders@wrc.org.za or download from www.wrc.org.za

This report forms part of a series of two reports. The other report is *Water Use of Macadamia Orchards* (WRC Report No 2552/2/21).

EXECUTIVE SUMMARY

BACKGROUND

The sustainability and growth of the avocado industry is highly dependent on the availability of adequate water for irrigation. However, it is highly unlikely that the water allocation to agriculture will increase and as result growers need to become more efficient in how they use water. The demand for more efficient water use, is also occurring at a time when climate change is predicted to increase the incidence and severity of droughts. In addition, increased demand for water resources by a growing population and industry is placing severe pressure on this limited resource. The onus is therefore on irrigated agriculture to manage water as efficiently as possible, to conserve water, soil and energy, whilst maximising productivity. In order to do this a thorough understanding of water use of avocado orchards is required. Currently there is a considerable gap in knowledge on water use of avocado orchards, which includes data on evapotranspiration (ET), transpiration (E_c) and evaporation (E_s) from planting until full maturity. Filling this knowledge gap through research is important to aid in irrigation scheduling and planning in avocado orchards and to assist in the fair allocation of water resources to growers and the Validation and Verification of Lawful Water Use.

A census in 2020 confirmed that 14 700 ha are planted to avocados in South Africa, with annual growth of approximately 800 ha (https://avocado.co.za/avocado-production-stats-regions/). The most important established growing areas for avocados are found in Limpopo, with smaller plantings in Mpumalanga, KwaZulu-Natal, Eastern Cape and Western Cape. 'Hass' is the main export cultivar and currently the most important rootstock used is 'Duke 7' but 'Dusa' is the preferred rootstock for new establishments. Two new rootstocks were also released in 2020, which could become dominant in future. South Africa is the fifth largest exporter of avocados worldwide and the avocado industry therefore makes an important contribution to the gross domestic product. As avocado are evergreen they require water all year round. As avocados in South Africa are largely grown in the summer rainfall region, a large portion of the water requirements can be provided by rainfall, but irrigation is crucial during dry periods and has become critical in areas suffering from droughts in recent years. This makes local avocado production unique as internationally avocados are produced in Mediterranean climates. Avocado orchards therefore represent a significant user of freshwater, with optimal irrigation of orchards required for optimal production. Importantly, as avocados are susceptible to Phytophthora root rot, overirrigation is very undesirable as this can lead to increased disease incidence.

Accurate information on the water use of avocado orchards is therefore important for water management in these orchards, to ensure that orchards are optimally irrigated, to develop water savings strategies to cope with water shortages caused by droughts and to know how to allocate water during different phenological phases with minimal impact on yield and quality.

AIMS AND OBJECTIVES

General aim

To quantify water use of avocado in relation to yield at orchard scale.

Specific objectives

1. To measure unstressed water use of avocado according to seasonal growth stages from planting to mature canopy size for selected cultivars and locations;
2. To model unstressed water use of avocado according to seasonal growth stages from planting to mature canopy size for selected cultivars and locations;
3. To determine the influence of water stress during different phenological stages of avocado on yield and quality for selected cultivars and locations;
4. To quantify water use efficiency and water use productivity of avocado for selected cultivars and locations

SCOPE OF THE PROJECT

The project encompassed the quantification of transpiration and evapotranspiration of four avocado orchards varying in canopy size across two climactic regions in South Africa. Weather data were collected in conjunction with these measurements in order to determine the driving variables for avocado water use. Ecophysiological measurements were also performed to ensure the determination of unstressed water use. These data were then used to evaluate water use models for use in avocado orchards and included crop coefficient and canopy conductance approaches. Finally, the water use data, together with yield, was used to derive water use efficiency and water use productivity values for two orchards. The second aspect of the project was to determine the impact of water stress at different phenological stages on yield and quality of avocados. Trees were water stressed at different phenological stages and yield and quality was assessed at the end of the season. Phenological stages where stress was implemented included flowering, fruit set, fruit growth and fruit maturation and these treatments were compared to a well-watered control.

METHODOLOGY

The study for the determination of water use of avocado orchards was conducted at Everdon Estates, approximately 10 km from the town of Howick in KwaZulu-Natal. The climate is cool, subtropical with a mean annual temperature of between 17 and 20°C, a mean January temperature of 20-23°C and an annual precipitation of 1074 mm (https://en.climate-data.org/africa/south-africa/kwazulu-natal/howick-27052/), which is an ideal climate for avocado production. Additional water use measurements were conducted in Tzaneen on McNoon farm, which forms part of the Westfalia Estate. Tzaneen has a warm subtropical climate, with a mean temperature of 19.7°C and a mean January temperature of 23-25°C. Mean annual rainfall for Tzaneen is 881 mm (https://en.climate-data.org/africa/south-africa/limpopo/tzaneen-15345/).

This study encompassed the measurement and modelling of avocado orchards from planting to mature canopy size and the impact of water stress at different phenological stages on yield and quality of avocados. The cultivar in all study orchards, except one, was 'Hass' grafted onto either 'Dusa' or 'Duke 7' rootstocks. The cultivar in the non-bearing orchard was 'Harvest', as this was the most suitable non-bearing orchard available on Everdon Estates for measurement of water use. 'Hass' and 'Hass'-type cultivars dominate the market in South Africa, with these cultivars accounting for more than 80% of nursery produced trees. Measurements to determine orchard water use (evapotranspiration and transpiration) were conducted in the 2017/18, 2018/19 and 2019/20 seasons in three orchards varying in canopy size in Howick. Transpiration was determined in a single intermediate orchard in Tzaneen for a year. A mature full-bearing orchard was characterized as an orchard where a complete hedgerow had formed and where canopy cover exceeded 60%, which is in contrast to that of intermediate orchards where separate trees were distinguishable and canopy cover was between 40 and 50%. Non-bearing trees were trees that had yet to bear a commercial crop and where canopy cover was lower than 15%. Details of these orchards are provided in Table 1. Weather variables were measured on hourly and daily time steps at each trial site and included solar radiation, air temperature, relative humidity, windspeed and rainfall. These variables were used to calculate reference evapotranspiration (ET_o) according to Allen et al. (1998). All orchards at Everdon Estate were irrigated using one 50 L h^{-1} microsprinkler per tree, whilst at Westfalia Estate each tree was irrigated with a 30 L h^{-1} microsprinkler.

Transpiration in these orchards was determined using the heat ratio method, which is a heat-pulse sap flux density method, whilst ET was determined in all the orchards in Howick using an open path eddy covariance system. Additional data collected included leaf area index (LAI), volumetric soil water content, tree water status and yield and quality. This additional data was used for modelling exercises and to explain the water use patterns of the avocado trees in response to weather variables. Attempts to model the water use of avocado orchards included the dual crop coefficient FAO-56 approach and approaches which took into consideration canopy conductance. The Penman-Monteith equation was used to estimate E_c with estimates of canopy conductance using a parameterised Jarvis approach, whilst direct estimates of E_c were obtained following a modified Jarvis Steward type model as proposed by Whitley et al. (2009).

Using the data (ET, E_c and yield and quality) obtained in the mature orchard and intermediate orchard, water use efficiency (WUE) was calculated as kg produced per m^3 of water evapotranspired and transpired. In addition, by considering grade of fruit from the trees determined in the packhouse, water use productivity (WUP) was determined as Rands per m^3 of water evapotranspired or transpired.

Table1 Details of avocado orchards where transpiration and evapotranspiration measurements were performed (E_c – Transpiration; ET – Evapotranspiration, ET_o – reference evapotranspiration)

Orchard	Intermediate bearing	Mature bearing	Non-bearing	Tzaneen
Cultivar and Rootstock	'Hass' on 'Dusa'	'Hass' on 'Dusa'	'Harvest' on 'Dusa'	'Hass' on 'Dusa' and 'R0.06'
GPS co-ordinates	26°26'25" S 30°15'55''E	29° 27'3'' S 30°16'46''	29°27'35.42"S 30°16'41.73''E	23°43'49.51"S, 30° 8'12.35"E
Start	01-09-2017 (ET) 23-12-2017 (E_c)	08-04-2017 (ET) 13-03-2018 (E_c)	07-10-2019 (ET) 12-09-2019 (E_c)	04-12-2018 (E_c)
End	04-09-2019 (E_c and ET)	22-09-2019 (E_c and ET)	02-10-2020 (E_c and ET)	23-01-2020 (E_c)
Duration (days)a	880 – ET 621 – E_c	559 – ET 752 – E_c	360 – ET 387 E_c	416 – E_c
Age (years)	5	12	2	6
Planting pattern (m)	7 m × 4 m (28 m^2)			8 m x 4 m (32 m^2)
Planting density (trees ha^{-1})	357			312
Orchard area (ha)	2.91 ha	6.94 ha	2.33 ha	7 ha
Canopy cover[a]	0.48	0.97	0.20	0.60
Height (m)a	4.2	7.3	1.7	5.2
ET_o (mm)	1071[x]		1042[y]	1308[z]
Rainfall (mm)	1012[x]		1068[y]	674[z]

Orchard	Intermediate bearing	Mature bearing	Non-bearing	Tzaneen
Irrigation (mm)	113 [x]	ND	108 [y]	ND
Transpiration (mm)	678 [x]	359 [x]	30 [y]	476 [z]
Evapotranspiration (mm)	1071 [x]	1152 [x]	1124 [y]	ND

[a]at the start of the trial
[c]ND – not determined
[x]2018-2019 (September to September)
[y]2019-2020 (October to October)
[z]2018-2019 (December to December)

Measurements for the water stress trial took place in the 2018/19, 2019/20 and 2020/21 seasons in a mature 'Hass' on 'Duke 7' avocado orchard at the ARC-Tropical and Subtropical Crops in Nelspruit. Trees in the mature orchard were irrigated by means of one 50 L h^{-1} microsprinkler per tree, with a wetted diameter of 2 m. The soil for the experimental site was a sandy-clay soil. Treatments included the implementation of water stress during flowering, fruit set, fruit growth and fruit maturation and a well-watered control. For the fully irrigated treatment, soil matric potential was kept below -40 kPa to ensure stress free conditions. For the stress treatments, the aim was to dry the soil out to be drier than -40 kPa, by withholding irrigation and placing plastic sheets in the drip area of the trees to exclude rainwater.

In order to ensure that water deficits were successfully implemented in the orchard a number of additional parameters were monitored, which included soil matric potential and midday stem water potentials. In addition, flowering intensity, fruit set, flush vigour, fruit growth and fruit abscission data were collected. Yield and quality of the trees in each treatment were determined at the end of each season. The impact of water stress during the maturation phase on the storability of fruit was also assessed and included the evaluation of a number of postharvest disorders and pathogens. Unfortunately, the yield in the 2019/20 was not accurately recorded due a large amount of theft from the orchard during the COVID-19 level 5 lockdown.

RESULTS AND DISCUSSION

Water use measurements were conducted in a cool subtropical climate in Howick (average seasonal ET_o of 1060 mm) for three years and a hot subtropical climate (seasonal ET_o 1308 mm) for a single year at Westfalia Estate in Tzaneen. Whilst rainfall almost matched ET_o in Howick, rainfall was significantly lower than ET_o in Tzaneen. The differences in climate between the two regions were also illustrated by the differences in maximum daily air temperature, maximum daily vapour pressure deficit (VPD) and maximum daily ET_o, where the maximums recorded in Howick were 36.8°C, 3.08 kPa and 7.03 mm, whilst at Tzaneen these were 42.5°C, 3.92 kPa, and 7.91 mm.

Results from all the study orchards demonstrated that ET and E_c followed seasonal trends, with higher rates recorded in the hot summer months and lower values in the cooler winter months. A distinct impact of canopy size on E_c was also noted, with bigger canopies having higher seasonal E_c volumes. Transpiration of the mature orchard was 678 mm, 359 mm for the intermediate orchard and 30 mm for the non-bearing orchard. However, the same was not observed for ET, with very similar seasonal ET between the orchards of three different sizes. Unstressed total seasonal water use or ET for the mature orchard was 1071 mm, 1152 mm for the intermediate orchard and 1124 mm for the non-bearing orchard. This was largely as a result of varying evaporation rates (E_s) between orchards, with orchards with smaller canopies having a greater orchard surface area unshaded, resulting in higher rates of evaporation from the soil and transpiration from a greater grass cover between rows. Water use efficiency (WUE_{ET}) and water productivity (WUP_{ET}) were calculated for two seasons in the mature and intermediate orchards using measured ET and average yields for the orchard block. Both WUE_{ET} and WUP_{ET} varied between the two seasons, but were fairly consistent between the two orchards. In the intermediate orchard WUE_{ET} varied between 1.18 kg m^{-3} in the 2017/18 season and 1.62 kg m^{-3} in the 2018/19 season. In the mature orchards WUE_{ET} varied between 1.23 kg m^{-3} in the 2017/18 season and 1.61 kg m^{-3} in the 2018/19 season. Variation was attributed to differences in ET and yield. The variation in ET, yield and price impacted differences in WUP_{ET} between seasons, with WUP_{ET} in the intermediate orchard varying between R30.47 m^{-3} and R53.00 m^{-3}. Similar differences were noted in the mature orchard with WUP_{ET} varying between R24.39 m^{-3} and R50.64 m^{-3}. If you consider an average fruit mass of 250 g, then it takes approximately 150-200 L to produce a single avocado on this farm. It should also be noted that WUP_{ET} is likely to be higher for this farm than many of the farms in the major avocado producing areas, as they have a unique marketing window that allows for higher prices to be realised.

The reasons for the seasonal response of E_c were determined when evaluating the response of E_c to environmental variables, where there was a general increase in E_c with increases in solar radiation (R_s), air temperature (T_{air}), VPD and ET_o. Importantly this increase did not continue at the same rate through every portion of the determinant variable and tended to plateau at higher VPD and ET_o, suggesting some form of physiological control over E_c in avocado. This response was reiterated when assessing the variation in transpiration crop coefficients (K_t) throughout the season, where higher values were recorded during the cooler winter months, than the hot and dry spring and summer months. This resulted from E_c not increasing at the same rate as ET_o in the spring and summer months, resulting in a decrease in the ratio between E_c and ET_o and a lower K_t.

Three modelling approaches for estimating E_c in avocado orchards were evaluated in this study. These included a crop coefficient approach (Allen and Pereira, 2009), the Penman-Monteith equation using canopy conductance (g_c) estimated using a Jarvis approach and an empirical Jarvis-type approach by Whitley et al. (2009) where transpiration is estimated directly. Transpiration crop coefficients estimated for three orchards with canopy cover >50%, using the approach of Allen and Pereira (2009) and parameters for avocados suggested by these authors, were not successful and resulted in large overestimations of E_c. However, by using a dynamic estimate of leaf resistance (r_{leaf}), derived from measured E_c, better estimates of monthly E_c could be obtained in all three orchards. Although the trend in r_{leaf} was the same for all orchards, it is the adjustment of r_{leaf} values for specific orchards in different environments that proved to be problematic. Despite these shortcomings, monthly values of r_{leaf} for orchards with different canopy covers were determined, which can be used together with tree height and canopy cover to estimate orchard specific K_t values on a monthly basis.

Although the Jarvis approach failed to provide accurate estimates of canopy conductance (g_c) on an hourly basis for the parameterisation orchard when considering modelling statistics, these values did provide fairly good estimates of daily E_c, which met most statistical criteria. However, statistical criteria were not met for hourly g_c values when the Jarvis parameters derived for the intermediate orchard were transferred to the mature orchard and the orchard in Tzaneen. However, when maximum g_c ($g_{c\ max}$) was adjusted for canopy size differences between the mature and intermediate orchard, much better estimates of g_c in the mature orchard were obtained. When used in the Penman-Monteith equation to estimate E_c, reasonable estimates of E_c were achieved for both the mature and Tzaneen orchards. This approach could therefore provide reasonable daily estimates of E_c for a number of orchards, but it is the adjustment for different canopy sizes and for different climatic regions that needs refinement.

Whilst good estimates of daily E_c were obtained in the parameterisation phase in the intermediate orchard using the Whitley et al. (2009) approach, poor estimates were obtained in a similar sized orchard in Tzaneen using the parameters derived in the intermediate orchard in Howick, suggesting that the prevailing weather could influence the optimised parameters for an orchard. Canopy size also predictably influenced the maximum E_c ($E_{c\ max}$) parameter and had to be adjusted in order to ensure good E_c estimates in the mature orchard. Importantly, fairly good estimates of fortnightly E_c could be achieved with this approach in all three orchards. This time step is short enough to allow retrospective assessment of irrigation practices and to allow adjustment of irrigation volumes for the following two weeks.

The study on the impact of water stress at different phenological stages on yield and quality demonstrated that avocado trees and yields are sensitive to water deficits. The fruit set stage is especially sensitive, as fruit set occurs during early spring when conditions are generally hot and dry, with very high VPD and low rainfall. If orchards are not adequately irrigated during fruit set, crop losses of more than 50% could potentially occur. The fruit growth stage is less critical as fruit growth typically takes place during the summer when rainfall is high. The probability for water stress during fruit growth is therefore low in years with “normal” rainfall, as was evident from challenges to dry the soil sufficiently to induce water stress during this study. Irrigation should therefore be applied strategically during periods of rainfall to ensure that soils do not dry out to stressful levels. During fruit maturation, fruit growth decreases significantly, while the moisture content of fruit decreases until the fruit reaches harvest maturity. This stage occurs during late summer and autumn when rainfall generally declines and the soil may dry out to levels where water stress may occur. Water stress, even for relatively short periods during fruit maturation may lead to higher incidences of postharvest physiological disorders, lowering the marketability of the fruit. When dry soil conditions occur early during fruit maturation, when significant fruit growth still takes place, fruit size might be impacted thereby further affecting the marketability of the fruit. Water stress, however, had no effect on flowering. Water deficit stress therefore negatively affects production, fruit size and quality, which will eventually negatively affect marketability and farm income. Irrigation must therefore be optimized, using proper measurement, monitoring and scheduling tools in order to avoid water stress. A reliable plant physiological indicator, which could aid in optimizing irrigation scheduling, should be investigated further, as results of this study showed that midday stem xylem water potential on its own is not a reliable indicator of water stress for avocado trees.

NEW KNOWLEDGE AND INNOVATION

There have been very few attempts to quantify water use of avocado orchards and to partition total water use or ET into E_c and E_s. This study has therefore generated a unique water use data set, which can be used by the industry for irrigation planning and design purposes, the issuing of fair water licenses and for possible expansion planning within existing water allocations. It should also lead to better irrigation scheduling, as this project aids our understanding of the environmental factors impacting water use and how water stress at different phenological stages impacts yield and quality. Growers therefore can start predicting how weekly weather will impact water use of the orchard and when irrigation should be optimal to prevent a loss of yield and when water savings can potentially be made. As avocado trees are also sensitive to waterlogging and Phytophthora, this study should also aid in the prevention of over-irrigation.

As this study is one of the first in the world to quantify ET of avocado orchards, it is also the first to provide reliable figures for water use efficiency and water use productivity. Values in literature were most likely calculated using applied water (irrigation and rainfall) and not ET, but despite these differences in the denominator, values from this study were very similar to those reported in literature. These values should allow benchmarking of the industry in future and provide an indication of the value of water used in the production of avocado fruit. As avocado is an oil storing crop with low yields, it is important to indicate the value of the product per volume of water evapotranspired.

There have also been no reports of water use modelling for avocado orchards and although FAO-56 (Allen et al., 1998) and Allen and Pereira (2009) provide suggestions for crop coefficients and basal crop coefficients for avocado orchards, these crop coefficients did not compare favourably to those determined in this study. This was particularly noticeable for the shape of the crop coefficient curve, with the K_t curve in this study having lower values in summer than winter. This study therefore improves on published crop coefficient values for avocado orchards. In addition, values for leaf resistance were determined, which can be used for the derivation of orchard specific K_t values when combined with canopy height and fractional cover.

CAPACITY BUILDING

There were three students registered on this project (1 PhD, 1 MSc and 1 BSc (Hons)), with an additional PhD student to register in 2021. The BSc (Hons) hydrology student graduated in 2020. Funding from this project will be used for the remaining three students to finish their studies.

Results from the study were also shared via a number of different forums, including presentations at local and international conferences, grower study groups, the SAAGA research symposium; a publication in a conference proceeding and a number of publications in the SAAGA yearbook and other popular publications.

CONCLUSIONS

This study has provided comprehensive measurements of ET and E_c over a number of seasons, in a number of different sized orchards, across two climatic regions. Average ET for the three orchards in Howick were very similar and ranged between approximately 1000 to 1150 mm per season or 10 000 to 11 500 m^3 per season. Transpiration was, however, dependent on canopy size and ranged from 30 mm per season for a young non-bearing orchard in a season to 680 mm in a mature orchard. As these values are specific to a single orchard for a single year, a number of models were evaluated to make these values applicable to a wide range of orchards in different climatic regions. Although, improvements are still required to the crop coefficient approach, this study has provided better estimates of both K_c values and K_t values for avocado orchards, which can be used with a fair amount of confidence to estimate seasonal water use, provided estimates of ET_o, canopy cover and tree height are available. Alternatively, if hourly weather data and estimates of LAI are available, the Jarvis approach provided reasonable estimates of g_c, which in turn provided fairly good estimates of daily and monthly E_c using the Penman-Monteith equation. A less data intensive modified Jarvis-Steward approach provided reasonable direct estimates of E_c, which can be used with good confidence for fortnightly estimates of E_c.

This study also assessed the impact of water stress at different phenological stages on yield and quality of avocado orchards, where it was demonstrated that avocado trees, and therefore yields, are sensitive to water deficits, even if water deficits are moderate or only occur for relatively short periods of time. Stress during times of low rainfall seemed to be particularly harmful to final yield and this typically occurs during the fruit set stage. At this stage there is a potential for more than 50% of the crop to be shed under stressful conditions. The probability for water stress during fruit growth is low in years with "normal" rainfall, but irrigation should be applied strategically during dry periods to ensure that soils do not dry out to stressful levels, as fruit growth can decline during these periods. Water stress, even for relatively short periods during fruit maturation may lead to higher incidences of postharvest physiological disorders, lowering the marketability of the fruit. Irrigation must therefore be optimized, using proper measurement, monitoring and scheduling tools in order to avoid water stress and to make the most of available rainfall.

RECOMMENDATIONS FOR FUTURE RESEARCH

This study represents the first step in determining water use of avocado orchards and whilst measurements were made in a number of orchards varying in canopy size in two climatic zones, some questions still remain, largely because the performance of water use models was not always acceptable in the different orchards. More robust ways of estimating canopy size need to be evaluated, as it was clearly evident in this study that transpiration was dependent on canopy size. Remote sensing techniques to determine canopy volume and radiation interception models, which account for changes in leaf area density as a result of pruning practices need, to be tested and parameterised for avocado orchards. This will allow for improved water use modelling in orchards with different canopy sizes. The relatively poor performance of the Jarvis approach to estimate canopy conductance suggests that more mechanistic approaches should be investigated for the estimation of canopy conductance, such as the approach by Villalobos et al. (2013). In addition, in order to understand constraints within the plant to water use, more detailed ecophysiological studies for avocado under a range of conditions need to be performed. This should include diurnal and seasonal variation in gas exchange and water relations and the manner in which crop load impacts these processes. Understanding the partitioning of ET between soil evaporation and transpiration is important as transpiration should ideally be maximised in orchards, whilst evaporation should be minimised. Modelling of evaporation needs to be done to account for changes in wetting patterns, as a result of irrigation and rainfall, in relation to changes in canopy size and shading of the orchard floor. This should allow for scenario testing by growers in order to try and minimise this component in orchards, thereby allowing for water savings.

Whilst two seasons of water stress treatments were completed in this study, there were stages when it was very difficult to implement water stress due to high rainfall, which typically occurred during summer. As a result, the impact of continuous mild water stress during these stages is still largely unknown. In addition, more research on the thresholds at which stress is experienced by avocado trees could contribute significantly to our knowledge of how to schedule irrigation for avocado trees. This could help answer the question of at what soil water depletion level irrigation should be implemented. The combined determination of predawn and midday stem water potentials together with gas exchange, could help determine suitable plant-based indicators of water stress, which could then be matched to soil water depletion levels.

GENERAL

The contract objectives have been met and, in some instances, they have been exceeded. Water use was quantified in four orchards in two different climatic regions. Three of these orchards fell within a cool subtropical zone in Howick, KwaZulu-Natal and the fourth was located in a warm subtropical climate in Tzaneen, Limpopo. The fourth orchard was an additional orchard to assist with modelling exercises. These orchards varied in canopy size from planting to full maturity and included a non-bearing orchard, an intermediate sized orchard and a mature orchard. Measurements of water use yielded valuable information on the partitioning of evapotranspiration into transpiration and evaporation and facilitated the parameterisation of three models for the estimation of orchard transpiration. Following the determination of yield in each season it was possible to combine yield data with the water use data to determine both water use efficiency and water use productivity of the orchards in the one climatic zone.

Despite initial struggles to conduct the water stress trial, two seasons of water stress at different phenological stages were successfully completed during the course of the study. However, the COVID-19 level 5 lockdown impacted our ability to harvest the trial in the 2019/2020 season and resulted in significant amount of theft in the orchard. Information gained from this trial will assist growers with knowing when to avoid water stress in their avocado orchards and how to schedule irrigation during times of reduced allocations to minimise the impact on yield and quality.

ACKNOWLEDGEMENTS

This project was directed, funded and managed by the Water Research Commission in collaboration with the South African Avocado Growers' Association (SAAGA). We would like to thank Westfalia Fruit for allowing us to use their productive orchards at Everdon Estate and Westfalia Estate and for providing a great deal of assistance when needed. Special thanks go to a number of individuals who assisted us throughout the study, Cecil Hackney (area manager), Bongeka Ndlovu (assistant area manager) and Andrew Fourie at Everdon Estate and Dr Zelda van Rooyen and Wilna Stones at Westfalia Technological Services for assisting with the selection of a suitable orchard on Westfalia Estate and for providing weather data. We would also like to acknowledge Mr Juan Pienaar from Avo Valley for allowing use to use one of his avocado orchards for the initial water stress trial. Mr Alwyn du Preez and Mr Stephan Schoeman are also thanked for assisting in trying to find a suitable site for the water stress trial. Mr Vivek Naiken from UKZN and Mr Ronnie Gilfillan from UP are thanked for a great deal of technical assistance for the duration of the project. Mr Mxolisi Gumede and Mr Joseph Masanganise are thanked for assistance with equipment installation and routine fieldwork at Everdon Estate. Mr Andries Bester from SAAGA is thanked for the invitations to present results from the study at study groups and for providing the SAAGA cost calculator for determining average input costs.

The authors would like to thank the Reference Group of the WRC Project for the assistance and the constructive discussions during the duration of the project:

Prof S Mpandeli (Chairman of the project 2016-2020)	Water Research Commission
DR L Nhamo (Chairman of the project 2020-2021)	Water Research Commission
Dr GR Backeberg	Water Research Commission
Dr SN Hlophe-Ginindza	Water Research Commission
Dr G Nortje	Subtrop/UNISA
Dr J Mehl	Subtrop
Dr E Strydom	SAMAC
Mr B Christie	SAMAC
Dr S Dzikiti	CSIR/Stellenbosch University
Dr MG Gush	CSIR
Mr S Schoeman	Private consultant
Mr A du Preez	Private consultant
Dr N Murovhi	ARC
Mr B Snijder	SAAGA
Mr JT Vahrmeijer	CRI

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LIST OF ABBREVIATIONS

ABA	abscisic acid
ARC	Agricultural Research Council
ARC-TSC	Agricultural Research Council – Tropical and Subtropical Crops
AWS	automatic weather station
CC	canopy cover
D	Willmot index of agreement
EC	eddy covariance
FAO	Food and Agriculture Organization of The United Nations
FC	field capacity
GPS	global positioning system
IO	intermediate orchard
IRGA	infrared gas analyser
MAE	mean absolute error
MO	mature orchard
NB	non-bearing orchard
OPEC	open path eddy covariance
PAR	photosynthetically active radiation (µmol s^{-1})
PFTE	polytetrafluoroethylene
PPO	polyphenol oxidase
PWP	permanent wilting point
R^2	coefficient of determination
RH	relative humidity (%)
RMSE	root of the mean square error
RWC	relative water content
SAAGA	South African Avocado Growers Association
SPAC	soil-plant-atmosphere-continuum
TDP	thermal dissipation probe
VPD	Vapour Pressure Deficit (kPa)
WRC	Water Research Commission
WUE_{ET}	water use efficiency based on evapotranspiration volumes (kg m^{-3})
WUP_{ET}	water use productivity based on transpiration volumes (R m^{-3})
WUE_T	water use efficiency based on transpiration volumes (kg m^{-3})
WUP_T	water use productivity based on transpiration volumes (R m^{-3})

Symbol	Description and units
A	photosynthesis (µmol m^{-2} s^{-1})
c_w	specific heat capacity of the wood matrix (J kg^{-1}° C^{-1})
c_s	specific heat capacity of the sap (J kg^{-1}° C^{-1})
C_p	specific heat capacity of air (J kg^{-1} K^{-1}))
d	zero plane displacement (m)
E_c	transpiration (ℓ or mm)
$E_{c\ max}$	maximum canopy transpiration (mm)
E_{leaf}	leaf transpiration rate (mmol H_2O m^{-2} s^{-1})
E_s	evaporation from the orchard floor (mm)
ET	evapotranspiration (mm or m^3)
ET_o	reference evapotranspiration (mm)
Fa	total number of fruit that abscised
f_c	observed fraction of soil covered by vegetation seen from directly above
f_{ceff}	effective fraction of ground covered or shaded by vegetation near solar noon
f_{IPAR}	fraction of intercepted photosynthetically active radiation
F_r	adjustment factor relative to stomatal control
Ft	sum of the total number for fruit
G	soil heat flux (W m_{-2})
g_a	aerodynamic conductance (m s^{-1})
g_s	stomatal conductance (mol m^{-2} s^{-1})
g_c	canopy conductance (m s^{-1})
$g_{c\ max}$	maximum canopy conductance (m s^{-1})
h	plant height (m)
H	sensible heat (W m^{-2})
iWUE	intrinsic water use efficiency (umol mol^{-1})
k	Von Karman's constant
k_w	thermal diffusivity of green (fresh) wood (cm^2 s^{-1})
K_c	crop coefficient
$K_{c\ ini}$	initial crop coefficient for the start of the season
$K_{c\ mid}$	crop coefficient for the mid-season
$K_{c\ end}$	crop coefficient for the end of the season
K_{cb}	basal crop coefficient

$K_{cb\ ini}$	initial basal crop coefficient at the start of the season
$K_{cb\ mid}$	basal crop coefficient for the mid-season
$K_{cb\ end}$	basal crop coefficient for the end of the season
$K_{t\ full}$	transpiration crop coefficients for fully grown orchard
K_d	canopy density coefficient
K_e	soil evaporation coefficient
k_{e1}	model parameter for vapour pressure deficit
k_{e2}	model parameter for vapour pressure deficit
k_{D1}	model parameter for vapour pressure deficit
k_{D2}	model parameter for vapour pressure deficit
k_R	model parameter for solar radiation
k_T	model parameter for temperature
K_t	transpiration crop coefficient
L	leaf length (mm)
LAI	leaf area index ($m^2\ m^{-2}$)
LE	latent energy ($W\ m^{-2}$)
Li	number of leaves counted before leaf abscission
m_c	moisture content of sapwood sample (%)
M_L	parameter that simulates the physical limits imposed on water flux through the plant root, stem and leaf systems
N	number of samples
P_a	atmospheric pressure (Pa)
RH_{min}	minimum relative humidity (%)
r_{leaf}	mean leaf resistance ($s\ m^{-1}$)
r_s	mean surface resistance ($s\ m^{-1}$)
R_m	arbitrary radiation constant (fixed at 1000 $W\ m^{-2}$ in this study)
R_n	net radiation ($W\ m^{-2}$ or $MJ\ m^{-2}\ day^{-1}$)
R_s	solar radiation ($W\ m^{-2}$ or $MJ\ m^{-2}\ day^{-1}$)
R_{so}	solar radiation under clear sky conditions ($MJ\ m^{-2}\ day^{-1}$)
S^2	sum of squares
SFD	sap flux density ($m^3\ m^{-2}\ h^{-1}$)
T_{air}	air temperature (°C)
T_{leaf}	leaf surface temperature (°C)
T_L	lower temperature limit to transpiration (°C)
T_U	upper temperature limit to transpiration (°C)
ψ_{leaf}	leaf water potential (MPa)

ψ_{pd}	pre-dawn leaf water potential (MPa)
ψ_{stem}	stem water potential (MPa)
u_2	wind speed at 2 m height (m s^{-1})
v_1	increase in temperature of upper thermocouple after the heat pulse is released (°C)
v_2	increase in temperature of the lower thermocouple after the heat pulse is released (°C)
V_c	corrected heat pulse velocity (cm h^{-1})
V_h	heat pulse velocity (cm h^{-1})
VPD_{air}	air vapour pressure deficit (kPa)
VPD_{leaf}	leaf to air vapour pressure deficit (kPa)
V_s	sap velocity (cm h^{-1})
V_w	volume of wood sample (cm^{-3})
w	wounding width (cm)
W	leaf width (mm)
X	distance between the heater and the upper and lower thermocouple (cm)
Z	wind measurement height (m)
z_o	roughness length (m)
Δ	slope of the saturation vapour pressure vs air temperature curve (kPa K^{-1})
ΔT	temperature difference
ΔT_o	temperature difference during a period of zero flow
ρ_a	density of dry air (kg m^{-3})
ρ_b	basic density of wood (g cm^{-3})
ρ_s	density of water (kg m^{-3})
Γ	psychrometric constant (kPa K^{-1})
Λ	the latent heat of vaporization (J kg^{-1})
∝	fraction of sunlit canopy leaf area
θ	soil water content
φ	latitude (radians)
δ	solar declination (radians)

1. INTRODUCTION

1.1 BACKGROUND

South Africa is ranked as one of the leading exporters of avocados globally, with approximately 55% of the crop exported mainly to Europe. The vast majority of avocados produced in South Africa are the dark-skinned 'Hass' and 'Hass-type' cultivars (80% of the plantings), with the remaining 20% green skinned varieties. A tree census in 2020 indicated that 14 700 ha are planted to avocado orchards in South Africa, with an annual increase of approximately 800 ha, which is based on tree sales (SAAGA, 2020). Most of these orchards are planted in the warm subtropical areas of Limpopo and Mpumalanga, but expansion has taken place to the cooler subtropical zones in South Africa. This allows a spread in harvest times from February through to November. Despite the long history of avocado orchards in South Africa, very little research has been conducted on the water use of these orchards and as a result there is some uncertainty regarding the volumes of water needed to produce avocados and how to schedule irrigation optimally in these orchards.

The lack of knowledge is exacerbated by the range of climates where avocados are grown, which impacts annual water use and the recent droughts which have forced growers who have relied solely on rainfall in the past to start irrigating their orchards. Many avocado producing regions in South Africa have experienced significant droughts in recent years and this has also prompted the question as to how water stress at different phenological stages impacts yield and quality. With this information in hand it will be easier for growers to determine how to irrigate their orchards when they receive reduced water allocations as a result of drought. In addition, an export orientated industry requires high quality fruit and an understanding of the impact of water stress on fruit quality could help improve irrigation scheduling to reduce the incidence of physiological disorders.

Research questions for this study therefore included

- What is the maximum unstressed water use of avocado orchards in South Africa?
- How does orchard water use vary from planting to a mature canopy size?
- What is the partitioning of water use between tree transpiration and evaporation from the soil and cover crop in orchards with different canopy sizes?
- What is the water use efficiency and water use productivity of well managed avocado orchards?

- What is the best approach to model water use of avocados, which allows the estimation of avocado orchard water use in the different climatic regions where avocados are grown in South Africa?
- How does water stress at different phenological stages impact yield and quality of avocado orchards?

This information is required in order to improve irrigation planning and irrigation system design for avocado orchards for optimal years and to decide how to allocate water throughout the phenological cycle during drought years with minimal impact on yield. In order to improve irrigation scheduling, more information is needed on how water use responds to weather variables and how these volumes can be accurately estimated for orchards in which measurements of water use are not available. It will also aid authorities in issuing water licenses and for grower organisations to defend water allocations.

1.2 AIMS AND OBJECTIVES

General aim

To quantify water use of avocado in relation to yield at orchard scale

Specific objectives

1. To measure unstressed water use of avocado according to seasonal growth stages from planting to mature canopy size for selected cultivars and locations;
2. To model unstressed water use of avocado according to seasonal growth stages from planting to mature canopy size for selected cultivars and locations;
3. To determine the influence of water stress during different phenological stages of avocado on yield and quality for selected cultivars and locations;
4. To quantify water use efficiency and water use productivity of avocado for selected cultivars and locations

1.3 APPROACH AND SCOPE

The project began with a comprehensive literature review, which documented current knowledge on avocado water use and the impact of water stress on avocado trees. Sources included local and international published literature, together with grey literature appearing in

Grower Association Yearbooks for example. Through this process gaps in current knowledge were identified. This was followed by the selection of appropriate orchards for measurements.

The measurement phase of the project encompassed the quantification of transpiration and evapotranspiration of four orchards varying in canopy size across two climactic regions in South Africa using a sap flow technique and open path eddy covariance systems. Orchards were selected based on the close proximity to researchers, a history of good management and good yields, the suitability for micrometeorological measurement techniques and differences in canopy size. In order to meet all these criteria a mature orchard, intermediate orchard and non-bearing orchard were selected at Everdon Estate just outside of Howick in KwaZulu-Natal. Orchards were instrumented in a staggered approach in line with the project budget and the availability of equipment from April 2017 to September 2019. Measurements typically lasted 2 years in the mature and intermediate orchard and a single year in the non-bearing orchard. Weather data were collected in conjunction with these measurements in order to determine the driving variables for avocado water use. Measurements of leaf area index were performed on a regular basis to provide a measure of canopy size. Ecophysiological measurements were also performed to ensure the determination of unstressed water use. As KwaZulu-Natal is not a major avocado producing region, an additional avocado orchard was instrumented in Tzaneen with sap flow equipment in December 2018 and measurements were made for a single year. The water use data were used to parameterise water use models for avocado orchards and included crop coefficient and canopy conductance approaches. Finally, the water use data together with yield and fruit price data was used to derive water use efficiency and water use productivity values for the two bearing orchards in Howick.

The second aspect of the project was to determine the impact of water stress at different phenological stages on yield and quality of avocados. For this purpose, an orchard was finally selected in Nelspruit at the ARC-Tropical and Subtropical Crops (TSC), with a sandy soil to facilitate the implementation of water stress. Trees were water stressed at different phenological stages and yield and quality were assessed at the end of the season. Phenological stages where stress was implemented included flowering, fruit set, fruit growth and fruit maturation and these treatments were compared to a well-watered control. Measurements continued for two seasons and at the end of each season yield and quality was determined.

2. LITERATURE REVIEW

2.1 WATER USE

2.1.1 PHENOLOGY AND MORPHOLOGY

The avocado has many morphological characteristics reflecting its rainforest origin in Central America and Mexico (Whiley and Schaffer, 1994) and is not considered as a drought tolerant tree (Whiley and Schaffer, 1994). This includes a shallow root system, which is relatively inefficient at taking up water and has low hydraulic conductivity. The root system has a high oxygen requirement and roots die after a short exposure to anaerobic conditions (Stolzy et al., 1967). Prevention of waterlogging is therefore important for root longevity and the control of *Phytophthora cinnamomi* (Reeksting et al., 2014). The tree has a vegetative growth bias, which is an ideal characteristic for competing for light in a rain forest environment, but often comes at the expense of fruiting (Carr, 2013). Growth occurs in flushes and as a result the canopy consists of leaves of a variety of ages, with varying photosynthetic efficiencies (Whiley et al., 1988). Leaves have a high stomatal density on the underside of the leaf (40 000-73 000 cm^{-2}) and have a limited vascular network (Scholefield and Kriedemann, 1979). Differences in stomatal densities within cultivars have been attributed to climatic differences between locations (Whiley et al., 1988). Trichomes are found on the leaves of some cultivars and on young leaves, as well as wax deposits. Wax deposits increase with leaf age and are eventually even deposited in stomatal cavities, subsequently resulting in decreased gas exchange in older leaves (Mickelbart et al., 2000). The xylem and phloem elements of the leaf are arranged in the same manner as other vascular tissue in the plant. A detailed study was carried out investigating xylem vessel features for the three avocado races (Guatemalan, Mexican and West-Indian) and race hybrids (cultivars 'Hass' and 'Fuerte'). Both 'Fuerte' and 'Hass' had a similar vessel frequency of approximately 12 xylem vessels per mm^2. This was less than for the three different avocado races, in which case it varied between 18 and 22 vessels per mm^2. However, 'Fuerte' and 'Hass' had larger vessel diameters than the three races, which made them more vulnerable to xylem cavitation and therefore water stress (Reyes-Santamaria *et al.*, 2002). Stomatal density on the exocarp of young fruit just after set was found to be approximately 50 to 75 stomata mm^{-2}. The transpiration rate of fruit is approximately 4.5 to 4.7 mmol m^{-2} s^{-1}, which is higher than for leaves and flowers on a surface area basis (Blanke & Lovatt, 1993). However, as the fruit grow and mature, stomata become less active and are plugged as the fruit matures and are referred to as lenticels (Carr, 2013).

The basic phenology of the avocado tree is illustrated in Figure 2.1. The magnitude of these events and the timing will change with year, region and cultivar, but the basic progression of events will remain fairly constant. Mature bearing trees have two major vegetative flushes in a full growth season. Following the completion of each vegetative flush is a period of root growth, which supports a rhythmic growth habit. The first vegetative flush occurs in spring and the second flush occurs over the summer period. Flower initiation begins in autumn, when the tree enters a quiescent stage, with flowering occurring in late winter, early spring. Blanke and Lovatt (1993) found that stomata occur on the abaxial surface of the petals and sepals at a density of 2.8 to 3.4 stomata mm^{-2}, which amounts to 78 to 96 stomata per flower. All floral parts are usually densely pubescent with trichomes on both the adaxial and abaxial surfaces of the flowers. Floral transpiration was found to be higher than transpiration of leaves with floral transpiration being between 1.2-1.3 mmol m^{-2} s^{-1}, comparing to leaves which transpire at 0.7-1.1 mmol m^{-2} s^{-1} (Blanke and Lovatt, 1993). A mature, bearing avocado tree bear more than one million flowers (Scora et al., 2002) and it could be expected that when in full bloom water loss can be significant due to floral transpiration, which can lead to water stress if not well-watered. However, the contribution of floral transpiration to total water use of an avocado tree was found to be rather low, contributing only 13% to total tree transpiration (Whiley et al., 1988). Immediately after flowering there is a fruit drop period, often as a result of competition between the developing fruit and new shoot growth (Whiley et al., 1988). Stress at this stage can increase fruit drop and thus it is important that water is not limiting at this stage. A second stage for fruit drop is also associated with the start of the summer vegetative flush and once again the avoidance of stress at this stage is critically important to minimise fruit drop. Sound water management at this time will limit the impact of this crop adjustment period on final yield (Whiley et al., 1988).

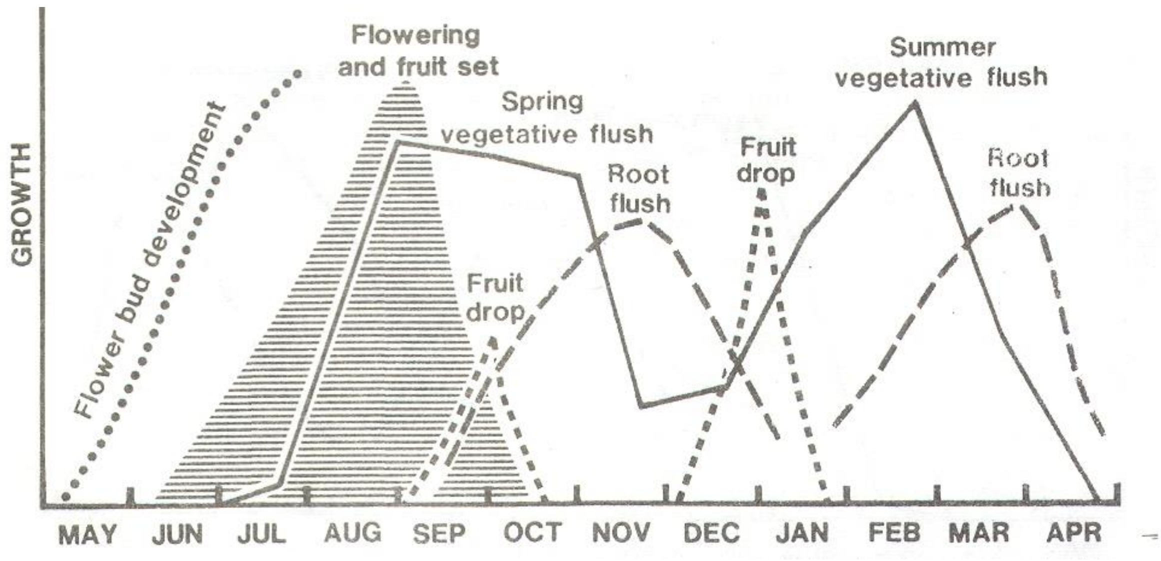


Figure 2.1: The phenological cycle for 'Fuerte' avocado trees in Queensland. A similar pattern occurs under South African conditions and for different cultivars. It is only the timing of the events and the magnitude of the events that change (Whiley et al., 1988).

2.1.2 ESTIMATES OF WATER USE

Locally, very few attempts have been made to determine the water requirements and crop coefficients for avocado. In Burgershall, for 'Fuerte' grafted on 'Duke 7' rootstocks it was shown that water use (evapotranspiration – ET) varied between 50 m^3 ha^{-1} day^{-1} (5 mm day^{-1}) during summer, decreasing to 15 to 20 m^3 ha^{-1} day^{-1} (1.5 to 2.0 mm day^{-1}) in winter (Hoffman and du Plessis, 1999). For 'Hass' grafted on 'Duke 7', seasonal water use was 40 m^3 ha^{-1} day^{-1} (4.0 mm day^{-1}) during summer, decreasing to 15 m^3 ha^{-1} day^{-1} (1.5 mm day^{-1}) in winter. Annual water use for 'Fuerte' was calculated as 10 200 m^3 ha^{-1} $annum^{-1}$ (1020 mm $annum^{-1}$), while it was 8 900 m^3 ha^{-1} $annum^{-1}$ (890 mm $annum^{-1}$) for 'Hass'. These numbers should, however, be viewed with some caution as a simple water balance was used to determine ET. Evapotranspiration was calculated by adding together the amount of irrigation applied to soil from 50% depletion of easily available water to field capacity and effective rainfall on the "wetted area" (precipitation more than 5 mm and 70% was considered effective) (Hoffman and du Plessis, 1999). This is therefore a representation of applied water and not actual water evapotranspired from the orchard.

Besides the determination of water requirements of avocado (Hoffman and du Plessis, 1999), no published work could be found where crop coefficients were determined for avocado under South African conditions. In a review by Du Plessis (1991) it was stated that "Very little work has been done in South Africa in this regard and crop factors obtained elsewhere will have to be used locally, or crop factors recommended for citrus may have to be considered in the meantime". The site-specific nature of crop coefficients (Allen and Pereira, 2009) could therefore have resulted in inaccurate estimates of avocado water use in South Africa. At least before 1990, no research on this aspect had been carried out. It would appear if some attempt to determining crop coefficients were made after 1990, as crop coefficients were provided by Kruger (2001) for two avocado production areas (Table 2.1). According to Carr (2013), crop coefficients for mature trees should be in the range of 0.4 to 0.6 and it can be seen from Table 1 that in some instances these crop coefficients were well above the figure given by Carr (2013). In addition, no detail on the methodology used to determine the crop coefficients in Table 2.1 were provided by Kruger (2001) and no other published work could be found indicating how these crop coefficients were determined. Cantuarias (1995) showed that under conditions of high evaporative demand (reference evapotranspiration (ET_o) = 7-15 mm day^{-1}) in the Negev, Israel, actual transpiration (E_c) of the trees only reached 3 mm day^{-1} and the ratio of E_c/ET_o (K_t or transpiration crop coefficient) remained low, between 0.13 and 0.21.

Table 2.1: Crop coefficients for mature avocado trees in the Nelspruit and Hazyview production areas (Kruger, 2001)

Month	A	S	O	N	D	J	F	M	A	M	J	J
Nelspruit	0.45	0.41	0.55	0.72	0.89	0.83	0.73	0.56	0.49	0.44	0.36	0.42
Hazyview	0.49	0.50	0.66	0.82	1.07	0.99	0.85	0.68	0.53	0.46	0.34	0.43

There are a few more reports of avocado water use in other parts of the world, but very little has been published in peer reviewed journals. Avocado (5 to 11 years-old and spaced 6 m x 6 m) ET in the northern coastal plain of Israel was relatively constant in the irrigation season (June to October Northern Hemisphere) at 3.0 to 3.5 mm day^{-1}. Crop coefficients or K_c (using E_{pan}) ranged from 0.42 (June) to 0.61 (October) (Shalhevet et al., 1979). Lahav et al. (2002) provide the following recommendation for mid-summer application rates in Mediterranean climates for young trees: year 1, 4-8 L tree^{-1} day^{-1}; year 2, 8-15 L tree^{-1} day^{-1}; year 3, 20-50 L tree^{-1} day^{-1} and year 4, 80-150 L tree^{-1} day^{-1}. In year 4, at 400 trees per ha, this equates to 3.2 to 6.0 mm day^{-1}. In southern California, in years with annual rainfall between 250 and 500 mm, avocado growers typically apply between 450 and 1500 mm irrigation water, depending on location (Faber, 2006). For mature orchards a K_c of 0.7 is recommended in this area, with a 10% leaching fraction, depending on water quality. In Australia irrigation volumes for avocado vary considerably among regions, from 300-500 mm in the high rainfall areas of northern

Queensland to 800-1800 mm in areas further south and Western Australia (reference in Carr (2013)).

2.1.3 ECOPHYSIOLOGY

Avocado stomata respond mainly to atmospheric vapour pressure deficit (VPD), soil water content and solar radiation. It was found that stomatal response to soil water content was rapid (less than an hour under soil drying conditions and approximately half an hour after re-watering) (Gil et al., 2008, Gil et al., 2009, Ramadasan, 1980). It was shown that electric signalling was possibly responsible for this rapid response. This signal is postulated to be transported via the phloem (Gil et al., 2008, Gil et al., 2009). When correlated with leaf water potential it was found that stomatal conductance started to decline when leaf water potential was approximately -0.4 MPa and then continued to decline until complete closure at -1.0 to -1.2 MPa (Schaffer and Whiley 2003, Whiley and Schaffer, 1994). Similar work in South Africa showed that stomatal conductance decreased when midday stem xylem water potential fell below -0.5 MPa (Roets et al., 2015). The rapid physiological responses to changes in soil water and VPD contributes to the adaptability of avocado to diverse climates, from humid to semi-arid (Scora et al., 2002). The decline in stomatal conductance at leaf water potentials of -0.5 MPa, which remains constant over a wide range of ET_o (Cantuarias, 1995), suggests isohydric behaviour of avocados (Jones, 2007). Stomata function as pressure regulators in water relations (Sperry et al., 2002) and limit the variability in leaf water potential with soil water availability and evaporative demand by controlling transpiration. As a result, the plant avoids damaging drops in leaf water potential that could result in cavitation.

Soil aeration has an important effect on stomatal response. When air content of the soil was between 7 and 22%, stomatal conductance was approximately 0.23 cm s^{-1}, however, when air content increased above 29%, stomatal conductance increased to approximately 0.43 cm s^{-1}. Low soil air content therefore causes stomatal closure as well (Ferreyra et al., 2007), as under flooded conditions or soil compaction. This is because low soil oxygen levels impair root functioning, resulting in lower uptake of water and nutrients, with subsequent stress, leading to stomatal closure. Stomata also respond to changes in solar radiation. It was shown that when photosynthetically active radiation (PAR) was reduced from > 1700 µmol m^{-2} s^{-1} to < 130 µmol m^{-2} s^{-1} in both well-watered and water stressed trees, stomatal conductance declined by approximately 40% (Whiley and Schaffer, 1994).

Sharon et al. (2001) measured hydraulic conductivity of the avocado rootstock ‘Dagania’ and found that the avocado, in fact, does not have such low hydraulic conductivity and that it was higher than in two citrus rootstocks ‘Troyer’ and ‘Macrophilia’. C*itrus* is reported to have very low hydraulic conductance (Kriedemann and Barrs, 1981). It was concluded that the root system is capable of supplying water to the canopy approaching or equal to transpiration losses, as long as soil water remains close to field capacity. Unfortunately, the work of Sharon et al. (2001) has been described as “not convincing” by Carr (2013), but no specific reasons were mentioned for the statement.

Reyes-Santamaría et al. (2002) determined relative conductivity of the three avocado races and race hybrids (‘Fuerte’ and ‘Hass’) based on xylem vessel characteristics. The Mexican and West Indian races and the hybrids had similar conductivities, whilst the Guatemalan race had the lowest conductivity. However, based on xylem vessel diameters, the hybrids (‘Fuerte’ and ‘Hass’) had a higher tendency for xylem cavitation and it was concluded that the hybrids would be more sensitive to water deficits than the races. Of the three races it could be expected that the Guatemalan race would be more sensitive to water deficits than the other two races. This also has implications for the leaf water potential at which stomata close and therefore water use.

2.1.4 IRRIGATION

The South African Avocado industry mainly uses microsprinklers to irrigate avocado orchards. In a survey carried out during 2015 (Unpublished data), it was found that approximately 89% of the respondents used microsprinkler irrigation. Drip irrigation was only used by approximately 3.5% of the respondents, whilst almost 7% of the respondents do not use irrigation at all (dryland). This may, however, be changing with an increase in the adoption of low flow drip for new plantings, which is being driven by droughts in traditional avocado producing regions in South Africa. It is important to note that in most of the avocado production areas of South Africa occasional dry periods occur and as this is an evergreen crop, supplementary irrigation is necessary. Even when rain occurs, rainfall events of less than 10 mm have been shown to be ineffective, with no effect on tree water status (Winer, 2003). It is therefore highly likely that dryland orchards will at some stage experience water stress, which will negatively affect production and fruit quality. It was clearly shown by Kruger and Magwaza (2012) that post-harvest ripening of fruit from a dryland orchard was significantly more uneven than fruit from irrigated orchards. Dryland production of avocados is therefore not recommended.

As far as irrigation scheduling is concerned, not many South African avocado growers schedule irrigation. From the survey mentioned above, only 50% of the respondents indicated that they schedule irrigation. However, if all avocado growers are taken into consideration, it might be much less. A lack of scheduling is, however, a word wide trend. Carr (2013) described that tensiometers in orchards in California were rusted and growers ceased to use them. The importance of irrigation scheduling was stressed by Du Plessis (1991), who indicated that stress should be prevented to ensure optimal production and this can only be achieved by accurate measurement. Guidelines, using soil-based measurements, were published (Du Plessis, 1991; Kruger, 2001) and it was recommended that not more than 50 to 60% depletion of easily available water should be allowed in the effective root zone of trees in order to prevent stress. This corresponded to a matric potential of -30 kPa for a sandy soil and -50 kPa for a clay soil. Du Plessis (1991) strongly recommended the use of tensiometers for scheduling purposes. There are, however, a number of capacitance-type probes available in South Africa at present for irrigation scheduling purposes, e.g. DFM probes and Aquacheck. The increased focus on sustainable production and water restrictions in many areas is hopefully changing scheduling practices in South Africa.

Other recommendations made in the past to reduce water use included the use of mulch (Faber et al., 2000, Moore-Gordon and Wolstenholme, 1996, Nzanza and Pieterse, 2012) and application of irrigation during the night when it is cooler and evaporation is lower. The widespread use of mulches in avocado orchards impacts the water balance of the orchard and more specifically evaporation from the orchard floor. Water use measurements should estimate E_c and evaporation (E_s) separately in order to accurately model both components of ET and allow extrapolation to a wide range of orchards.

2.2 WATER USE EFFICIENCY AND WATER PRODUCTIVITY

In literature there is considerable variation in the use of the terms water use efficiency and water use productivity. In this project we will use the definition of van Halsema and Vincent (2012), where water efficiency (WUE) is defined as the ratio WUE = [product]/[water consumed] (e.g. kg m^{-3}) and focusses on more crop per drop. Water use productivity (WUP) on the other hand takes into account eh value of the product produced, and is defined as WUP = value product/[water consumed] (e.g. in R m^{-3}). It therefore represents an 'efficiency parameter of water utilisation at farm level, with all the scale and context specific limitations of the classical irrigation efficiency' (van Halsema and Vincent, 2012). Water use efficiency can also be defined on a physiological or leaf level and can be expressed in terms of stomatal regulation (intrinsic WUEi) or transpiration (instantaneous WUE). The former is calculated as A/g_s and the latter as A/E_c, where A is photosynthesis, g_s is stomatal conductance and E_c is transpiration, all determined with a photosynthesis system.

Estimations of WUP and WUE are difficult in avocado due to the alternate bearing nature of the crop and although attempts have been made to quantify WUE for avocados, there is still no reliable data. A number of years of data are therefore required in order to determine an accurate average of WUE. Most of the irrigation experiments have also been conducted in Mediterranean climates which is not representative of the climate in which avocados are produced in South Africa. Over a five year experiment in the coastal plain of Israel yield responses to irrigation in 'Ettinger' were 1.1 kg m^{-3} and 0.7 kg m^{-3} for 'Fuerte' (Kurtz et al., 1992). In another irrigation experiment in Israel yields of 'Hass' fruit were found to increase at 2.2. kg m^{-3}, whilst for 'Fuerte' yield increased at 1.6 kg m^{-3}. In Australia in a two year study on four farms WUE ranged from 0.3 to 3.2 kg m^{-3} (Aleemullah et al., 2001). Considering all the results available, Carr (2013) suggests that the best estimate of WUE for avocado (based on relatively low yields of between 9-10 t ha^{-1}) is between 1 and 2 kg fruit m^{-3}. This relatively low estimate of WUE for avocado is understandable considering the high oil content of the fruit and the resultant low yields per hectare, compared to most other fruit crops.

2.3 THE INFLUENCE OF WATER STRESS ON YIELD AND QUALITY

2.3.1 EFFECTS OF WATER STRESS ON ROOT GROWTH

As an adaptive strategy to water stress, an increase in the root-to-shoot ratio of plants generally occurs, when subjected to moderate water deficits, to facilitate water absorption (Shao et al., 2008). For avocado, Chartzoulakis et al. (2002) showed that root growth is as sensitive to water deficits as shoot growth, as the root-to-shoot ratio was unaffected by water deficits. However, under severe and prolonged conditions of water deficits and infection with *Phytophthora cinnamomi* root rot, considerable loss of roots occur. This resulted in compensatory loss of leaves, lower leaf water potentials, reduced stomatal conductance and therefore lower photosynthetic activity and disturbed mineral uptake.

Avocado roots are very sensitive to flooding conditions and exposure to flooding of only a few days can cause severe damage or result in tree death. Although it was initially believed that tree death after flooding was caused by *Phytophthora cinnamomi* root rot, it was shown that root death is as a result of anoxia (Reeksting et al., 2014, Schaffer, 2006). Optimal functioning of roots requires high soil oxygen levels, with impaired root functioning occurring when soil air content decreases below 17% (Ferreyra et al., 2007). When oxygen is excluded from the soil, or replaced by water, as during flooding, the roots switch from aerobic to anaerobic respiration, producing toxic by-products (acetaldehyde) that are possibly responsible for root death. Root death and impaired root functioning cause water stress due to altered water and mineral uptake, causing stress symptoms similar to drought stress symptoms. These symptoms include, declined rates of A, E_c and decreased g_s (Reeksting et al., 2014, Schaffer, 2006, Schaffer and Ploetz, 1989). When flooding occurs in saline soils, chloride is rapidly transported to the leaves resulting in chloride toxicity of the leaves and further root death (Crowley and Escalera, 2013). In addition, damage caused to the roots by flooding creates conditions conducive for *Phytophthora cinnamomi* root rot infection (Ben-Ya'acov and Michelson, 1995, Lahav et al., 2013, Schaffer and Ploetz, 1989). Pruning of trees directly after flooding may to some extend elevate the damaging effects of stress caused by the flooding (Sanclemente et al., 2014).

2.3.2 EFFECTS OF WATER STRESS ON VEGETATIVE GROWTH

Schaffer and Whiley (2002) concluded that vegetative growth in avocado is less sensitive to water deficits than reproductive growth. This is based on the findings of Whiley et al. (1988) who demonstrated that diurnal water deficits of inflorescences were greater than for the mature leaves subtending these inflorescences. However, irrigation experiments in California (Faber, 2006, Richards et al., 1962) and Israel (Kalmar and Lahav, 1977, Kurtz et al., 1992, Lahav and Aycicegi-Lowengart, 2006, Lahav et al., 1992) demonstrated that vegetative growth was positively correlated with irrigation frequency. As with most of other crops, the impact of water deficits on vegetative growth would be dependent on the severity of the stress, with severe stress causing a reduction in vegetative flushes. Chartzoulakis et al. (2002) stressed 2 year old ‘Hass’ and ‘Fuerte’ plants in 50 L containers and they concluded that ‘Hass’ growth was more sensitive to water stress than ‘Fuerte’, but that the root:shoot ratio was not altered. The authors concluded this was because shoot and root growth were equally sensitive to water stress. It is evident that more research is required under field conditions to understand the impact of water stress on vegetative growth in avocados. Chartzoulakis et al. (2002) also observed a change in leaf anatomy in the trees as a result of water deficits, which included a reduction in leaf thickness and a concomitant change in leaf porosity which restricted rates of CO_2 diffusion within the leaf.

2.3.3 EFFECT OF WATER STRESS ON FRUIT SET AND YIELD

Water stress causes a definite reduction in yield (Lahav et al., 1992, Lahav et al., 2013) and also increases the variation in yield between individual trees (Vuthapanich et al., 1998). Yield reduction during water stress is rarely caused by a reduction in flowering intensity. This is because water stress does not affect flower induction and therefore does not affect flowering intensity. Flowering in avocado is induced during late autumn by low temperatures and not by water availability, or the lack thereof, or by changes in day length (Chaikiattiyos et al., 1994). Avocado trees may therefore still flower profusely even under conditions of water stress. However, continuous water stress throughout flower anthesis will result in low fruit set. The concentrations of six (glucose and fructose) and seven (D-mannoheptulose and perseitol) carbon sugars and sucrose, as well as boron, strongly determines fruit set potential of avocado flowers. Boron binds to perseitol and is then transported to the flowers via the phloem (Boldingh et al., 2016). The role of boron in successful fertilization of flowers that eventually lead to improved fruit set was demonstrated in a number of crops (Ganie et al., 2013). For avocado flowers that did not set fruit, it was shown that either no pollen tube germination occurred or the ovules were non-viable (Garner and Lovatt, 2016). As water stress resulted in impaired water and nutrient absorption and translocation, the transport of carbohydrates and boron to the flowers may be negatively affected, which may result in lower fruit set. This requires further investigation.

After fruit set, reduction in yields may be the combined effect of smaller fruit and a higher rate of fruit abscission under conditions of water stress. A relationship was found between abscisic acid (ABA) accumulation and seed coat browning, ovule or seed abortion and reduced fruit growth, which subsequently resulted in fruit abscission and lower yields (Garner and Lovatt, 2016).

2.3.4 EFFECTS OF WATER STRESS ON FRUIT DEVELOPMENT

The first three to four months after fruit set is vital and water stress during this period was shown to affect many aspects of fruit physiology, which cannot be rectified by more the return to optimal conditions later during fruit development. During the first 16 weeks after fruit set most calcium is absorbed by the fruit. Calcium is important for cell membrane stability and post-harvest fruit quality. Water stress during this time negatively affected calcium uptake and distribution to the fruit and subsequently post-harvest fruit quality (Bower, 1988). Calcium translocation to fruit can further be reduced by vigorous vegetative growth during spring, which usually coincides with fruit set and early fruit growth, due to competition for water and nutrients (Witney et al., 1990). Under severe water stress, calcium and water can even be removed from the fruit for translocation to the leaves, resulting in more severe water-stressed fruit (Blanke and Whiley, 1995). Calcium accumulation in fruit is further cultivar dependent, with 'Fuerte' in general having lower fruit calcium levels than 'Hass' (Witney et al., 1990), which explains why 'Fuerte' fruit are more prone to postharvest physiological disorders than 'Hass' fruit.

Water stress may also negatively affect fruit size, although results from different studies on the effect of water stress on fruit size have been inconsistent. In research conducted in Israel, the application of deficit irrigation (70% of ET) yielded significantly smaller fruit compared to full irrigation (100% of ET) (Winer et al., 2007). Daily fruit growth was also reduced under water stress conditions (Winer, 2003). However, in three other irrigation studies no correlation between applied irrigation and fruit size was found (Faber et al., 1994, Kurtz et al., 1992, Levinson and Adato, 1991). Faber et al. (1994) concluded that fruit size was rather related to yield and not to applied water, while Kurtz et al. (1992) ascribed smaller fruit size to irrigation frequency and not to the amount of irrigation water applied per irrigation event.

Avocado is an oil-containing fruit and production of this oil requires a large quantity of energy. Energy is obtained from photosynthates and stored carbohydrates. The high amount of energy required to produce an avocado crop would also imply a relatively high amount of water required. Gerbens-Leenes and Nonhebel (2004) showed with calculations that the amount of water needed to produce oily fruit, such as an avocado is considerably more than for the production of a starchy fruit, such as an apple. It can therefore be expected that water stress during oil accumulation will negatively affect oil accumulation and therefore post-harvest fruit quality. Water stress can also result in water being withdrawn from the fruit, with fruit being water stressed, resulting in subsequent physiological disorders after harvest. The different physiological disorders and how they are related to water stress, will be discussed below.

An avocado fruit disorder, ascribed specifically to water stress, is a blemish, usually on the fruit stem, termed ring-neck (Hofman and Jobin-Décor, 1999, Schaffer and Whiley, 2002). This is characterized by irregular superficial dried tissue at the abscission site of the pedicle, which becomes separated from the pedicle, leaving a scar (Schaffer and Whiley, 2002). As it is superficial it might not affect nutrient, water and photo-assimilate transport to the fruit and it is therefore more likely that any disorders of the fruit are directly related to water stress and not due to ring-neck. In this instance, Hofman and Jobin-Decor (1999) found that fruit with ring-neck were also smaller. The smaller fruit were most likely directly caused by water stress and not by ring-neck.

2.3.5 EFFECTS OF WATER STRESS ON FRUIT QUALITY

Tree water stress will cause lower water availability to fruit and restrict translocation of minerals and carbohydrates to fruit. This will lead to various postharvest physiological disorders (Arpaia, 1994). The following postharvest physiological disorders are of economic importance and their presence usually results in rejection of consignments by various markets.

2.3.5.1 Uneven fruit ripening

Differences in fruit water content between individual fruit at harvest was shown to be the most important factor contributing towards variation in ripening (Blakey et al., 2009, Bower et al., 2007). From a marketing point of view, uneven fruit ripening is highly undesirable, especially in cases where fruit are pre-ripened before they are sent to retailers A number of factors usually contribute to differences in fruit water content, which include soil heterogeneity, faulty irrigation systems and restrictions layers in soil, which results in individual trees in the same orchard having access to different volumes of water. Water stress close to harvest is also a contributing factor to uneven ripening.

2.3.5.2 Diffuse mesocarp discoloration

Diffuse mesocarp discolouration is a grey or brown discolouration of the mesocarp, which is most intense in the distal half of the fruit and is most prominent towards the end of the season (Cutting and Wolstenholme, 1992). Long term cold storage of avocado fruit was shown to increase the severity of diffuse mesocarp discoloration, because long term cold storage increases cell damage, with a subsequent increase in electron leakage from damaged cells. Most electron leakage was found to occur where mesocarp browning occurred (Hershkovitz et al., 2005). The possibility of the involvement of ethylene during cell damage was shown by Pesis et al. (2002) who demonstrated that ethylene increased the activity of polyphenol oxidase (PPO), the enzyme causing the oxidation of phenols in the mesocarp leading to browning. The application of the ethylene inhibitor, 1-methylcyclopropene, reduced the incidence of diffuse mesocarp discoloration and other post-harvest storage disorders by inhibiting ethylene action (Hershkovitz et al., 2005, Pesis et al., 2002, Woolf et al., 2005). 1-methylcyclopropene inhibits ethylene action by binding irreversibly to ethylene receptors subsequently preventing ethylene from binding on the receptors (Blankenship and Dole, 2003). 1-methylcyclopropene also caused a delay in expression of genes related to ethylene biosynthesis and the formation of new ethylene receptors (Ma et al., 2009).

Water stress and concentrations of potassium and magnesium in fruit were identified as important pre-harvest factors contributing to diffuse mesocarp discoloration. Bower (1985) showed that low soil water content (-80 kPa at 300 mm depth in the root zone) resulted in a significant increase in PPO activity in both ripe and unripe fruit. This could possibly be mediated by higher ethylene levels caused by water stress. Potassium and magnesium have been implicated in post-harvest fruit disorders as well, primarily because of the interaction with calcium for uptake by the roots. Higher incidences of diffuse mesocarp discoloration and pulp spot was associated with a higher (Mg+K)/Ca-ratio of fruit (Hofman et al., 2013).

2.3.5.3 Vascular browning

Vascular browning is a disorder characterized by the browning and hardening of the vascular strands in the mesocarp of the fruit. This disorder usually develops during cold storage when fruit are stored at temperatures between 3 and 5°C for more than two weeks (Bill et al., 2014). It was also shown that fruit which develop vascular browning had higher levels of ethylene than fruit that did not develop vascular browning (Florissen et al., 1996). Even though this disorder generally develops during postharvest storage, pre-harvest factors contribute towards the susceptibility of fruit towards this disorder. Vascular browning was strongly correlated with the (Mg+K)/Ca-ratio of fruit. Fruit with vascular browning had a higher (Mg+K)/Mg-ratio than fruit that did not had the disorder (Thorp et al., 1997). There may therefore exist a specific threshold level for the (Mg+K)/Ca-ratio whereby the fruit become more susceptible for the disorder once the threshold level is reached. Since water stress alters the absorption and translocation of minerals, and contributes to elevated ethylene levels, vascular browning may manifest as a postharvest physiological disorder if orchards are subjected to water stress during fruit development.

2.3.5.4 Anthocyanin (pink) staining

A pink staining of the vascular tissue in the fruit is sometimes evident in ripe ‘Hass’ fruit when cutting the fruit. This was found to be more common in the newly selected ‘Hass’ type cultivar ‘Maluma’ (unpublished data). This pink staining is termed anthocyanin staining. Not much work has been carried out to determine the causes of anthocyanin staining, but no correlation was found between the disorder and fruit mineral content or fruit maturity. It is speculated that low orchard temperatures during fruit development or maturation contribute to this disorder (Thorp et al., 1997). It is unknown if water stress would cause or contribute to the development of this disorder.

2.4 MODELLING WATER USE OF SUBTROPICAL CROPS

The lack of, but high demand for, irrigation related information specific to avocado creates a need for research which can be extrapolated to a wide range of growing regions. The successful extrapolation of site-specific data can be achieved by means of crop water use modelling but requires proper parameterisation if accurate results are to be obtained (Allen et al., 2011, Allen et al., 1998, Boote et al., 1996). The most common modelling approach used, not only by researchers but also by farmers, is the relatively simple FAO-56 crop coefficient approach (K_c) (Allen et al., 1998). With this model, crop ET can be determined by calculating reference ET of an unstressed and uniform short grass reference surface (ET_o) (Allen et al., 1998), from site specific weather data, and multiplying it with a suitable K_c (Equation [1]). The K_c encompasses crop specific characteristics and relates these characteristics to that of a reference short grass surface.

$$ET = K_c \times ET_o \qquad [1]$$

One of the major limitations of this model in avocado is the lack of suitable K_c values, as there has been no systematic attempt to accurately quantify avocado water use. Reported K_c values for avocado were approximately 0.4-0.6 Carr (2013), with Kruger (2001) suggested values of between 0.36 and 1.07 for South African conditions. Values for avocado orchards are also provided in FAO-56 (Allen et al., 1998)Although crop coefficients are meant to be transferable across a range of conditions, they can be highly variable and are especially influenced by canopy cover, accompanying vegetation characteristics and varying managing practices, including irrigation and pruning (Allen et al., 1998).

The FAO-56 crop coefficient model, in its simplest form, assumes a large degree of linearity between ET_o and ET. The degree of linearity, however, becomes less significant when comparing two distinctly different cropping surfaces, i.e. uniform short and smooth reference grass surface and tall, rough orchard canopies (Annandale and Stockle, 1994). The transferability of K_c values obtained from one site to that of multiple sites is therefore limited to similar climatic zones and orchard characteristics. Possible solutions to the limitations of extrapolation of K_c values have been published (Allen and Pereira, 2009, Rosa et al., 2012), and therefore the K_c model remains a valuable model to use, especially in strategic water planning, where estimates of seasonal or long term water use are required, as opposed to a daily or hourly time step for irrigation scheduling. Given the lack of water use studies on avocadoes, the successful parameterisation of this model should be a research priority, as the relatively simplistic nature of the model and ease of use by both farmers and irrigation consultants could significantly improve current water management and also aid in better irrigation system design.

One of the technical advantages of the FAO-56 model is the fact that a dual crop coefficient approach can be used to distinguish between the two main components of ET, namely evaporation and transpiration. The dual crop coefficient approach is an extension of Equation [1], and separates K_c into the basal crop coefficient (K_{cb}) or transpiration component and the soil evaporation component (K_e) as outlined in Equation [2]. Partitioning ET between these components allows for more accurate estimations of crop ET on a daily basis and throughout the growing season, as the fraction of canopy cover, which changes over the season (Figure 2.2), and irrigation wetting patterns, which significantly influences both K_{cb} and K_e, can both be accounted for.

$$ET=(K_{cb}+K_e) \times ET_o \qquad [2]$$

Allen et al. (1998) also proposed crop coefficient curves, which divides crop coefficients into the initial-stage, mid-stage and end-stage of crop development and therefore accounts for canopy development over a season (Figure 2.2).

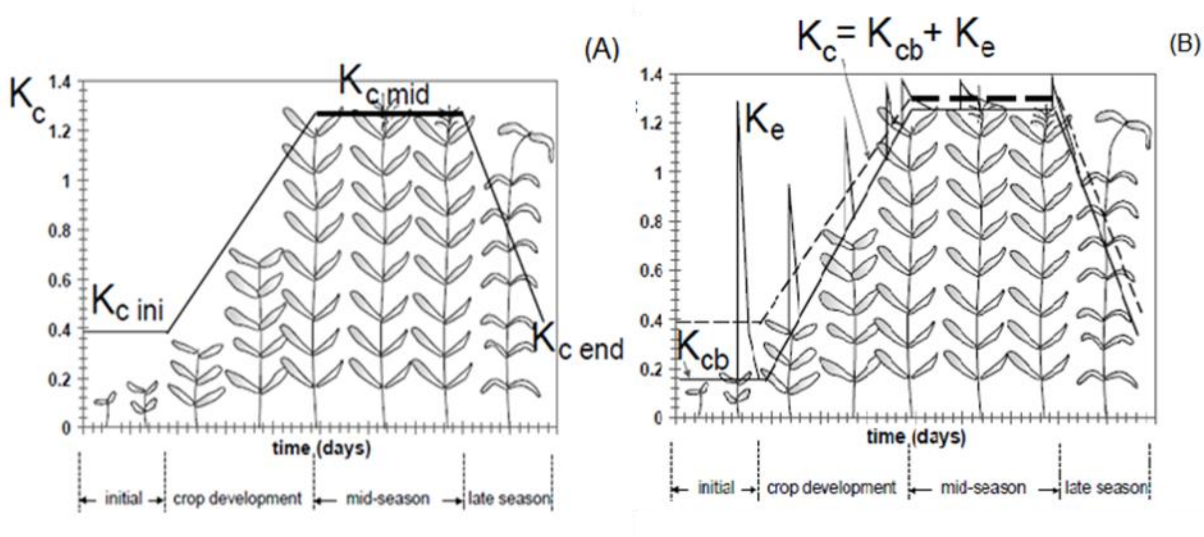


Figure 2.2: (A) General single crop coefficient (K_c) curve and (B) variation in dual crop coefficients including basal crop coefficient (K_{cb}) and soil evaporation coefficient (K_e) throughout the various crop stages as adapted from Allen et al. (1998)

In mature evergreen crops, such as macadamia, avocado and citrus, the canopy size changes significantly less over a season compared to both deciduous annual crops, and therefore the difference in crop coefficients between the crop developmental stages is rather small (Allen et al., 1998). In citrus for example, both K_c and K_{cb} changed by 0.05 between the initial-stage, mid-stage and end-stage of crop development for the same percentage of canopy cover (Allen et al., 1998). A range of other citrus studies have shown that K_c changes on average by 0.07 between autumn, summer, winter and spring (Castel, 1997, Castel et al., 1987, García Petillo and Castel, 2007, Snyder and O'Connell, 2007, Taylor et al., 2015).

Allen and Pereira (2009) suggested that for a mature avocado orchard (Canopy cover of 70%) the $K_{c\ ini}$ is 0.5, the $K_{c\ mid}$ is 1.0 and the $K_{c\ end}$ is 0.9. Similarly, for an orchard of the same size a $K_{cb\ ini}$ of 0.35, a $K_{cb\ mid}$ of 0.95 and a $K_{cb\ end}$ of 0.85 should be used. Due to the large differences in values between the different stages, these values proposed by Allen and Pereira (2009) need to be evaluated against measured data. These changes in the crop coefficient can largely be attributed to environmental conditions, as well as the changes in canopy size and the accompanying aerodynamic changes. However, changes in the crop coefficients can also be driven by physiological factors such as stomatal regulation of water use. Allen and Pereira (2009) included a term (F_r) in the estimation of K_{cb} or K_t, to account for the degree of stomatal control over transpiration, but due to the lack of water use data for avocadoes, this approach has yet to be tested in this crop.

Determining the contribution of physiological factors to the K_t is rather difficult when considering the timeframe of physiological changes (days to weeks) relative to that of reported K_t values (months). In crops that exert significant stomatal control over transpiration, as found in crops following a predominantly isohydric strategy, which may include avocadoes, the K_t model might provide reasonable estimates of seasonal E_c, given the reduction in variation of model input parameters brought about by averaging, but may fail to give reasonable and reliable estimates of daily or weekly E_c. The FAO-56 model is therefore sometimes replaced by models which incorporate crop physiological parameters, such as the Penman-Monteith model (Monteith and Unsworth, 1990) often referred to as “big leaf” models. These models have one major assumption being that entire crop fields or orchards are treated as a single surface with uniform characteristics.

The Penman-Monteith equation (Monteith and Unsworth, 1990) is given in Equation [3], where λ is the latent heat of vaporization of water (J kg^{-1}), E_c is canopy transpiration (kg m^{-2} s^{-1}), Δ is slope of the vapour pressure curve (kPa K^{-1}), R_n is net radiation at the crop surface (W m^{-2}),

G is soil heat flux (W m^{-2}) taken as 10% of R_n, ρ_a is the density of dry air (kg m^{-3}), C_p is the specific heat capacity of the air (J kg^{-1} K^{-1}), VPD is saturation vapour pressure deficit (kPa), γ is the psychrometric constant (kPa K^{-1}), g_a is the aerodynamic conductance (m s^{-1}) and g_c is the canopy conductance (m s^{-1}).

$$\lambda E_c = \frac{\Delta(R_n - G) + \rho_a C_p g_a VPD}{\Delta + \gamma\left(1 + \frac{g_a}{g_c}\right)} \quad [3]$$

Even though a large portion of the parameters required to solve Equation [3] can be obtained from an automated weather station, g_a, g_c and R_n are often estimated or modelled. The most widely used models for g_c is that proposed by Jarvis (1976). This model, and various extensions of the model, are often used in conjunction with the Penman-Monteith equation to generate reasonable values of E_c. It should also be noted that E_c is often measured by means of sap flow or eddy covariance techniques and g_c is then calculated by means of the inversion of Equation [3] (Granier and Breda, 1996, Lu et al., 2003, Oguntunde et al., 2007). In most applications of Equation [3], the Jarvis (1976) type model (Equation [4]) and variations of this model also require a set of seasonal response terms describing the functional relationships among g_c, R_s, VPD, air temperature (T_{air}) and soil water potential (θ), to give modelled predictions of g_c, which are needed in Equation [3]. The functional relationships describing the response of g_c to R_s, VPD, T_{air} and θ can be assessed mathematically as has been described by Whitley et al. (2009), Stewart (1988), Wright et al. (1995) and Harris et al. (2004). In most studies of irrigated tree water use, θ is often ignored from the Jarvis (1976) type models (Equation [4]), as it is assumed that θ would have a limited impact on g_c. The functional terms of the Jarvis type model can be described as outlined in Equations [5]-[8]. These mathematical relationship of g_c as encapsulated by Equation [4], weights maximum g_c ($g_{c\,max}$) with each response function (Equations [5]-[8]), which have values between 0 and 1, and the maximum value of 1.0 is attained only at certain optimum conditions, which rarely occur (e.g. Jarvis (1976); Wright et al. (1995)) and as a result $g_{c\,max}$ is rarely achieved.

$$g_{c,j} = g_{c\,max} f(R_S) f(VPD_{air}) f(T_{air}) \quad [4]$$

$$f(R_s) = \frac{R_s}{R_m}\left(\frac{R_m + k_R}{R_s + k_R}\right) \quad [5]$$

$$f(T_{air}) = \frac{(T_{air}-T_L)(T_H-T_{air})^t}{(k_T-T_L)(T_H-k_T)} \quad [6]$$

$$t = \frac{T_H-k_T}{k_T-T_L} \quad [7]$$

$$f(VPD) = k_{e1} VPD_{air} \exp(-k_{e2} VPD_{air}) \quad [8]$$

Equation [5] describes the radiation response, showing an asymptotic saturating function that plateaus at R_m, which is approximately 1000 W m^{-2}, with k_R (W m^{-2}) describing the curvature of the relationship. Hyperbolic saturating functions describing R_s have been applied extensively at leaf, tree and canopy scales for conductance (Granier et al., 2000, Kelliher et al., 1993) and for tree water use (Komatsu et al., 2006). The temperature response function in Equation [6] typically describes the physiological response of g_c to temperature with parameters T_L and T_H in Equations [6] and [7] being the lower and upper temperature limit to g_c, and is often fixed at 0°C and 45°C, respectively, as this is the physiological temperature limits for most crops. The modelling parameters k_{e1} and k_{e2} of Equation [8], describe the rate of change in g_c at low and high atmospheric demand and has been used successfully in native Australian forests by Whitley et al. (2009). There are, however, multiple variations to Equations [5]-[8] and assessing the response of g_c to each of the environmental variables is critical to ensure optimal model performance.

In crops exhibiting strict stomatal control over transpiration, including citrus (Kriedemann and Barrs, 1981, Sinclair and Allen Jr, 1982) and olive (Fernández et al., 1997, Giorio et al., 1999), a Jarvis-type model has provided accurate estimates of g_c (Cohen et al., 1983, Oguntunde et al., 2007, Villalobos et al., 2000). It would, therefore, be logical to test such models on avocadoes, as reasonable estimates of g_c could then be utilized in solving E_c using Equation [3].

One of the major limitations to using g_c to obtain reliable estimates of E_c, especially in so-called "big leaf" models, is that most g_c estimates scale leaf level g_s to an entire canopy by using average measurements of leaf area index (LAI). This poses an array of problems, considering that unequal distribution of solar radiation within the canopy and variations in leaf age and angle, in combination with microclimatic variations within the canopy, could lead to some erroneous estimates of g_c when simply scaled by means of LAI. In an attempt to overcome these limitations, Leuning et al. (1995) developed a multilayer approach in which the canopy is divided into various layers, g_s is estimated for each layer, and weighted with the LAI for the layer. This approach still uses averages of LAI in scaling g_s from a leaf level to a canopy level, which would subsequently lead to erroneous estimates of g_c.

Acknowledging the limitations linked to the scaling of g_s to g_c through the use of LAI, another approach for modelling g_c has been developed by Villalobos et al. (2013). In this approach, g_c is modelled directly using measurements of E_c, and is based on the concept that E_c is directly proportional to radiation interception. In well coupled sclerophyllous tree crops such as olive (Orgaz et al., 2007, Villalobos et al., 2000), this modelling approach has been shown to be rather effective and could prove to be equally effective for avocado, although no such studies have been published to date. Nevertheless, this direct approach for estimating g_c is used to determine crop specific modelling parameters *a* and *b* (Equation [9]) by means of linear regression of $(f_{IPAR}*R_s)/g_c$ against VPD_{air}. After mathematical determination of parameters, *a* and *b*, direct estimates of daily E_c (mm day^{-1}) can be obtained using Equation [9]:

$$E_c=0.3708\frac{f_{IPAR}R_s}{a+b\ VPD_{air}}\frac{VPD_{air}}{P_a} \qquad [9]$$

where f_{IPAR} is the fraction of photosynthetically active radiation intercepted by the canopy (dimensionless), R_s is the total daily solar radiation (J m^{-2} d^{-1}), P_a is the atmospheric pressure (kPa), and the coefficient 37.08 × 10^{-3} incorporates the conversion of units for Joules of R_s to mol quanta and from mol to kg of H_2O.

To date, there have been no attempts to model avocado water use based on measured water use. However, from an assessment of available literature on water use of subtropical crops, it is proposed that models incorporating g_c should be investigated if reasonable estimates of avocado ET are to be achieved. Although g_c is rather difficult to measure, models using derivatives of Jarvis-type models (Cohen et al., 1983, Oguntunde et al., 2007, Testi et al., 2006, Villalobos et al., 2000) or the model by Villalobos et al. (2013) could potentially be used to obtain reliable measures of g_c.

3. MATERIALS AND METHODS

3.1 WATER USE OF AVOCADO ORCHARDS

3.1.1 ORCHARD DESCRIPTIONS

Avocado orchards for water use measurements were selected according to tree age in order to quantify water use in mature, intermediate and non-bearing orchards which differed in canopy size. These orchards were situated on Everdon Estate, which forms part of Westfalia Fruit Estates near the town of Howick (29° 26’37’’S, 30°16’22’’E, 1080 m altitude) (Figure 3.1) and Westfalia Estate close to Tzaneen (23°43'49.51"S, 30° 8'12.35"E) (Figure 3.3).

A mature, full-bearing, 11 year-old ‘Hass’ on ‘Dusa’ avocado orchard (at the start of measurements in 2017, planted in 2006) was selected, with a full-bearing orchard defined as orchards in which a hedgerow has fully formed and canopy cover exceeds 60% (Table 3.1 and Figure 3.2 A & B). Four-year-old ‘Hass’ on ‘Dusa’ trees (at the start of measurements in 2017, planted in 2013) were selected to represent an intermediate bearing orchard (Table 3.1 and Figure 3.2 C &D). Intermediate-sized avocado orchards were defined as bearing orchards, which have not formed a hedgerow and where separate trees were distinguishable, with a canopy cover of between 40 and 50%. In 2019, a nearby, 2-year-old, non-bearing ‘Harvest’ on ‘Dusa’ avocado orchard was identified for measurement (Table 3.1 and Figure 3.2 E & F). Non-bearing trees were defined as trees that have yet to produce a commercial crop and have a canopy cover lower than 15%. All these orchards were planted with a 7 x 4 m spacing (29 m^{-2} and 357 trees ha^{-1}) and were irrigated with 50 L h^{-1} microsprinklers. Due to the undulating topography row orientation varied for the three orchards, with the mature orchards orientated in an east-west direction, the intermediate orchard in a north west-south east direction and the non-bearing orchard in a north east-south west direction (Figure 3.1).

Figure 3.1: The Everdon Estate orchards located 5 km north-west of Howick in the KwaZulu-Natal Midlands.

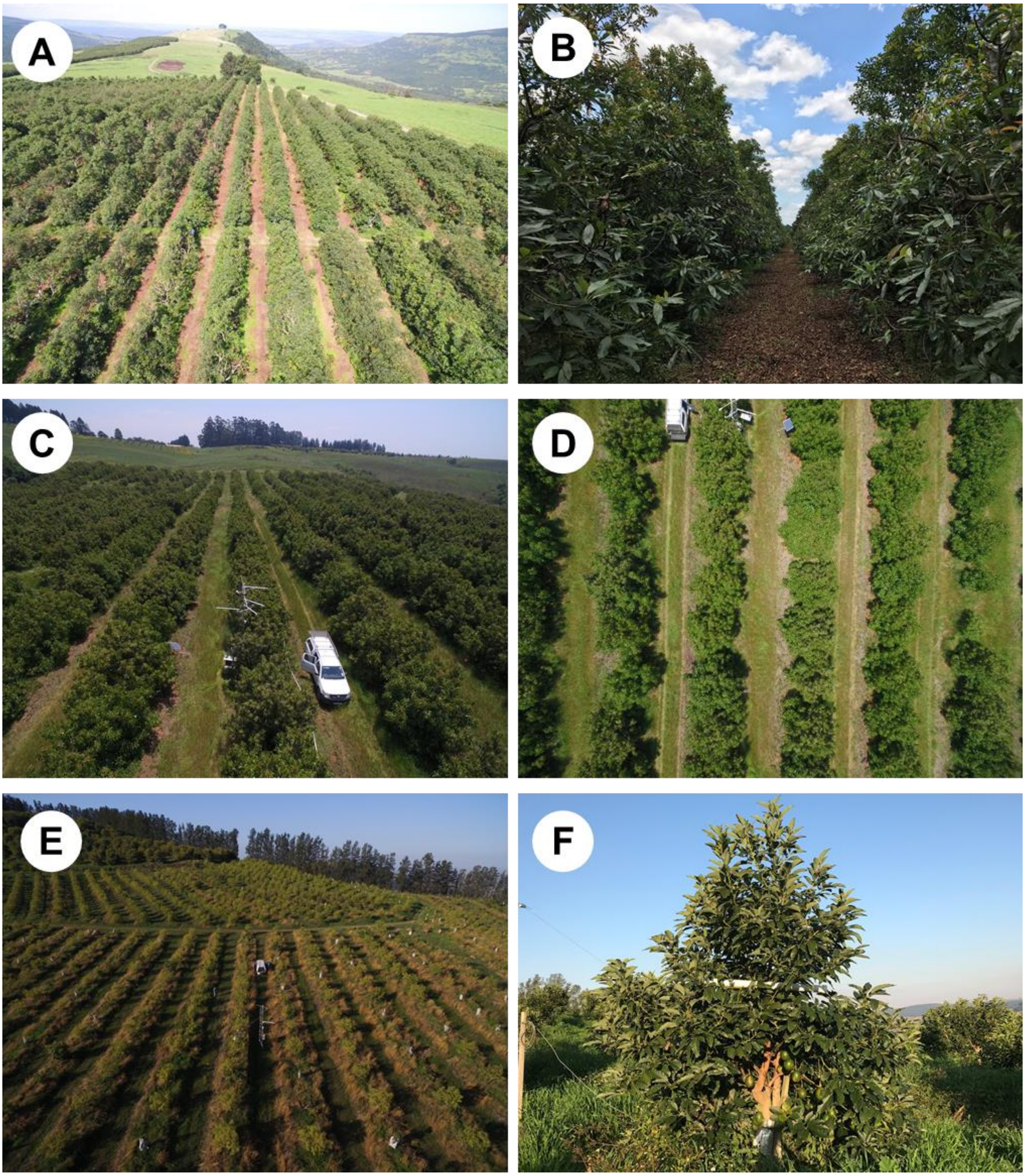


Figure 3.2: Avocado orchards where water use measurements were conducted on Everdon Estate outside of Howick, KZN. A) and B) The mature 'Hass' avocado orchard (MO). C) and D) the intermediate 'Hass' avocado orchard (IO). E) and F) the non-bearing 'Harvest' avocado orchard (NB).

An additional mature ‘Hass’ avocado orchard was instrumented in Tzaneen on McNoon farm (23°43'49.51"S, 30° 8'12.35"E), which forms part of Westfalia Estate. Four trees were instrumented with sap flow equipment, with two trees on the ‘Dusa’ rootstock and two on the newer ‘Leola’ (Merensky 6) rootstock (Figure 3.3). The trees were planted in November 2012 and were 6 years old at the start of the measurements. This is an experimental block for rootstock evaluation and is approximately 1 ha in size, with the whole irrigation block being approximately 7 ha in size. The trees were planted at a spacing of 4 m x 8 m (32 m^2 per tree and 312 trees ha^{-1}) on small ridges in an east-west direction. The equipment was installed from 3-4 December 2018. The four trees had an average height of 5.2 m and an average width of 4.8 m, giving a canopy cover of approximately 0.6. The trees have formed a complete hedgerow. The trees were irrigated with one 30 L h^{-1} microsprinkler per tree.

Figure 3.3: Mature 'Hass' avocado trees on McNoon farm 20 km north of Tzaneen. The red block indicates the experimental trees instrumented with sap flow equipment

Table 3.1 Details of the 'Hass' avocado orchards where water use measurements were conducted

Cultivar	'Hass' (Howick)	'Hass' (Howick)	'Harvest' (Howick)	'Hass' (Tzaneen)
Rootstock	'Dusa'	'Dusa'	'Dusa'	'Dusa' and 'R0.06'
Age	5 years old (planted in 2013)	12 years old (planted in 2006)	2 years old (planted in 2017)	6 years old (planted in 2012)
Orchard block area	2.91 ha	6.94 ha	2.33 ha	7 ha
GPS coordinates	26°26'25" S 30°15'55''E	29° 27'3'' S 30° 16' 46''	29°27'35.42"S 30°16'41.73''E	23°43'49.51"S, 30° 8'12.35"E
Tree spacing	7 m × 4 m (28 m^2)			8 m x 4 m (32 m^2)
Row orientation	NE-SW	E-W	NE-SW	E-W
Irrigation	Microsprinkler irrigation Delivery rate of 50 L h^{-1} Wetted diameter 1.7 m			Microsprinkler irrigation Delivery rate 30 L h^{-1} Wetted diameter 1.7 m
Canopy dimensions	Height – 4.2 m Width – 3.8 m Breadth – 3.6 m	Height – 7.3 m Width – 6.8 m Breadth – 4 m	Height – 1.7 m Width – 1.2 m Breadth – 1.2 m	Height – 5.2 m Width – 4.8 m Breadth – 4 m
Canopy cover (fraction)	0.48	0.97	0.20	0.60
Leaf Area index	3.15 m^{-2}	4.75 m^{-2}	1.9 m^2 m^{-2}	ND
No. of experimental trees	4			
Tree circumference	1 – 43.5 cm 2 – 63 cm 3 – 39 cm 4 – 53.5 cm	1 – 95.6 cm 2 – 75.4 cm 3 – 98.7 cm 4 – 101.2 cm	1 – 11.9 cm 2 – 15.7 cm 3 – 14.5 cm 4 – 19.5 cm	1 – 63.5 cm 2 – 60 cm 3 – 65.2 cm 4 – 62.5 cm

3.1.2 WATER USE MEASUREMENTS

3.1.2.1 Transpiration

Sap flow measurements were performed using the heat ratio method of the heat pulse velocity sap flux density technique as developed by Burgess et al. (2001) and described in citrus by Taylor et al. (2015) using locally manufactured equipment (Figure 3.4). This technique was used on four sample trees in each orchard based on a stem circumference survey conducted at each of the respective orchards. Four custom made heat pulse probe sets were inserted at four different depths below the cambium in the three orchards (MO and IO in Howick and the orchard in Tzaneen). Depths selected in each tree trunk were used to account for the radial variation in sap flux within the conducting sapwood. Each probe set consisted of two Type T (copper/constantan) thermocouples (embedded in 2.0 mm outside diameter polytetrafluoroethylene (PFTE) tubing) placed equidistantly (0.465 cm) upstream and downstream of the heater probe inserted into a brass collar (0.25 cm). These probe sets were inserted above the rootstock in the scion and below the lowest branch, with probes being equally spaced around the trunk, taking care to avoid any abnormalities in the trunk. The heat pulse velocity (V_h) in cm h^{-1} for each probe set was calculated following Marshall (1958) as:

$$V_h = \frac{k_w}{x} \ln\left(\frac{v_1}{v_2}\right) * 3600 \qquad [10]$$

where k_w is the thermal diffusivity of green (fresh) wood (assigned a value of 2.5 x 10^{-3} cm^2 s^{-1} (Marshall, 1958)), x is distance in cm between the heater and either the upper or lower thermocouple, v_1 and v_2 are the maximum increases in temperature after the heat pulse is released (from initial temperatures) as measured by the upstream and downstream thermocouples and 3600 converts seconds to hours. Heat pulse velocities were measured and logged on an hourly basis using a CR1000 data logger and an AM16/32B multiplexer (Campbell Scientific Ltd, Logan, Utah, USA). Wounding corrections were performed by using wounding coefficients *b, c*, and *d* obtained from a numerical model developed by Burgess et al. (2001) using the following equation:

$$V_c = bV_h + cV_h^2 + dV_h^3 \qquad [11]$$

where V_c is the corrected heat pulse velocity. The functions describing the correction coefficients in relation to wound width (w) were as follows:

$$b = 6.6155w^2+3.332w+0.9236 \quad [12]$$

$$c = -0.149w^2+0.0381w-0.0036 \quad [13]$$

$$d = 0.0335w^2-0.0095w+0.0008 \quad [14]$$

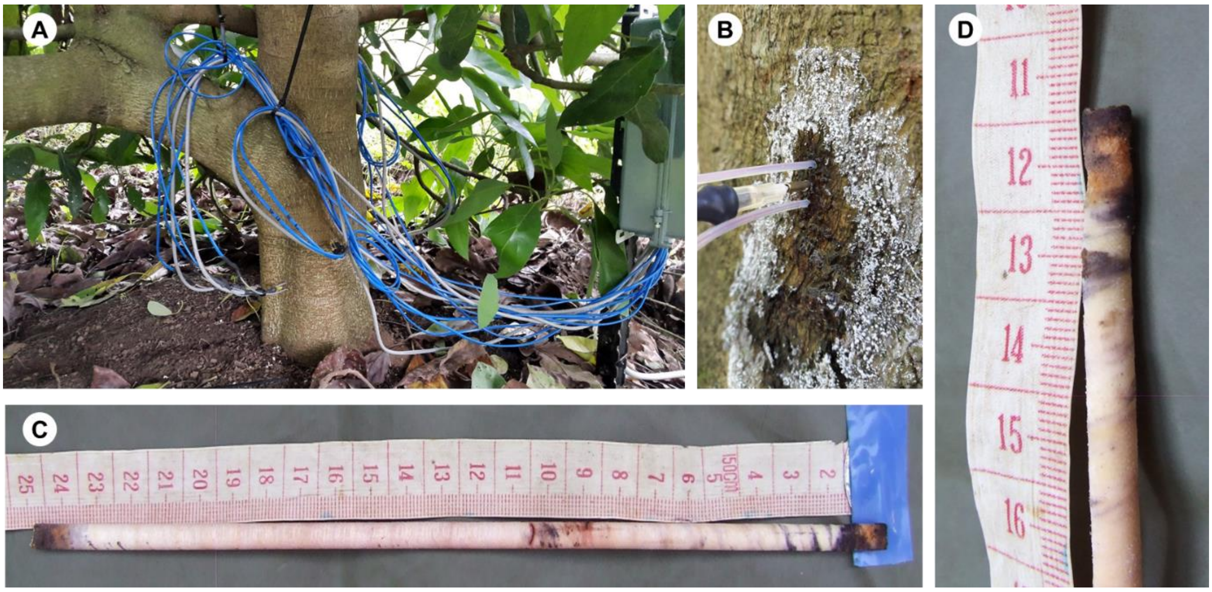


Figure 3.4: A) A stem at the intermediate orchard instrumented with four sets of heat ratio measurement thermocouples and heaters. Junction box located on the right-hand side. B) A pair of thermocouples with a heater between them. C) Cores taken from the mature orchard, D) clearly showing the bark to be 10 mm thick.

The wound width was assessed through visual inspection and subsequent measurement of the outer diameter of the wound. The presence of heartwood was determined by taking wood cores with an incremental borer. These core samples were stained using safranin, with unstained areas being marked as non-conducting wood (Figure 3.5). From numerous cores, a ratio between sapwood and heartwood was developed from which the sapwood area for the different trees was determined. Other wood characteristics, including sapwood moisture content (m_c) and density (ρ_b) were determined from additional core samples taken during the measurement period.

Following the determination of m_c and ρ_b, sap velocity (V_s) was calculated from the corrected heat pulse velocity using the equation proposed by Marshall (1958) that was later modified by Barrett et al. (1995):

$$V_s=\frac{V_c\rho_b(c_w+m_c c_s)}{\rho_s c_s} \qquad [15]$$

where c_w and c_s are specific heat capacity of the wood matrix (1200 J kg^{-1}°C^{-1} at 20°C (Becker and Edwards, 1999) and sap (water, 4182 J kg^{-1}°C^{-1}) at 20°C (Lide, 1992), respectively, and ρ_s is the density of water (1000 kg m^{-3}). Volumetric flow for individual probes was calculated as the product of V_s and its cross-sectional area of conducting sapwood. Whole stem flux (Q) was calculated, by means of a weighted average of heat pulse velocity with depth (Equation [16]), as applied by Hatton et al. (1990).

$$Q=\pi\left[r_1^2*v_1+\left(r_2^2-r_1^2\right)*v_2+\left(r_3^2-r_2^2\right)*v_3+\left(r_4^2-r_3^2\right)*v_4\right] \qquad [16]$$

where v_x is the heat pulse velocity measured by sensor x, placed between radii r_{x-1} and r_x. Integrated volumetric sap flow of the individual trees (L day^{-1}) was converted to transpiration (mm day^{-1}) using the ground area allocated to each tree in the orchard, i.e. 32 m^2. Orchard transpiration was calculated as a weighted average of sampled trees as suggested by Hultine et al. (2010), based on a stem circumference survey at the start of the study.

Figure 3.5 Avocado core sample stained with safranin to determine sapwood area

During September 2019 the non-bearing orchard was instrumented with a thermal dissipation probe (TDP) sap flow system, also known as the Granier method. It is a continuous heat sap flow technique and has been used widely due to its simplicity, high degree of reliability and low cost (Lu et al., 2004). The TDP method relates sap flux density, (SFD, m^3 m^{-2} s^{-1}), to a temperature difference, ΔT, measured between a constant heater needle and unheated needle located approximately 4 cm lower in the xylem, which are both inserted radially into the sapwood (Figure 3.6). Due to the variability in the size of the stems in the non-bearing orchard, two smaller trees were instrumented with TDP10 (10 mm long) probes and two were instrumented with TDP30 (30 mm long) probes. The stainless steel needles were inserted into the sapwood, one 40 mm above the other (Steppe et al., 2010). The empirical relationship is based on experimental regressions in three species and artificial columns filled with synthetic fiber and sawdust (Granier, 1985) and is expressed as:

$$\boldsymbol{SFD = 0.000119\left(\frac{\Delta T_o - \Delta T}{\Delta T}\right)^{1.231}} \qquad [17]$$

where ΔT_o is the temperature difference ΔT assessed during a period of zero flow (i.e. the maximum temperature difference between the two needles) (Vandegehuchte and Steppe, 2013). The empirically determined coefficients (0.000119 and 1.231) do not apply under all conditions and in all species, which is one of the reasons why calibration is required. The temperature difference, ΔT, in the TDP method was measured between a heater probe that emitted heat constantly and an unheated reference probe located approximately 40 mm from each other. According to Vandegehuchte and Steppe (2013) exact spacing is less important in this method, as long as the reference probe is not influenced by the heated probe. The TDP set (model 2 x TDP10 and 2 x TDP30, Dynamax Inc., Houston, TX, USA) consisted of two 10/30 mm long stainless steel needles with an outside diameter of 1.2 mm. Holes were drilled into the branch using a drill guide supplied by the manufacturer. The probes were attached to a Dynamax FLGS-TDP XM1000 sap velocity system (Dynamax Inc., Houston, TX, USA), which consisted of a CR1000 logger, a AM16/32B multiplexer (Campbell Scientific, Logan, Utah) and an adjustable voltage regulator that was set at 2 V for the TDP10 probes and 3 V for the two TDP30 probes. Data were logged every 15 min. In July 2020 all probes were changed to TDP30 sensors as these were providing the best data from the trees.

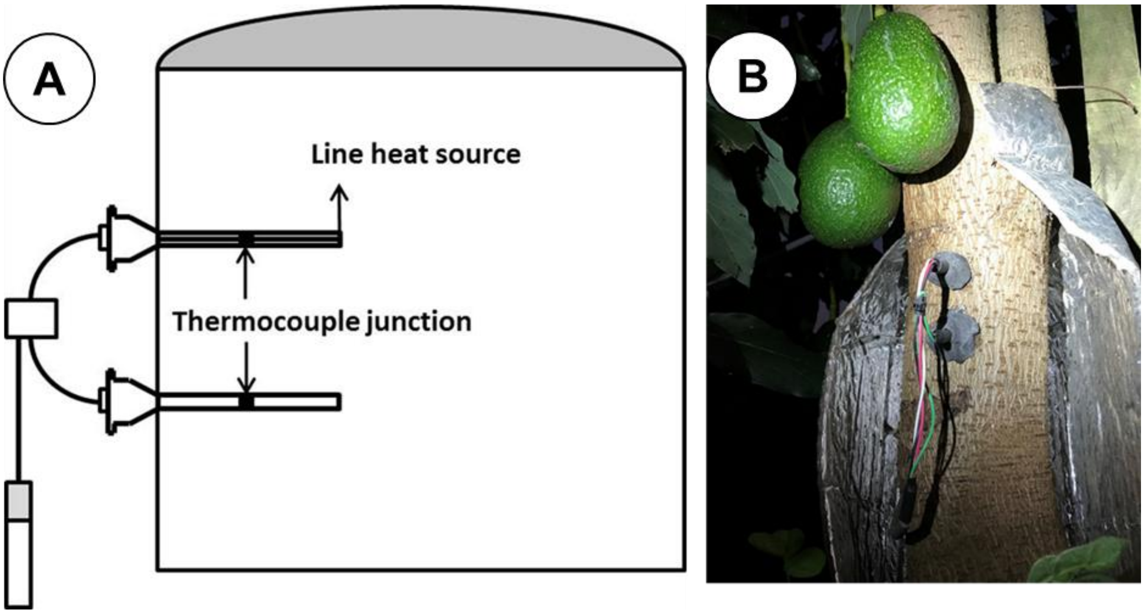


Figure 3.6: A) Schematic representation of the thermal dissipation technique and B) the insertion of the probe into an avocado tree in the non-bearing orchard

3.1.2.2 Evapotranspiration

Total evaporation or ET from all three orchards was measured using eddy covariance systems at each site above the tree canopies. Lattice masts were erected at the intermediate (Figure 3.7) and mature orchards (Figure 3.8) in April and September 2017 respectively. A similar micrometeorological measurement system was installed at the mature, full-bearing orchard, except that an EC150 infrared gas analyser (IRGA) was used instead of a LiCor 7500A gas analyser. In addition to the full eddy covariance systems, which included the measurement of net radiation, sensible heat flux, latent heat flux and soil heat flux, the radiation balance was also monitored (CNR4, Campbell Scientific Inc., Logan, Utah, USA). Soil heat flux was measured following Tanner (1960) at inter-row and in-row positions to accommodate for the spatial variation in soil heat flux across the orchard. Two infra-red (SI-111, Apogee, UT, USA) thermometers were installed at each site to monitor canopy temperatures on either side of a row. Variables were measured at 5.5 m above the ground in the intermediate orchard and 9.2 m from the ground in the mature orchard. In September 2019 the equipment at the intermediate orchard was dismantled and re-installed at the non-bearing orchard in October and November 2019 (Figure 3.9). The eddy covariance system was configured similarly to when used over the intermediate orchard, but was run without the infrared gas analyser to minimise current drain.

Half-hourly eddy covariance data were subjected to a quality control process to avoid under- or overestimation of fluxes. Erroneous data can result from dew or harsh weather conditions, especially rainfall. EddyPro® software was used to apply corrections to the high frequency data and calculate the 30-minute fluxes with corrections for density fluctuations, tilt correction, time lag compensation according to Foken et al. (2004). Sensible (H) and latent (LE) heat fluxes were corrected using the Webb-Pearman-Leuning correction procedure. Thereafter, the 30-minute data was gap-filled using REddyProc software developed by Max Planck Institute of Biogeochemistry. Finally, total evaporation was calculated from corrected and gap filled latent flux (LE). Negative LE flux data frequently noted at night, were discarded and not included in daily accumulated totals of evapotranspiration.

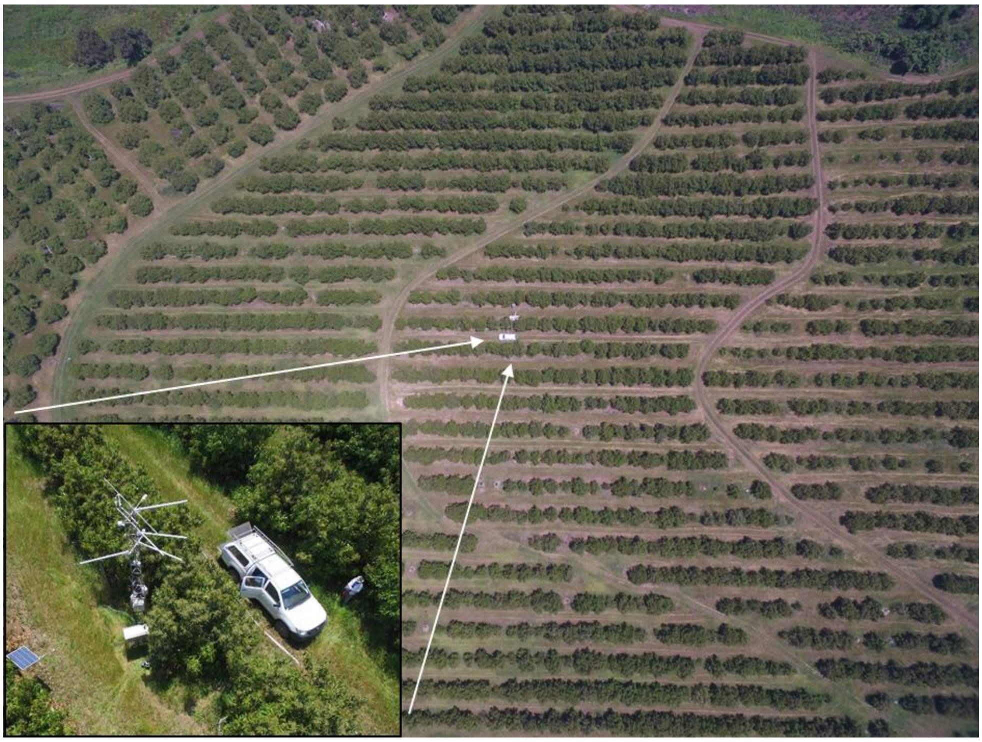


Figure 3.7: Location of the intermediate orchard (IO) eddy covariance system on a 6 m lattice mast

Figure 3.8: Location of the mature orchard (MO) eddy covariance system on a 12 m lattice mast (Albert Fall Dam visible in the distance)

Figure 3.9: Location of the non-bearing orchard (NB) eddy covariance system on a 6 m lattice mast

Energy balance closure was very good for the intermediate orchard (Figure 3.10 A) and was reasonable for the mature orchard (Figure 3.10 B), which gave confidence in the measurements in these orchards.

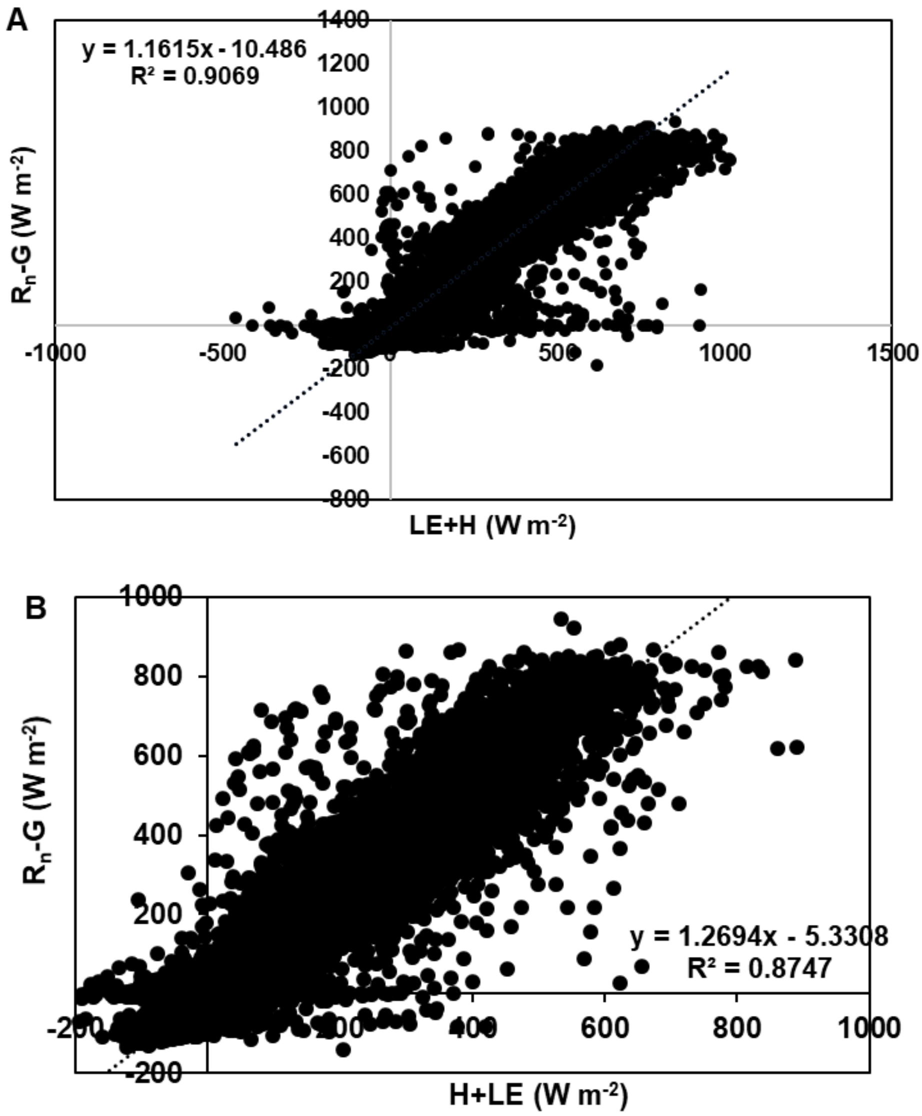


Figure 3.10: Energy balance closure for the evapotranspiration measurements in the A) intermediate and B) mature orchards in Howick

3.1.2.3 Irrigation volumes

A water meter was installed within an irrigation line at the beginning of a tree row to measure the volume of irrigation water applied (Figure 3.11). A PS-1 Irrigation Pressure switch attached to an EM50 logger (Decagon Devices Inc, Pullman, WA, USA) was used to monitor irrigation timing and duration.

Figure 3.11 Layout of irrigation monitoring and soil water sensors in the intermediate and mature orchards. A) water meter, B) pressure switch

3.1.3 WEATHER DATA

An automatic weather station (AWS) owned and maintained by the Agricultural Research Council (ARC) provided supporting weather data. It is located at the Everdon Estate offices in a kikuyu pasture (Figure 3.12) and provided rainfall (TE525, Texas Electronics Inc., Dallas, Texas, USA), air temperature and relative humidity (CS215, Campbell Scientific Inc., Logan, Utah, USA), solar irradiance (LI-COR, Lincoln, Nebraska, USA), wind speed and direction (Model 03002, R. M. Young, Traverse city, Michigan, USA). The rain gauge rim was at 1.2 m above the ground surface and the remaining sensors, 2 m above the ground. Vapour pressure deficit (VPD) was calculated from the air temperature and relative humidity sensor at the 10s scan interval of the datalogger (CR1000, Campbell Scientific Inc.). Daily summaries were downloaded by the ARC and provided for the site. The station is within 1.5 km of the measurement sites in the orchards. Hourly weather data to assess the response of transpiration to weather variables was obtained from the Eddy Covariance tower at each site.

Figure 3.12: Location of the automatic weather station (AWS) operated by the Agricultural Research Council (ARC) at Everdon Estate in Howick

In Tzaneen, weather variables were captured using a ClimaVue 50 (METER, Pullman WA, USA) attached to a CR300 datalogger (Campbell Inc, Logan, Utah, USA) from 14 February 2019 (Figure 3.13). Weather variables were collected on both an hourly and daily basis and consisted of solar radiation, temperature, humidity, windspeed and rainfall.

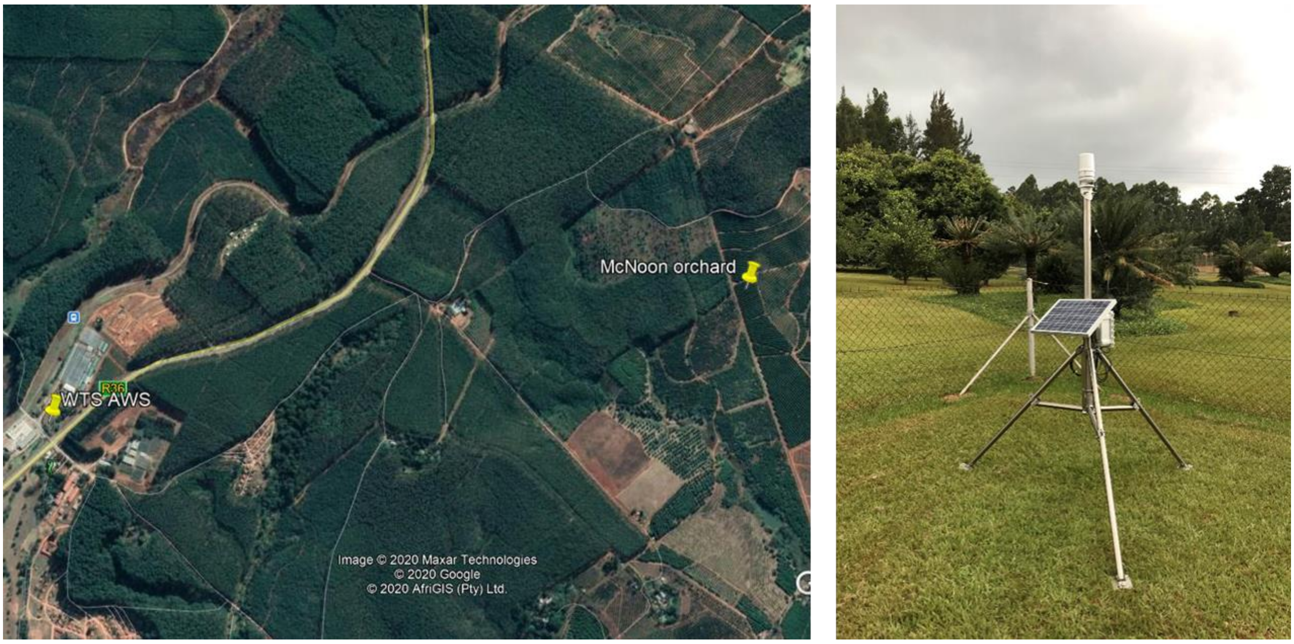


Figure 3.13: Location of automatic weather station located close to the Westfalia offices in Tzaneen relative to the measurement orchard and the automatic weather station consisting of a ClimaVue 50 system.

3.1.4 TREE CHARACTERISTICS

Canopy dimensions (height, width, and breadth) were measured throughout the trial in both orchards. Measurements of leaf area index (LAI) were performed using a Li Cor LAI-2200C plant canopy analyser under diffuse light conditions, in the early morning or late afternoon. Sampling was performed by measuring at four points under each measurement tree and in the open for a clear sky reading. Canopy cover was determined by taking images above the canopy with a RGB camera using a Phantom 3 drone, following which the images were processed using the Canopeo image analysis tool developed in the Matlab programming language (Patrignani and Ochsner, 2015).

3.1.5 ECOPHYSIOLOGY MEASUREMENTS

Leaf water potential gives an indication of water stress and was monitored on randomly selected days. Measurements were taken before sunrise on four trees. The leaf water potential on the third leaf on three shoots of each tree was measured using a pump-up pressure chamber (PMS Instruments, OR, USA). All measurements were averaged to obtain a single result for leaf water potential for a morning.

3.1.6 DETERMINATION OF YIELD AND QUALITY

The intermediate orchard was harvested in July 2018 and August 2019. Avocado fruit were hung late for the mature orchard and were only harvested in August 2018 and 2019. A minimum dry matter requirement of 21% or moisture content of 80% was reached before commencing with the harvest. At harvest, avocado fruit were packed into lug boxes, labelled and transported to the packhouse for weighing, sorting, grading and packing. The yield per hectare was determined from the total yield for the block divided by the number of hectares. The grading was done based on defects ranging from minor to major and resulted in the classification of fruit into class one, two and three depending on fruit quality. Damage included hail, sunburn, insect and picking damage, as well as toned pedicel and small fruit. The rejected fruits were used for oil processing. Fruit size distribution was determined using the international fruit count system as indicated in Table 3.2, with the count number being equal to the amount of fruit of a given size that fit into a 4 kg carton.

Table 3.2: Fruit size distribution of avocado

Number of fruit per 4 kg carton	Weight(g)
Count 10	366-450
Count 12	306-365
Count 14	266-305
Count 16	236-265
Count 18	211-235
Count 20	191-210
Count 22	171-190
Count 24	156-170
Count 26	146-155
Factory grade	<146

3.1.7 WATER USE EFFICIENCY AND WATER PRODUCTIVITY

It was agreed that in this project the terms water use efficiency and water use productivity cannot be used interchangeably and the determination for each will be as follows:

Water use efficiency

$$WUE = \frac{yield}{ET} \qquad [18]$$

Where yield is defined as the t or kg per ha and ET is defined as the measured total evaporation (ET) of the orchard in m^3. The units for WUE were therefore kg m^{-3}.

Water use productivity

$$WUP = \frac{Output}{ET} \qquad [19]$$

Where Output is defined as the value of the produce and will consider the quality of the avocado fruit and the fact that quality influences the price of the product. As a result, the different grades of fruit harvested from the study orchard were determined together with the mass of product for each grade and the associated price that that grade would receive on the market. The units for WUP were therefore R m^{-3}. Seasonal evapotranspiration and transpiration were calculated on an annual basis from September in one year to September in the next year. This was done to avoid including the same ET in two seasons, considering that in this avocado production region fruit can remain on the tree for more than a year. This is done to secure high prices at the end of the season.

3.2 THE IMPACT OF WATER STRESS ON YIELD AND QUALITY OF AVOCADO ORCHARDS

3.2.1 ORCHARD DESCRIPTION

Initial attempts to quantify the response of avocado to water stress at different phenological stages on yield and quality were carried out on a commercial farm in the Brondal region. Unfortunately, due to the high clay content of the soils and high rainfall, it was impossible to induce any water stress in this orchard over two seasons. As a result, the study was moved to the experimental farm of the Agricultural Research Council: Tropical and Subtropical Crops (ARC TSC; 25°27'23.32''S; 30°58'09.45''E) (Figure 3.14 and Table 3.3). The orchard consisted of bearing 'Hass' avocado trees grafted on 'Duke 7' rootstocks (Figure 3.15). Trees were 23 years of age at the commencement of the study in 2018. Rows of trees were planted in a north-south orientation at a spacing of 5 m x 3 m (15 m^2), giving a density of 667 trees ha^{-1}. The soil for the experimental site was a sandy-clay soil. The top soil consisted of 88%

sand, 3% silt and 9% clay, while the sub-soil consisted of 86% sand, 3% silt and 11% clay. Trees in the orchard were irrigated with microsprinklers with a delivery rate of 50 L h^{-1} and a wetted diameter of 2 m. Microsprinklers were placed between adjacent trees. Small valves placed in the micro-sprinkler tube were used for the stress treatments to withhold irrigation during the different phenological stages.

Figure 3.14: Trial site for avocado stress trial at the experimental farm of the Agricultural Research Council: Tropical and Subtropical Crops (ARC TSC)

Table 3.3: Details of the 'Hass' avocado orchard at the ARC TSC Experimental Farm

Cultivar	'Hass'
Rootstock	'Duke 7'
Age	22 years old (planted in 1996)
Orchard block area	Approximately 0.5 ha ('Hass' consists of 0.13 ha, with 'Fuerte', 'Pinkerton' and' Edranol' being the other cultivars planted in the block)
GPS co-ordinates	25°27'23.32''S; 30°58'09.45''E
Tree spacing	5 m x 3 m (667 trees ha^{-1}); not planted on ridges
Row orientation	North-South
Irrigation	Microsprinklers, with sprinklers placed halfway between trees having a delivery rate of 50 L h^{-1} and a wetting radius of 2.0 m (Figure 2 D).
Canopy dimension ($\bar{x}$ = 10 measurements)	Height 3.7 m, Width 3.3 m, Breadth 4.1 m
Canopy cover	0.66
No of experimental trees	8 trees per treatment x 5 treatments = 40 experimental trees
Tree stem circumferences ($\bar{x}$ = 10 measurements)	81.9 cm

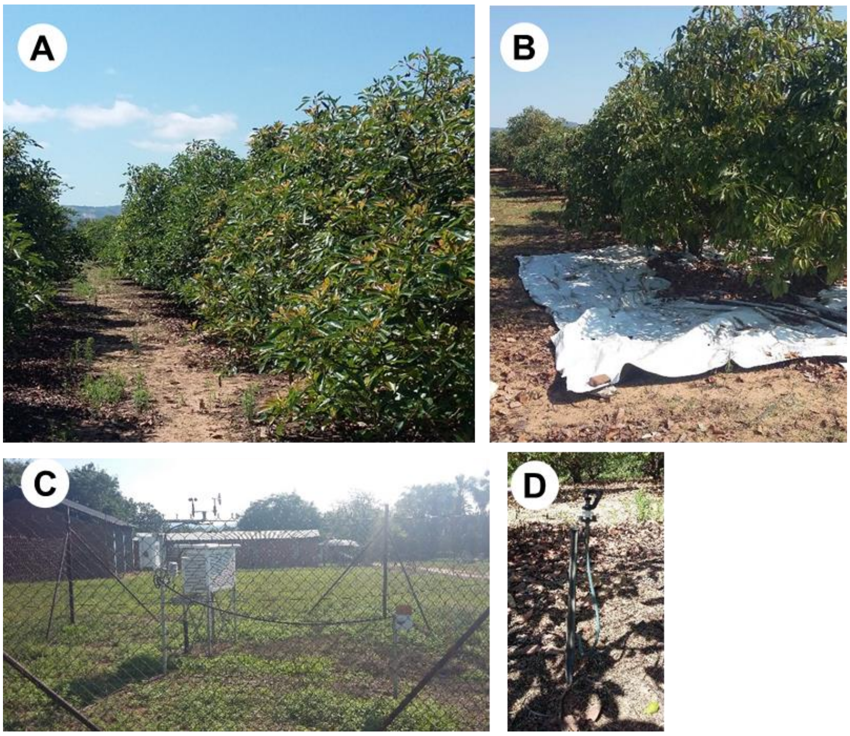


Figure 3.15: Water stress trial site at the ARC TSC. A) The orchard that consist of 'Hass' avocado trees grafted on 'Duke 7' rootstocks; B) the weather station from which weather data was obtained; C) white plastic sheets which covered the drip area under the trees to exclude rainwater and to increase the possibility of inducing water stress; and D) microsprinkler irrigation in the orchard with a 50 L h^{-1} delivery rate

3.2.2 EXPERIMENTAL DESIGN AND THE IMPLEMENTATION OF WATER STRESS TREATMENTS

The trial was carried out using a randomized block design, consisting of five treatments and six replicates per treatment (Figure 3.16). The treatments consisted of a fully irrigated control treatment and four water stress treatments applied during flowering, fruit set, fruit growth and fruit maturation, respectively. For the fully irrigated treatment, soil matric potential was kept below -40 kPa to ensure stress free conditions. For the stress treatments, the aim was to dry the soil out to be drier than -40 kPa, as suggested by Van Eyk (1994) for avocado, by withholding irrigation and placing plastic sheets in the drip area of the trees to exclude rainwater (Figure 3.15 B). Exclusion of rainwater with the plastic sheets was, however, not always successful, especially when heavy rains occurred.

		Block 4						Block 3											Block 2						Block 1						
C	X	X	O	X	4	4	X	O	3	3	X	5	O	O	O	O	O	O	O	O	X	X	2	2	1	1	X	3	3	X	X
B	X	X	1	1	X	3	3	X	4	2	2	X	5	O	O	O	O	O	O	5	5	X	1	1	X	4	4	X	5	5	X
A	X	5	5	X	2	2	X	4	O	X	X	1	1	X	O	O	X	X	X	4	4	X	3	3	X	X	O	X	2	2	X
	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1

<u>Treatments</u>

1) Fully irrigated - no stress
2) Stress between flowering and fruit set
3) Stress during fruit growth
4) Stress during fruit maturation
5) Partial root zone drying

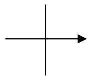


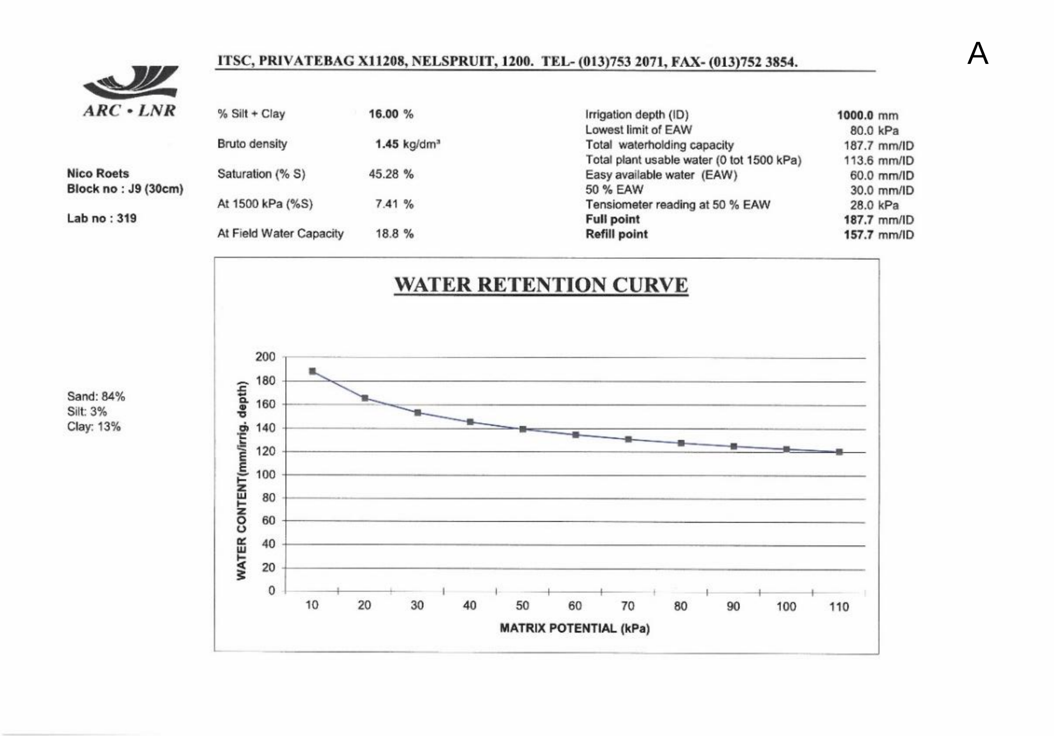
Figure 3.16: Experimental design for the experimental site at ARC TSC (Note that the ‘Fuerte’ and ‘Edranol’ trees are planted on the eastern and western side of the ‘Hass’ block respectively and row A and C are therefore not guard rows; the “O” denotes missing or dead trees)

3.2.3 MEASUREMENTS AND DATA COLLECTION DURING EACH STRESS PERIOD

Weather data was obtained from an automatic weather station of the Agricultural Research Council: Soil, Climate and Water, situated approximately 150 m from the experimental site (Figure 3.15 C). Weather variables provided by the weather station included minimum and maximum temperatures, minimum and maximum relative humidity, rainfall, solar radiation and wind speed. Reference evapotranspiration (ET_o) was calculated according to the FAO-56 procedure (Allen et al., 1998).

Soil matric potential was measured with Watermark probes (Irrometer Company, Inc., USA), installed at 30 and 60 cm depths in the root zone of trees of each treatment. These probes were connected to a Watermark 900M logger (Irrometer Company, Inc., USA) that logged data at hourly intervals. A water retention curve for both the top (30 cm) and sub-soil (60 cm) was obtained from the Soil Science Laboratory of the ARC: TSC and used for irrigation scheduling purposes (Figure 3.17). From the water retention curves, calculations were made using the method of Saxton (1986) to determine field capacity (FC) and permanent wilting point (PWP) of both the topsoil and sub-soil. For the top-soil FC and PWP was at 17.8 (0.178 cm^3 water per cm^3 soil) and 10.1% (0.101 cm^3 water per cm^3 soil), respectively, while FC and PWP for the sub-soil was at 19.7 (0.197 cm^3 water per cm^3 soil) and 11.9% (0.119 cm^3 water per cm^3 soil), respectively. By extrapolating from the water retention curves FC for the top and sub-soil was at approximately -14.7 and -16.3 kPa, respectively. Permanent wilting point could not be estimated from the water retention curves but possibly fell below -1 500 kPa.

A



B

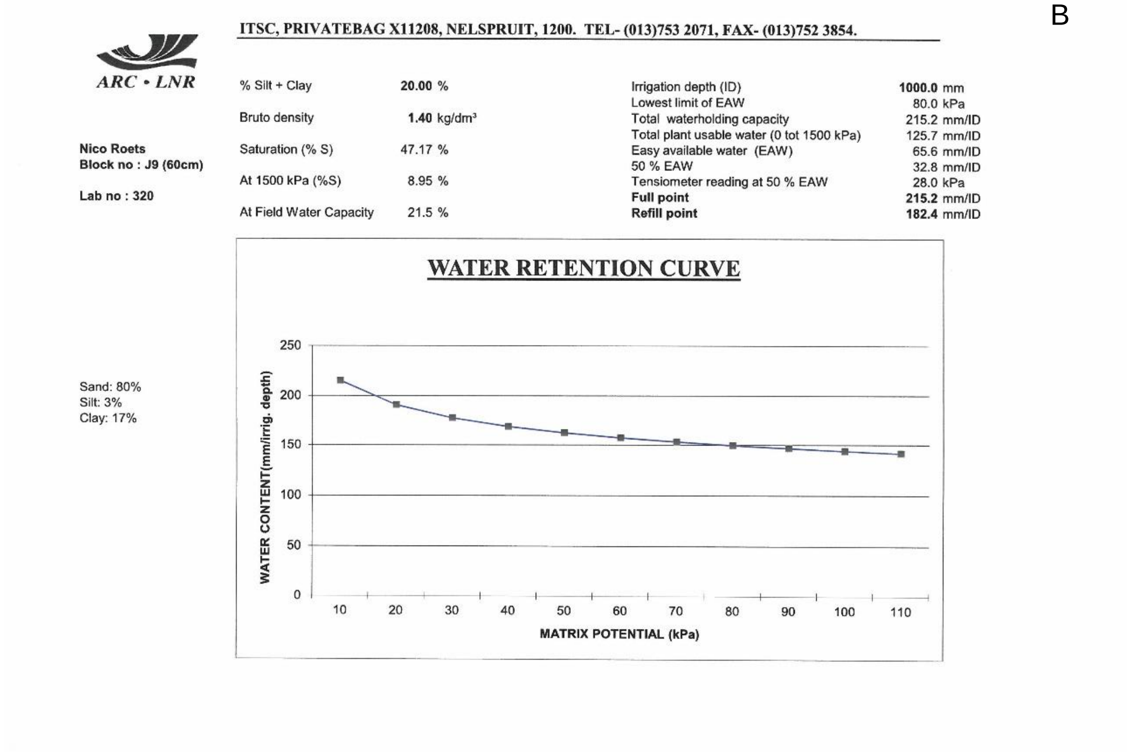


Figure 3.17: Water retention curves for the soil of the ARC TSC experimental site (A: top soil – 30 cm; B: sub-soil – 60 cm)

Relevant phenology measurements were made for each phenological stage at which a water stress was applied. During fruit set, twenty inflorescences per tree were marked during flowering. After fruit set, the number of fruit per inflorescence were counted. On the same marked inflorescences, the vigour of the spring flush was measured after the spring flush hardened off, by determining the length of the shoot with a tape measure. Five leaves per branch (20 leaves per data tree) were then randomly selected and the length and width measured. Leaf area was calculated, based on the oval shape of the leaves, as follows:

$$\text{Area} = \pi\ (½\ L \times ½\ W) \qquad [20]$$

where L is the length of the leaf and W is the width of the leaf.

During fruit growth, data was collected on fruitlet abscission during the November fruitlet abscission period ("November drop"). The number of fruit that abscised were counted on a daily basis after collecting the dropped fruit from the orchard surface for each tree. When no more fruit dropped, the number of fruit that remained on the tree were then counted. Fruitlet abscission was then calculated as:

$$\text{Fruitlet abscission} = Fa\ /\ Ft \times 100 \qquad [21]$$

where Fa is the total number of fruit that abscised and Ft is the sum of the total number of fruit (those that abscised and remained on the tree).

All fruit that dropped were also taken to the laboratory and weighed individually on a laboratory scale. Thereafter the dropped fruit were cut open to assess any visible defects that could give an indication for possible reasons that led to fruitlet abscission. Embryo viability of the fruit that dropped was further assessed by removing the embryos of fruit that dropped. The embryos were then dipped into a 1% tetrazolium chloride solution, where after they were incubated for 6 hours at 39°C to ensure staining of the embryos. Live embryos stained a reddish colour, while dead embryos did not stain. Embryos of fruit that did not drop were also stained for comparative purposes.

During fruit maturation, fruit were harvested when harvest maturity (moisture content below 77%) was reached. All fruit from each data tree was harvested and weighed using a field scale. After weighing all fruit from the data trees, fruit samples were drawn and individual fruit were weighed to obtain fruit size data. Unfortunately, a large number of fruit were stolen during the COVID-19 lockdown during 2020 and yield data for the 2019/20 season had to be estimated. This estimation was done using data on the number of fruit that remained on the tree after the "November drop" period and multiplying this number with the average fruit mass of the individual fruit. During 2018/19, samples of 15 fruit per replicate (only from the fully irrigated and water stress during fruit maturation treatments) were drawn and cold stored for a 28 day period at 5.5°C. For the 2019/20 season, samples of only 6 fruit per replicate could be obtained for cold storage due to the low availability of fruit. During cold storage, fruit were weighed every two days to determine fruit moisture loss during cold storage. After the 28 day cold storage period, fruit were ripened at 21°C. Once fruit were ripe, quality assessments were performed. Fruit were evaluated for the incidences of fungal decay and postharvest physiological disorders. Fungal decay that was assessed included the incidences of stem-end-rot and body rot. Stem-end-rot is a decay caused by infection of a number of possible fungi, which include *Lasiodiplodia theobromae*, *Botryosphaeria dothidea* spp and *Nectria pseudotrichia*. These fungi infect the fruit from the stem-end and once infected, the infection spreads throughout the mesocarp causing the fruit to rot (Manicom, 2001). Body rot is caused by the fungus *Colletotrichum siamense*, which infects the fruit through the fruit skin from where it causes decay of the mesocarp (Manicom, 2001). These fungi may already be present while fruit are still on the tree, but they usually remain latent until fruit start to soften during ripening. Postharvest physiological disorders that were assessed included, vascular browning, vascular staining and diffuse mesocarp discoloration. Vascular browning is the browning and hardening of the vascular bundles that go through the mesocarp from the stem-end to the seed (Bill et al., 2014). Vascular staining is the pink staining of mesocarp tissue directly adjacent to the vascular bundles (White et al., 2009). Diffuse mesocarp discoloration is the grey coloration of the mesocarp from the base of the seed (Cutting and Wolstenholme, 1992). Even though these postharvest physiological disorders develop during cold storage, pre-harvest stress conditions are strongly linked to their occurrence.

When water stress was applied during flowering, flowering intensity during full flowering was assessed. Ten inflorescences per tree were marked and the number of flowers were counted for each inflorescence once in full bloom.

For all phenological stages, midday stem xylem water potential was measured on a weekly basis to provide an indication of tree water status and stress. In this instance, two leaves (one on the east and one on the western side of the tree) were closed in dark foil bag for approximately 60 minutes. After the 60 minutes elapsed, the leaves were detached from the trees and the turgor pressure of the leaves determined with a Scholander Pressure Chamber (PMS Instruments, Inc., USA). These measurements were carried out at midday, which was between 11:00 and 13:00. Correlations between midday stem xylem water potential and soil matric potential were also obtained using the midday stem xylem water potential measurements for the trees where a Watermark sensor was installed in the drip area of that specific tree.

To determine the correlations between midday stem xylem water potential and other physiological parameters, such as leaf transpiration and the rate of photosynthesis, four leaves were selected per data tree. Transpiration, photosynthesis and stomatal conductance were measured using an infrared gas analyser (ADC LC-pro SD, Bioscientific Ltd., UK). Directly after measuring transpiration and photosynthesis, the leaves were closed in dark foil bags for an hour for stem xylem water potential measurements. These measurements were also carried out during midday to correlate with midday stem xylem water potential.

3.2.4 STATISTICAL ANALYSIS OF DATA

All data was analysed using GenStat statistical software (Genstat, version 14, 2010, Hemel Hempstead, UK). Treatments and seasons were compared using a two-way analysis of variance. Treatment, season and treatment x season interactions were regarded as statistically significantly different when $P < 0.05$ (95% confidence level). For leaf abscission data, the treatments and seasons were compared using covariance analysis, where the number of leaves counted before leaf abscission (L_i) was used as a co-variate. Once statistically significantly differences were determined, means were separated using Duncan's multiple range test at the 95% confidence level. In cases where linear correlations were obtained between variables, Pearson's product correlation coefficient was determined. Correlations were regarded as being statistically significant when $P < 0.05$.

3.3 MODELLING APPROACHES

3.3.1 DUAL CROP COEFFICIENT APPROACH

The strict definition of a basal crop coefficient (K_{cb}) includes some evaporation when the soil surface is dry (Allen et al., 1998) and as direct measurements of E_c were made using a sap flow method in this trial, transpiration crop coefficients (K_t) were derived instead of K_{cb}, as proposed by Villalobos et al. (2013). Daily K_t values were calculated by dividing measurements of E_c by daily ET_o as follows:

$$K_t = \frac{E_c}{ET_o} \quad [22]$$

Estimates of K_t were calculated according to the procedure outlined by Allen and Pereira (2009), where K_t during conditions of nearly full ground cover ($K_{t\ full}$) is multiplied with a density coefficient (K_d), which is linked to the abundance of vegetation present, and is presented as follows:

$$K_t = K_{t\ full} \times K_d \quad [23]$$

Where daily values of K_d were calculated in accordance with Allen and Pereira (2009) as:

$$K_d = \min\left(1, M_L f_{c\ eff}, f_{c\ eff}^{\left(\frac{1}{1+h}\right)}\right) \quad [24]$$

where $f_{c\ eff}$ is the effective fraction of ground covered or shaded by vegetation [0.01-1] near solar noon, M_L is a multiplier on $f_{c\ eff}$ describing the effect of canopy density on shading and on maximum relative evapotranspiration per fraction of ground shaded [1.5-2.0], with a value of 2.0 recommended for avocado (Allen and Pereira, 2009) and h is tree height. Following model parameterisation a value of 1.5 for M_L provided better estimates for avocado.

The $f_{c\ eff}$ was calculated according to Allen et al. (1998) as follows:

$$f_{c\ eff} = \frac{f_c}{\sin(\beta)} \leq 1 \quad [25]$$

where f_c is the observed fraction of soil surface that is covered by vegetation as seen from directly overhead. As $f_{c\ eff}$ is usually calculated at solar noon, β (mean elevation angle of the sun above the horizon during the period of maximum evapotranspiration) can be calculated as:

$$\beta = \arcsin\left[\sin(\varphi)\sin(\delta)+\cos(\varphi)\cos(\delta)\right] \quad [26]$$

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

Furthermore, in accordance with Allen and Pereira (2009), $K_{t\,full}$ can be approximated, for large stand size (greater than about 500 m^2), as a function of mean plant height (h, m) (Table 3.4) and adjusted for climate using wind speed (u_2, m s^{-1}), percentage minimum relative humidity (RH_{min}), and the degree of stomatal control on E_c relative to most agricultural crops (F_r, unitless), as follows:

$$K_{t\,full} = F_r\left(\min(1.0+0.1h,\ 1.20)+[0.04(u_2-2)-0.004(RH_{min}-45)]\left(\frac{h}{3}\right)^{0.3}\right) \quad [27]$$

where F_r [0-1] is a relative adjustment factor for stomatal control and was calculated as follows:

$$F_r \approx \frac{\Delta+\gamma(1+0.34u_2)}{\Delta+\gamma\left(1+0.34u_2\frac{r_{leaf}}{100}\right)} \quad [28]$$

where r_{leaf} is the mean leaf resistance (s m^{-1}); Δ is the slope of the saturation vapour pressure versus air temperature curve (kPa °C^{-1}) and γ is the psychrometric constant (kPa °C^{-1}). r_{leaf} for most agricultural crops under full cover conditions (when the LAI exceeds 3.0 m^2 m^{-2}) is 100 s m^{-1} (Allen and Pereira, 2009). Allen and Pereira (2009) suggested a value of 300 s m^{-1} for the initial and midseason periods and 400 s m^{-1} at the end of the season. As LAI for the intermediate orchard in Howick and the orchard at Tzaneen was less than 3.0 m^2 m^{-2} the term $r_{leaf}/100$ in Equation [28] was replaced with $r_s/50$, where r_s is estimated bulk canopy resistance, as suggested by Allen and Pereira (2009). Both r_{leaf} and r_s values for each orchard were estimated by inverting Equation [27], after solving for F_r by inverting Equation [28], using known daily values of $K_{t\,full}$. $K_{t\,full}$ values were calculated using measured daily K_t and K_d estimated from measured data. These r_{leaf} and r_s values were subsequently used to estimate F_r for independent seasons of measurements using Equation [28] in order to estimate K_t and E_c values for model validation purposes.

Taylor et al. (2015) demonstrated that the use of a single value of r_{leaf} in the estimation of crop coefficients was not appropriate for estimating water use of citrus and suggested that the use of monthly estimates of r_{leaf} might provide more accurate estimations of water use in citrus. Thus although, Allena and Pereira (2009) provide an estimate for r_{leaf} for avocados (300 m s^{-1} for the initial and midseason and 400 m s^{-1} for the end of the season), this may not be reasonable for this subtropical crop. Various methods of estimating r_{leaf} for the accurate determination of K_t values for the different orchards was therefore attempted.

Table 3.4: Measured and calculated canopy parameters for the mature bearing, immature bearing and non-bearing avocado orchards in Howick and the mature orchard at Tzaneen used as input parameters in the FAO-56 dual crop coefficient model.

Orchard	Mature	Intermediate	Non-bearing	Tzaneen
Between Row Width (m)	7.0	7.0	7.0	8.0
Canopy Width (m)[a]	6.4	4.9	2.48	4.6
Canopy Height (m)[a]	7.3	4.6	2.6	5.3
$f_{c\ eff}$	0.91	0.56	0.20	0.59

[a]Mean seasonal measurements

3.3.2 MODELLING TRANSPIRATION USING A CANOPY CONDUCTANCE MODEL IN CONJUNCTION WITH THE PENMAN-MONTEITH APPROACH

3.3.2.1 Calculation of canopy conductance

Canopy conductance (g_c) was calculated using hourly transpiration measurements obtained in the IO orchard by inverting the Penman-Monteith equation (Monteith and Unsworth, 1990) as follows:

$$g_c = \frac{\lambda E_c \gamma g_a}{\Delta(R_n) + \rho_a C_p g_a VPD - \lambda E_c(\Delta - \gamma)} \qquad [29]$$

where λ is the latent heat of vaporization of water (J kg^{-1}), E_c is canopy transpiration (kg m^{-2} s^{-1}), Δ is the slope of the vapour pressure curve (kPa K^{-1}), R_n is net radiation at the crop surface (W m^{-2}), G is soil heat flux (W m^{-2}) taken as 10% of R_n, ρ_a is the density of dry air (kg m^{-3}), C_p is the specific heat capacity of the air (J kg^{-1} K^{-1}), VPD is saturation vapour pressure deficit (kPa), γ is the psychrometric constant (kPa K^{-1}), g_a is the aerodynamic conductance (m s^{-1}) and g_c is the canopy conductance (m s^{-1}). Net radiation was determined using net radiometers mounted on the lattice mast above the orchards in Howick. For the orchard in Tzaneen, R_n was estimated from solar irradiance measured at the AWS using an estimate for the albedo of avocado trees determined in the intermediate orchard in Howick using the four component net radiometer.

Aerodynamic conductance (g_a) was calculated as suggested by Rana et al. (2005):

$$g_a = \frac{k^2 u_z}{\ln((z-d)/z_o)\ln((z-d)/(h-d))} \quad [30]$$

where k is the von Karman's constant equal to 0.4, u_z is the wind speed (m s^{-1}) at the z wind measurement height (m), d is the zero plane displacement estimated as d = 0.67h, z_o is the roughness length taken as 0.1h and h is the mean orchard height (Table 3.4). Windspeed above the canopy was determined by a sonic anemometer mounted above the canopy for the orchards in Howick. For the orchard in Tzaneen windspeed at 10 m above the ground was calculated according to Campbell and Norman (2012) from windspeed recorded at 2 m by the AWS.

3.3.2.2 Modelling Canopy Conductance

Canopy conductance was modelled using a Jarvis-type model (Jarvis, 1976), similar to the one used by Oguntunde et al. (2007), on an hourly basis with weather data as follows:

$$g_{c,j} = g_{c\,max} f(R_s) f(VPD_{air}) f(T_{air}) \quad [31]$$

where $g_{c,j}$ is the canopy conductance predicted by the Jarvis model, $g_{c\,max}$ is the maximum canopy conductance (m s^{-1}), $f(R_S)$ is a function of solar radiation, $f(VPD_{air})$ is a function of vapour pressure deficit and $f(T_{air})$ is a function of air temperature. The functions have values ranging between 0 and 1. A response function for soil water content has been included in the Jarvis-type model in some studies, particularly native forests (e.g.), but as the orchards in this study were well-irrigated this function was set to one. The control functions of temperature and solar radiation were similar to those of Oguntunde et al. (2007) and took the following forms:

$$f(R_S)=\frac{S_R}{R_m}\left(\frac{R_m+k_R}{S_R+k_R}\right) \quad [32]$$

$$f(T_{air})=\frac{(T_{air}-T_L)(T_H-T_{air})^t}{(k_T-T_L)(T_H-k_T)} \quad [33]$$

$$t=\frac{T_H-k_T}{k_T-T_L} \quad [34]$$

where k_R and k_T are model parameters for the respective functions in which they are used, T_L and T_H are the lower and upper temperature limit to transpiration fixed at 0 and 45°C, respectively (Oguntunde et al., 2007). R_m is an arbitrary radiation constant, often fixed at 1000 W m^{-2} (e.g. Sommer et al. (2002); Wright et al. (1995)). For the control function for vapour pressure deficit the equation derived by Zhang et al. (1997) was used. The equation is stated as:

$$f(VPD_{air})=\frac{1+k_{D1}VPD}{1-k_{D2}VPD} \quad [35]$$

where k_{D1} and k_{D2} are modelled parameters.

3.3.2.3 Model Parameterisation

Parameters $g_{c\,max}$, k_R, k_T, k_{D1} and k_{D2} were optimised by minimising the sum of squares of the residuals of the day-time (08:00 to 17:00) measured and modelled canopy conductance as:

$$S^2(k)=\sum_{i=1}^{n}\left(g_{c,i}-g_{c,j}(k,x_i)\right) \quad [36]$$

where $g_{c,i}$ is the i^{th} value of canopy conductance calculated using Equation [29] using measured transpiration data, $g_{c,j}$ is the corresponding canopy conductance value predicted by the Jarvis model, k represents the model parameters (k_R, k_T, k_{D1} and k_{D2}) and x_i is the input variables of the i^{th} model value. Minimisation of S^2 was carried out by optimising k using the solver function in Microsoft Excel. Parameterisation was carried out in the intermediate orchard in Howick, as the best estimates of g_c were obtained in this orchard.

3.3.2.4 Model Validation

Validation of the model was performed by calculating g_c using the optimised parameters of the Jarvis model and subsequently using these values in the Penman-Monteith equation to estimate hourly E_c. Only E_c values for the day-time (08:00 to 17:00) period were used to evaluate the performance of the model. These values were compared to the day-time E_c measured using the sap flow measurements in the intermediate and mature orchard in Howick and the orchard in Tzaneen.

3.3.3 MODELLING TRANSPIRATION USING A MODIFIED JARVIS STEWARD TYPE MODEL

The E_c model proposed by Whitley et al. (2009) was modified by excluding the volumetric soil water content (θ) function from the equation given that the avocado orchards were irrigated throughout the duration of the trial and soil water deficits were unlikely to have placed a limitation on $E_{c\ max}$ in this study. Measurements of pre-dawn leaf water potential support the assumption that water stress did not occur in measurement trees. Air temperature (T_{air}) as a modulating factor for $E_{c\ max}$, was included and the model took the following form:

$$E_c = E_{c\ max} f(R_S) f(VPD_{air}) f(T_{air}) \quad [37]$$

Both the R_S and T_{air} response functions took the same form as that presented in Equations [32] to [34], with T_L, T_H and R_m fixed at 0°C, 45°C and 1000 W m^{-2} respectively. The response function of VPD_{air} was, however, different to that used in the g_c model and took the following form as proposed by Whitley et al. (2009):

$$f(VPD) = k_{e1} VPD_{air} \exp(-k_{e2} VPD_{air}) \quad [38]$$

where, parameters k_{e1} and k_{e2} describe the rate of change at low and high VPD_{air} and were generated as part of the model parameterisation phase.

Similar to the parameterisation of the g_c model, parameters $E_{c\ max}$, k_R, k_T, k_{e1} and k_{e2} were optimised by minimising the sum of squares of the residuals of the measured and modelled E_c (Equation [36]). This model was run on a daily time step.

3.3.3.1 Model Validation

Validation of the model was performed by simulating E_c using the optimised parameters of the Whitley et al. (2009) model and comparing these values to measured E_c for the day-time (08:00 to 17:00) period using the sap flow measurements in the MO and IO orchard.

3.3.3.2 Scaling $g_{c\ max}$ and $E_{c\ max}$ for orchards with varying canopy size.

The study attempted to model E_c in two avocado orchards where the trees had different canopy sizes, but were located in close proximity of one another. A third orchard in a different location was used to assess if the model could be scaled for canopy size and still apply to a different climatic region. As a result, adjustments for variations in canopy size needed to be made given that the intermediate sized orchard was used to parameterise both the g_c and E_c models. It was decided that the g_c model (Equation [31]) would need scaling on the $g_{c\ max}$ term, and was subsequently scaled using measurements of LAI. Scaling was done by dividing $g_{c\ max}$ obtained during the model parameterisation phase by the average LAI of the IO orchard during the same period. By dividing $g_{c\ max}$ with LAI, a leaf area specific $g_{c\ max\ LAI}$ (mm m^2 s^{-1} m^{-2}) could be obtained and substituted back into Equation [31] so that canopy adjusted g_c was obtained as:

$$g_{c\ mod} = \text{LAI}\ g_{c\ max\ adj} f(R_s) f(VPD_{air}) f(T_{air}) \qquad [39]$$

Similarly, adjustments for canopy size needed to be made for the $E_{c\ max}$ term of Equation [37]. However, given that the study aimed to keep the input parameters of the model easily obtainable, the LAI adjustment used in the g_c model was replaced by an adjustment for canopy size using $f_{c\ eff}$ as proposed by Allen and Pereira (2009). The $E_{c\ max}$ obtained during the model parameterisation phase of the IO orchard was divided by the $f_{c\ eff}$ value of the orchard to obtain $E_{c\ max\ fc\ eff}$ (mm h^{-1}). This term was substituted into Equation [37], so that $E_{c\ mod}$ was obtained as:

$$E_{c\ mod} = f_{c\ eff}\, E_{c\ max\ adj}\ f(R_S) f(VPD_{air}) f(T_{air}) \qquad [40]$$

3.3.4 STATISTICAL ANALYSIS

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

4. RESULTS AND DISCUSSION

4.1 AVOCADO WATER USE

4.1.1 SEASONAL WEATHER AND TREE PHENOLOGY

Average temperature was fairly similar over the three production seasons (taken as September to September) with the mean temperature being 17.1°C, 17.7°C and 17.6°C during the 2017/18, 2018/19 2019/20 seasons respectively. During all three seasons of measurement, the highest average temperatures were recorded from December to March and were approximately 4-5°C higher than the respective mean annual temperature (Figure 4.1 and Figure 4.2). However, in each season some of the highest maximum temperatures were recorded from September to December. On 5 days, daily maximum temperatures exceeded 35°C. Mean daily solar radiation was slightly higher in the 2018/19 season (15.99 MJ m^{-2} day^{-1}) and 2019/20 seasons (15.90 MJ m^{-2} day^{-1}), as compared to the 2017/18 (15.07 MJ m^{-2} day^{-1}) season. Highest daily solar radiation coincided with the highest mean daily temperatures, occurring from December to March in both seasons (Figure 4.1 and Figure 4.2). Mean annual rainfall was significantly higher during the 2017/18 season (1180 mm), compared to the 2018/19 (1013 mm) and 2019/20 (1080 mm) seasons. Annual rainfall in all three seasons was very close to the long-term average of 1074 mm for Howick (https://en.climate-data.org/africa/south-africa/kwazulu-natal/howick-27052/).

Average air vapour pressure deficit (VPD_{air}) was similar during both the 2017/18 (0.78 kPa) and 2018/19 (0.83 kPa) seasons, which was lower when compared to the 2019/20 season (0.90 kPa) (Figure 4.3). Highest monthly VPD values were observed from September to October (flowering and fruit set) in all three seasons. Total reference evapotranspiration (ET_o) increased for each season, with 1015 mm in the 2017/18, 1071 mm in the 2018/19 and 1093 mm in the 2019/20. This increase in seasonal ET_o over the three seasons was reflected in the seasonal average ET_o and maximum daily ET_o, with the 2018/19 (avg. 2.93 mm day^{-1} and max. 6.92 mm day^{-1}) and 2019/20 (avg. 2.99 mm day^{-1} and max. 7.04 mm day^{-1}) seasons having both a higher average ET_o and daily maximum ET_o, compared to the 2017/18 season (avg. 2.78 mm day^{-1} and max. 6.60 mm day^{-1}). The highest average daily ET_o was observed from September to November of all three seasons, with average daily ET_o during this period being 3.4 mm day^{-1} (Figure 4.3). Reference evapotranspiration greater than 6.0 mm day^{-1} was recorded on 32 occasions from October to February during the three seasons.

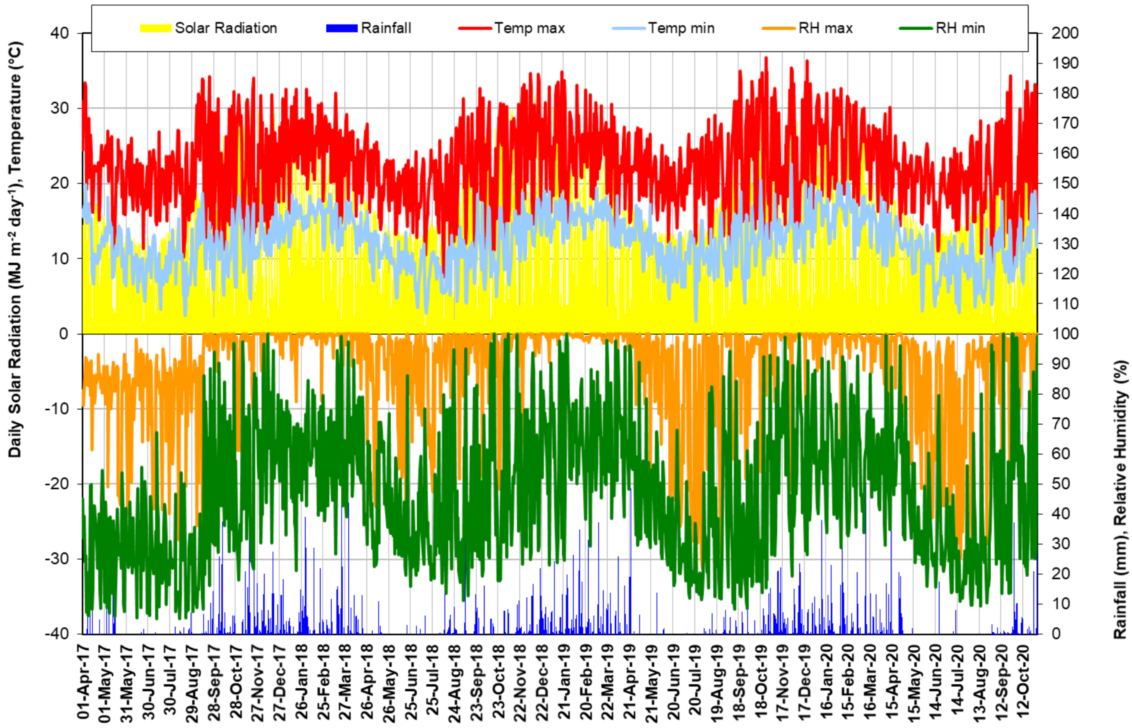


Figure 4.1: Maximum and minimum daily air temperature, maximum and minimum relative humidity, total daily rainfall and solar radiation obtained from the automated weather station located in Howick for three seasons (1 April 2017 to 31 October 2020)

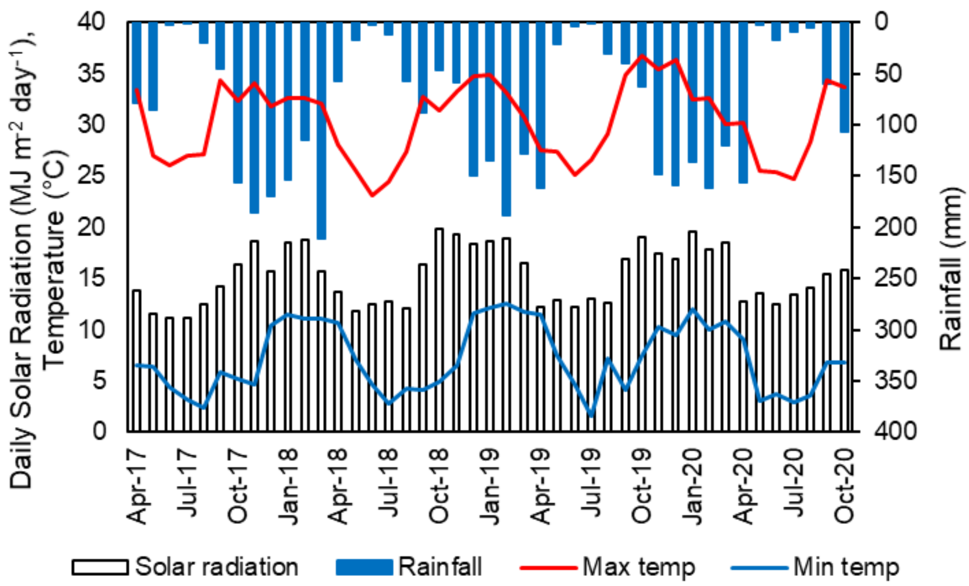


Figure 4.2: Monthly average daily solar radiation and maximum and minimum temperatures, together with total monthly rainfall for the Howick site for three seasons (April 2017 to October 2020)

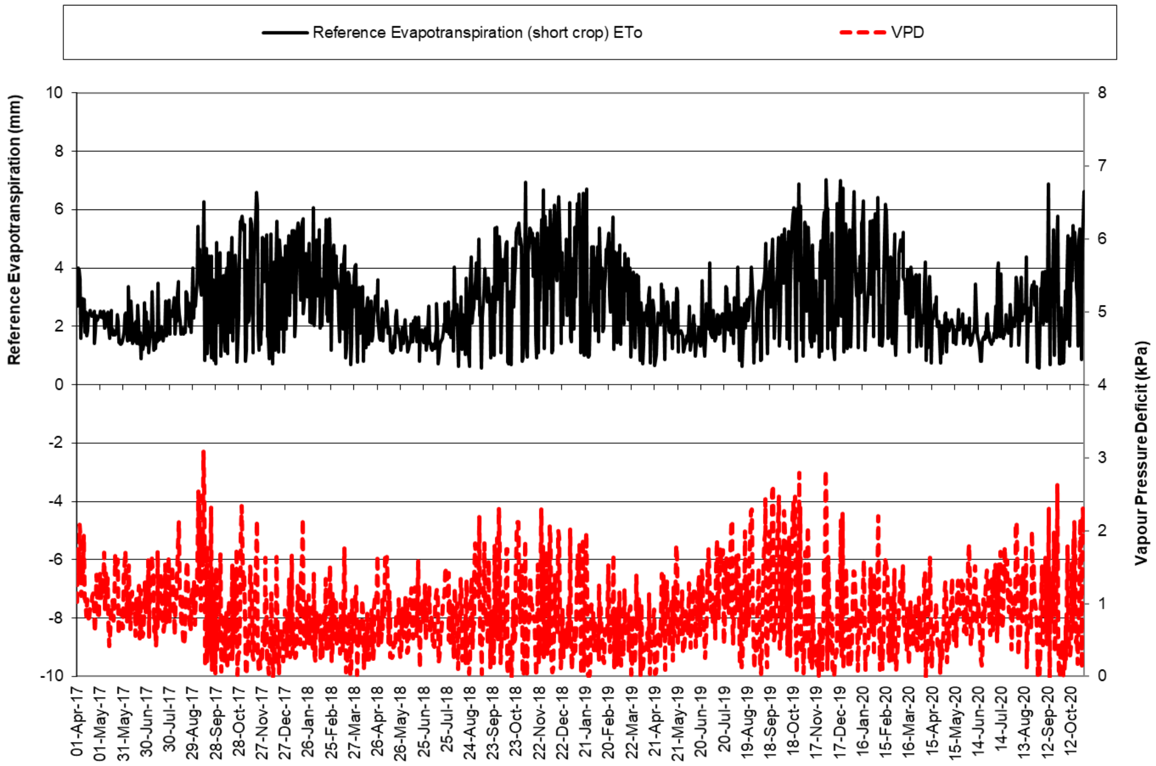


Figure 4.3: Reference evapotranspiration (ET_o) and vapour pressure deficit (VPD) determined from variables measured by the automatic weather station located for the Howick site for three seasons (1 April 2017 to 31 October 2020)

A second site in Tzaneen was chosen for a single season of measurements in a mature avocado orchard in order to have a data set in a contrasting climatic region for modelling purposes. Weather data for a single season (1 December 2018 to 3 March 2020) quite clearly illustrated that the weather conditions (Figure 4.4 and Figure 4.5) differed quite considerably to those in Howick. Average daily temperature during this season was 20.6°C, with daily maximum temperatures of over 35°C recorded on 46 days and an absolute maximum of 42.5°C. Typically the highest daily temperatures occurred between December and March and were typically 2-5°C higher than the annual average. This period coincided with highest average daily values for solar radiation, with an average daily solar radiation over the measurement period of 16.6 MJ m^{-2} day^{-1}. In the 2019 calendar year 719 mm of rainfall was recorded, which is below the average annual rainfall for Tzaneen of close to 881 mm per annum (https://en.climate-data.org/africa/south-africa/limpopo/tzaneen-15345/).

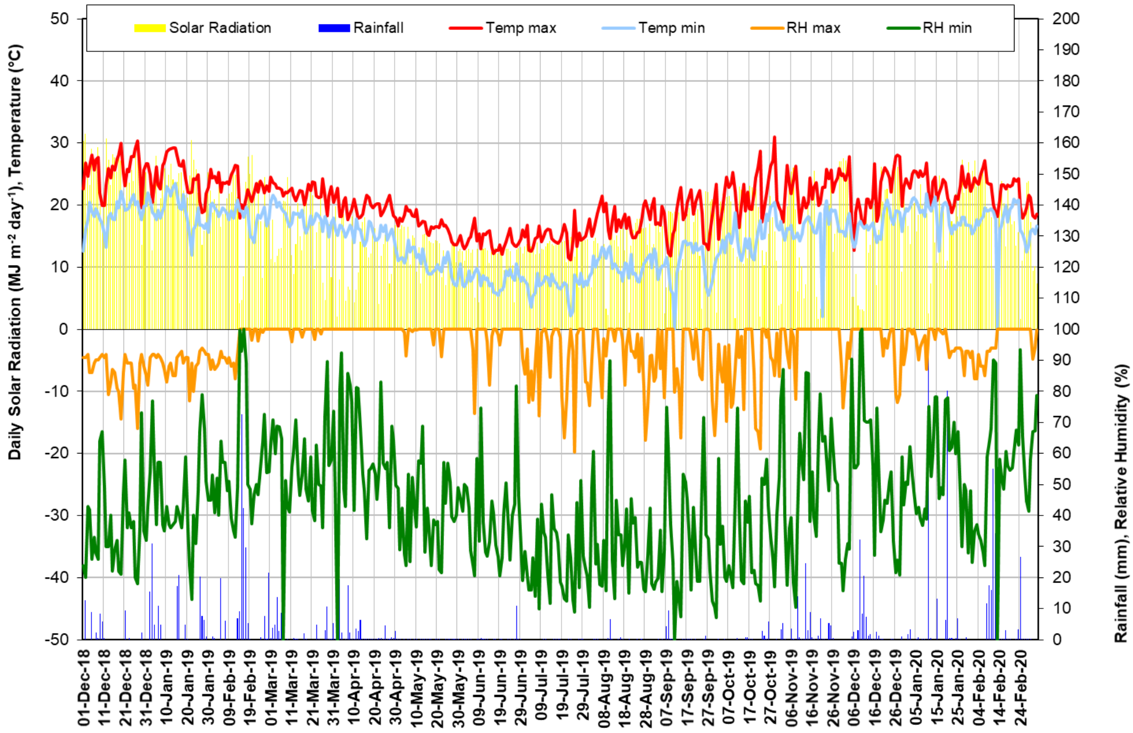


Figure 4.4: Maximum and minimum daily air temperature, maximum and minimum relative humidity, total daily rainfall and solar radiation obtained from the automated weather station located at Westfalia Estate in Tzaneen for one season (1 December 2018 to 3 March 2020)

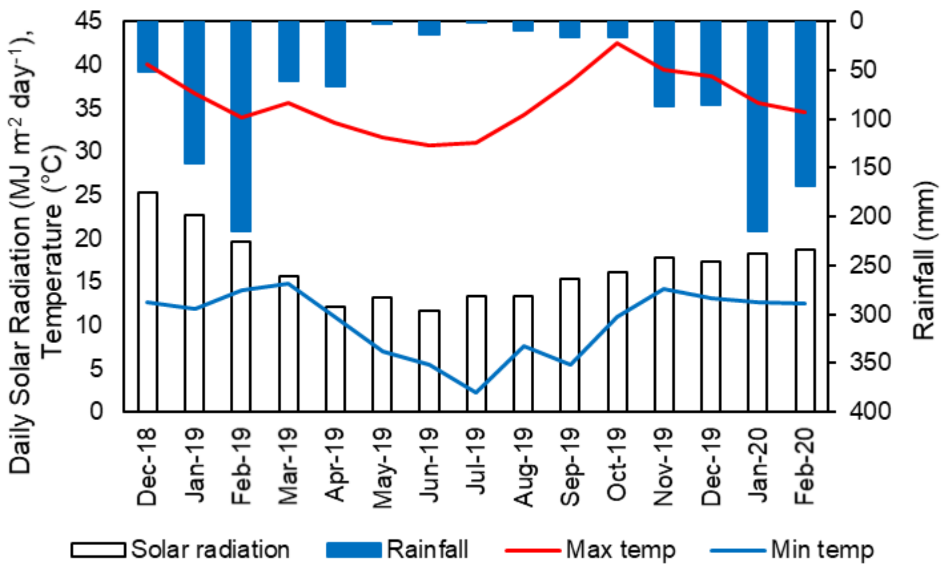


Figure 4.5: Monthly average daily solar radiation and maximum and minimum temperatures, together with total monthly rainfall for Westfalia Estate in Tzaneen, where water use measurements in an avocado orchard were performed (December 2018 to February 2020)

Average VPD for the calendar year was 1.25 kPa, with a maximum of 3.92 kPa in October 2019. Reference evapotranspiration for the 2019 calendar year was 1261 mm, with a daily average of 3.45 mm day^{-1} and a maximum of 6.98 mm day^{-1}. Daily average ET_o was highest from December through to February. Tzaneen therefore represented a hotter and drier environment than Howick.

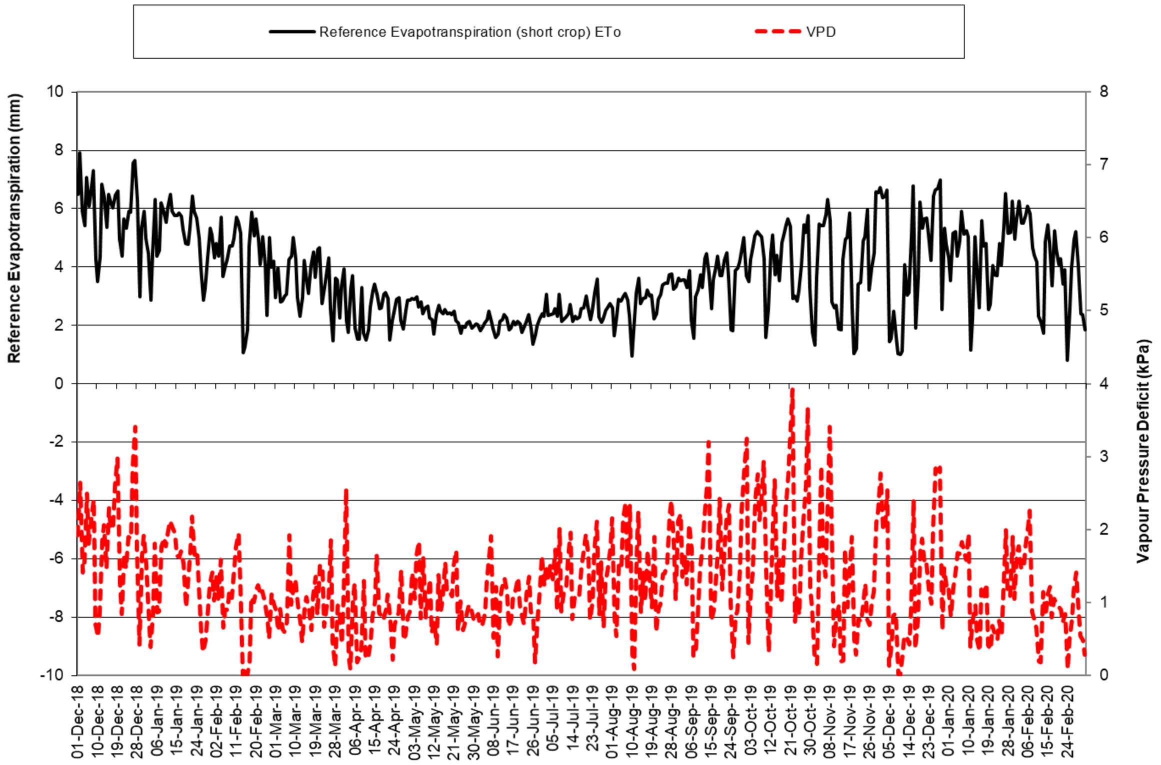


Figure 4.6: Reference evapotranspiration (ET_o) and vapour pressure deficit determined from variables measured by the automatic weather station located on Westfalia Estate in Tzaneen for one season (1 December 2018 to 3 March 2020)

4.1.2 CANOPY MEASUREMENTS

At the start of measurements in the orchards in Howick the trees in the mature orchard (MO) had a significantly higher LAI (4.0 m^2 m^{-2}) than trees in the Intermediate orchard (IO) (2.5 m^2 m^{-2}) (Figure 4.7). However, a number of severe pruning events in the MO orchard resulted in very similar LAI values between the two orchards from July 2018. The trees in the MO were allowed to get very tall (7.2 m), as compared to the IO trees (4.2 m) and as a result of intense shading in the MO orchard, the inner part of the canopy was devoid of leaves and fruit (Figure 4.8). This would also have influenced LAI measurements and water use of the orchard. When comparing estimates of fractional cover using aerial images, there is a clear decline in fractional canopy cover from July 2019 to January 2020 in the mature orchard, when there was a concerted effort to open up the canopy of the trees (Figure 4.9). Importantly, data from the mature orchard following the severe pruning was not considered in the estimates of water use efficiency and water use productivity and in modelling exercises. There was a significant difference in effective fractional cover between the two orchards, with the MO orchard having a significantly higher canopy cover. Fractional canopy cover of the orchard in Tzaneen was between that of the two orchards in Tzaneen, which is important for the modelling exercises. The discrepancies between measurements highlights the difficulty of the measurements and the large number of factors which influence the final value. Finding a robust method that can readily be employed by growers should be considered a priority for any exercise attempting to estimate water use of different orchards.

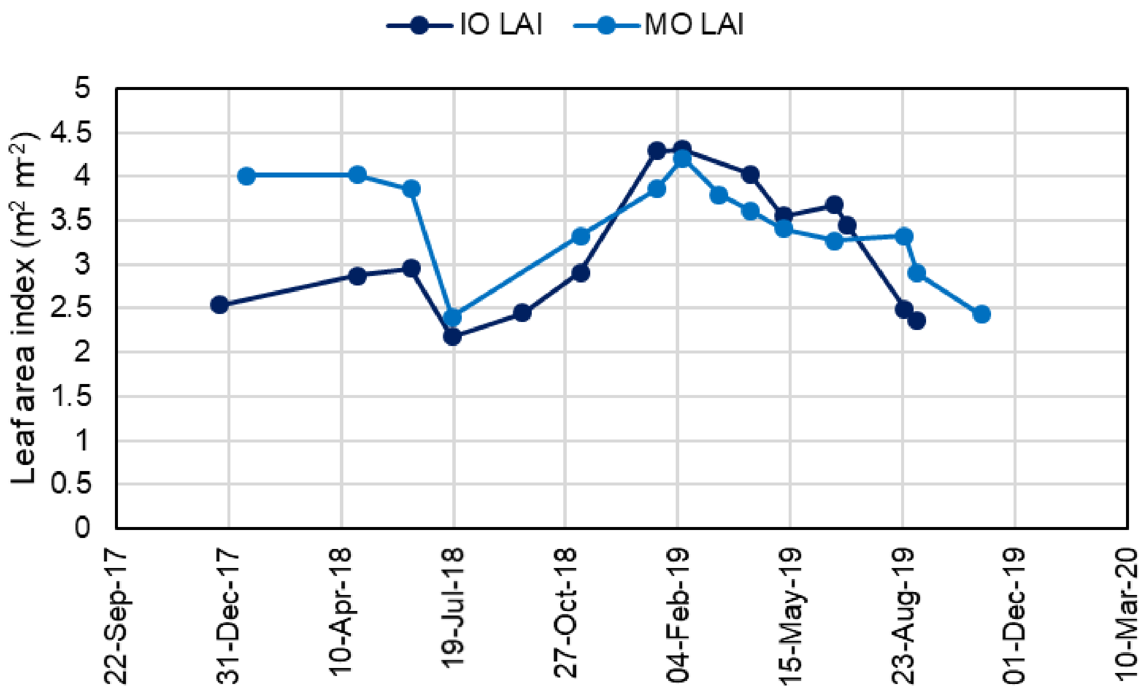


Figure 4.7: Leaf area index of the 'Hass' trees in the intermediate (IO) and mature (MO) orchards in Howick

Figure 4.8: A) Intermediate orchard in December 2018, B) mature orchard in July 2018 and C) mature orchard in July 2020 showing the clear differences between canopy architecture in the orchards and the impact of pruning

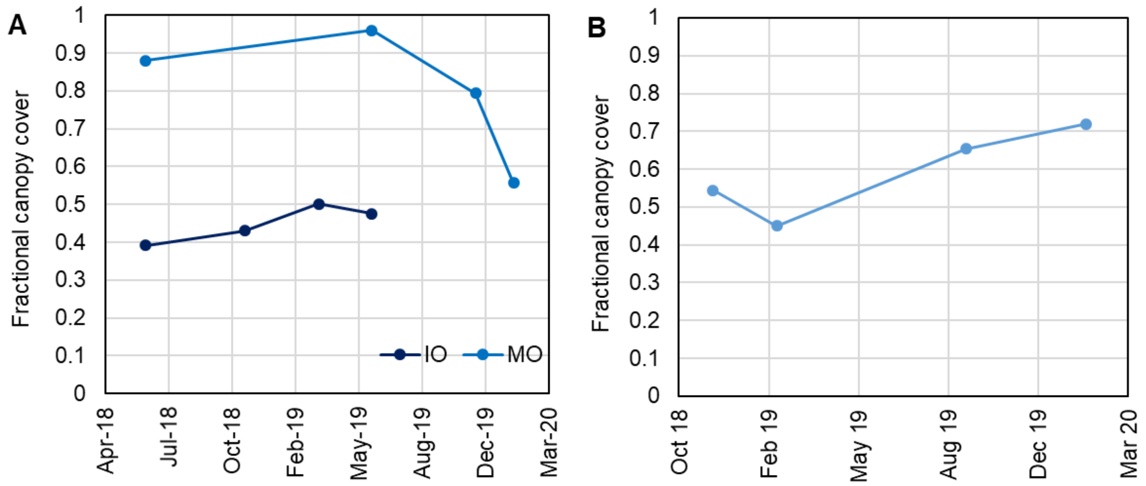


Figure 4.9: Fractional canopy cover of A) mature (MO) and intermediate (IO) orchards in Howick and B) the orchard in Tzaneen, as determined from aerial images

The LAI of the non-bearing orchard was significantly lower that the IO and MO orchards in Howick, as expected. In general, there was a steady increase in LAI (1.5 to 2.6 m^2 m^{-2}), but a slight reduction in winter 2020 may reflect of some pruning of the trees and die back or cutting of the significantly tall ground cover in the orchard. As some of this ground cover was very close to the trees and extended above the lower part of the canopy and across the tree row, it was included in LAI measurements, especially for those measurements below the tree canopy.

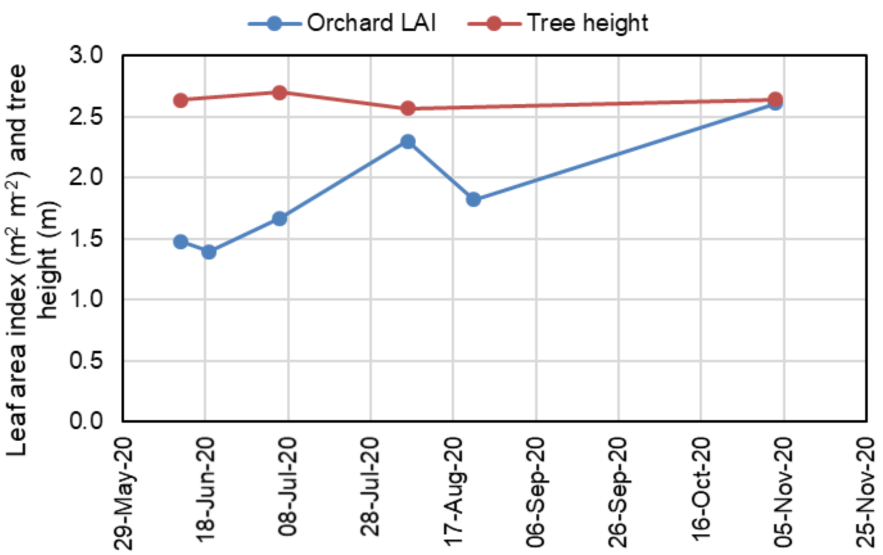


Figure 4.10: Orchard leaf area index and height of the non-bearing 'Harvest' trees on in Howick

4.1.3 TRANSPIRATION, EVAPORATION AND EVAPOTRANSPIRATION RATES

The complete set of water use data collected in avocado orchards in Howick during this study is illustrated in Figure 4.11. Measurements of ET began in the intermediate orchard (IO) on 15 April 2017 and continued until 4 September 2019. In this orchard E_c measurements began on 23 December 2017 and continued until 4 September 2019. In the mature orchard (MO) measurements of ET began on 23 September 2017 and have continued to date. Transpiration measurements began in 13 March 2018 and continued until 22 September 2019. The eddy covariance system from the IO was moved to the non-bearing orchard (NB) on 16 November 2019 and have continued to date. Transpiration measurements in this orchard started on 12 September 2019 and have also continued to date. This data will be analysed until October 2020.

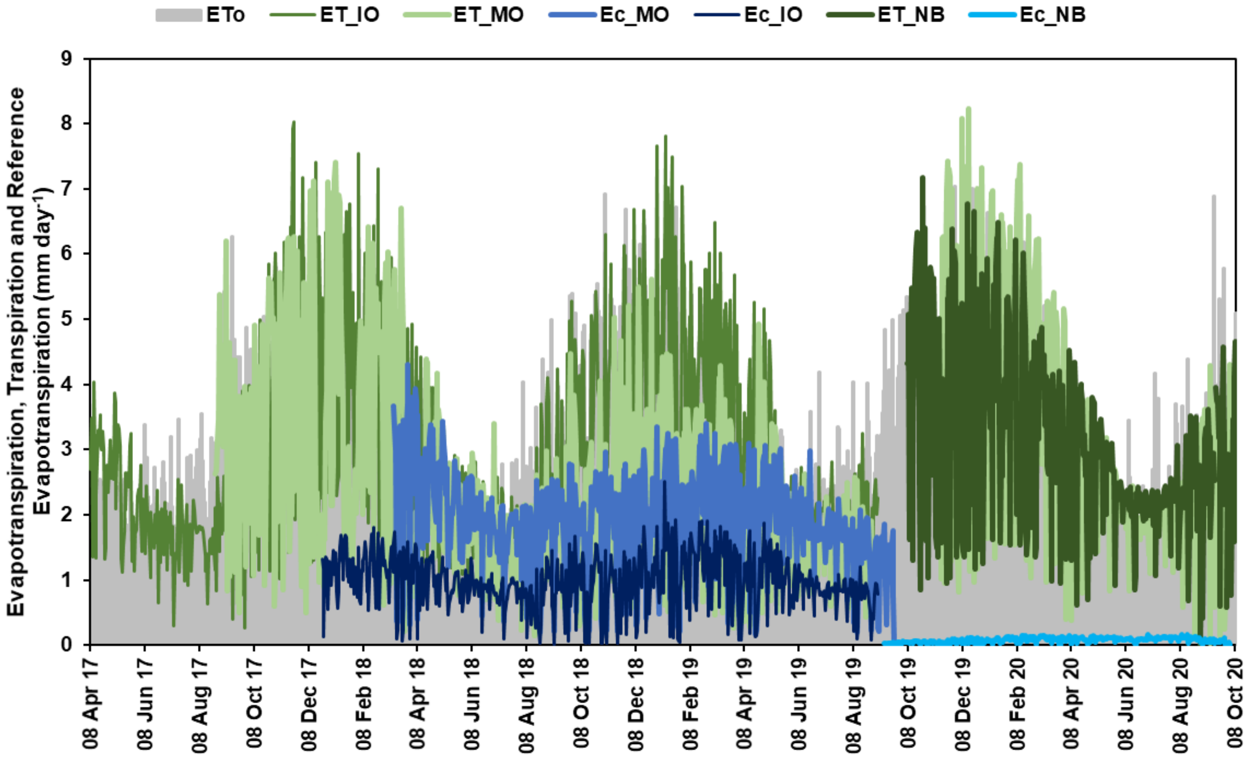


Figure 4.11: Transpiration (E_c), evapotranspiration (ET) and reference evapotranspiration (ET_o) for the entire duration of measurements in the three avocado orchards in Howick. Mature bearing orchard (MO), intermediate bearing orchard (IO), non-bearing orchard (NB).

Total E_c for the mature orchard for the 2018/19 season (September to September) was 678 mm, with ET during this season 752 mm. Measurements of ET in this orchard began before the transpiration measurements and in the 2017/18 season the orchard ET was 1063 mm (Table 4.1). This reflects the changes in canopy size between the two seasons as a result of pruning (Figure 4.7). The maximum transpiration rate recorded in this orchard was 4.32 mm day^{-1} (121 L day^{-1}) and the lowest was 0.17 mm day^{-1} (4.8 L day^{-1}). Transpiration typically mirrored changes in atmospheric evaporative demand (ET_o), but the ratio between the two did not stay constant, with E_c failing to increase at the same rate as ET_o in late spring and early summer (Figure 4.11). For a large part of the season E_c closely tracked ET, suggesting that in this orchard soil evaporation (E_s) did not form a major proportion of total ET.

Table 4.1: Average daily transpiration (E_c) and evapotranspiration (ET) rates (mm day^{-1}) across multiple seasons in the mature orchard (MO), intermediate orchard (IB) and non-bearing (NB) avocado orchards in Howick and the mature orchard in Tzaneen

Orchard	Season	2017/18		2018/19		2019/20	
		E_c	ET	E_c	ET	E_c	ET
MO	Spring		3.35	1.75	2.12	-	3.12
	Summer		3.46	2.01	2.57	-	4.28
	Autmn	2.45	2.65	2.02	2.01	-	3.25
	Winter	1.75	1.62	1.67	1.55	-	1.93
	Average	**2.10**	**2.77**	**1.86**	**2.06**	-	**3.15**
	TOTAL (mm)	**-**	**1063**	**678**	**752**	-	
IO	Spring	-	3.13	0.88	3.20	-	-
	Summer	1.13	4.19	1.14	4.29	-	-
	Autmn	1.02	2.82	1.11	3.19	-	-
	Winter	0.80	1.80	0.81	1.96	-	-
	Average	**0.98**	**2.98**	**0.99**	**3.16**	**-**	**-**
	TOTAL (mm)	-	**1087**	**359**	**1152**	**-**	**-**
NB	Spring	-	-	**-**	**-**	0.04	**-**
	Summer	-	-	**-**	**-**	0.08	3.71
	Autmn	-	-	**-**	**-**	0.10	3.03
	Winter	-	-	**-**	**-**	0.10	2.17
	Average	-	-	**-**	**-**	**0.08**	**3.06**
	TOTAL (mm)	-	-	**-**	**-**	**30.0**	**1124**
Tzaneen	Spring	-	-	**-**	**-**	1.09	**-**
	Summer	-	-	1.75	**-**	**-**	**-**
	Autmn	-	-	1.34	**-**	**-**	**-**
	Winter	-	-	1.05	**-**	**-**	**-**
	Average	-	-	**0.98**	**-**	**-**	**-**
	TOTAL (mm)	-	-	**476#**	**-**	**-**	**-**

#December 2018-December 2019

As indicated by the LAI (Figure 4.7) and fractional canopy cover (Figure 4.9) data, the trees in the IO orchard were smaller than the trees in the MO orchard. As a result, seasonal E_c in this orchard was 359 mm in the 2018/19 season, with E_c varying between 0.02 mm (0.6 L day^{-1}) and 2.51 mm (70 L day^{-1}). In the 2017/18 season ET was 1087 mm, whilst in the 2018/19 season it was 1152 mm (Table 4.1). In this orchard there was a greater difference between seasonal ET and E_c, indicating that a greater proportion of the water use of the orchard consists of E_s and transpiration by the cover crop. In the IO orchard more sunlight reached the floor, resulting in a good grass cover between tree rows. In the MO orchard at the start of the trial the trees were large and canopy cover was 0.9, resulting in very little light penetrating to the orchard floor and thus a very sparse cover of grass existed between rows. Comparisons of E_c measurements between the two differently sized orchards, during the same measurement period, revealed that a strong linear relationship (R^2= 0.76) existed between total daily E_c of the two orchards (Figure 4.12). The orchard in Tzaneen had a canopy size intermediate between the MO and IO orchard and this was reflected in the seasonal E_c of 476 mm (Figure 4.13). Transpiration ranged between 0.06 and 2.63 mm day^{-1} in this orchard (1.9-74 L day^{-1}).

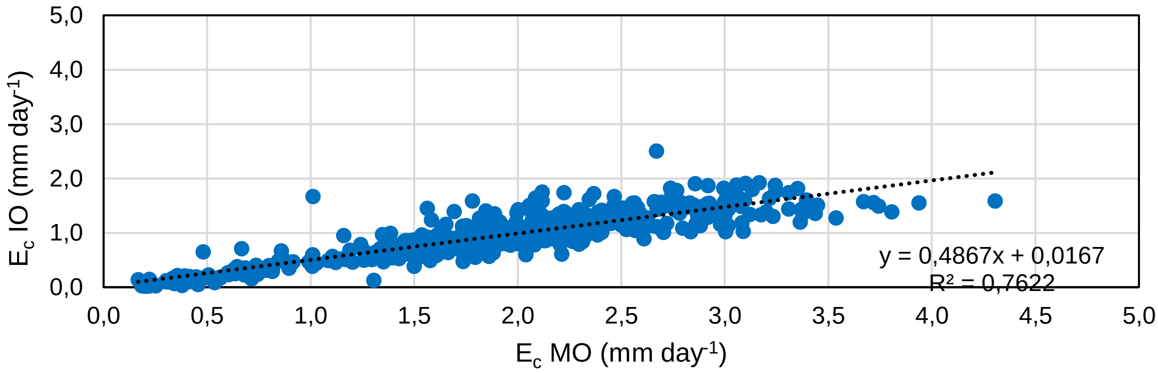


Figure 4.12: Linear relationship between daily transpiration of mature orchard (MO) and intermediate (IO) orchards from 13 March 2018 to 3 September 2019.

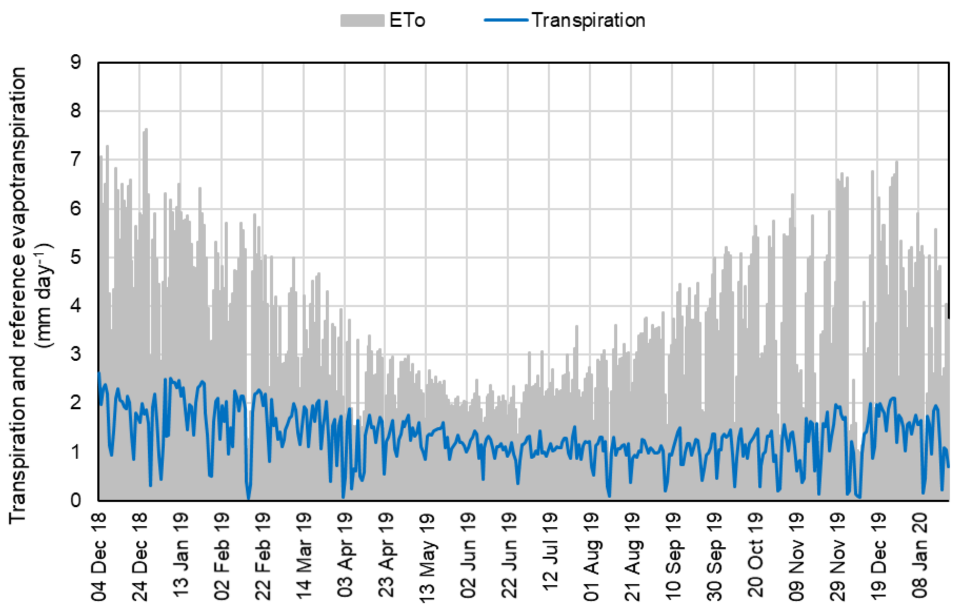


Figure 4.13: Reference evapotranspiration (ET_o) and transpiration (E_c) of the 'Hass' avocado orchard on McNoon farm in Tzaneen from 4 December 2018 to 23 January 2020

In the non-bearing orchard transpiration rates were very low, but when the tree size is considered relative to the area allocated to the tree, these rates are reasonable (Figure 4.14 A). Transpiration rates varied between 0.036 and 0.156 mm day^{-1} (1-4.4 L day^{-1}), with a seasonal total of 30.0 mm. Importantly, ET of this orchard was very comparable to ET of the mature orchard. In the same period ET in the non-bearing orchard was 914 mm, whilst ET of the mature orchard was 1033 mm. This illustrates the important contribution of E_s and transpiration of all the other vegetation in the orchard to total water use of a very young orchard. A large part of the orchard floor in these orchards was exposed to radiation and there was significant vegetation or cover crop between rows. Whilst this cover crop can serve a purpose to stabilise ridges and contribute to soil organic matter, the contribution of the transpiration of this cover crop to the orchard water balance cannot be ignored. In future, careful management of this evaporative component in young orchards could lead to significant water savings. Similar results have been found in young apple orchards by Dzikiti et al. (2018). In Mediterranean climates Lahav et al. (2013) recommend mid-winter daily water application rates of 4-8 L day^{-1} tree^{-1} for avocado trees in year 1 and 8-15 L day^{-1} tree^{-1} for trees in year 2. These values are higher than those reported in the current study (maximum of 4 L day^{-1} tree^{-1}), but given that Lahav et al. (2013) recommends water application rates and not tree water use, the transpiration rates determined in this study are realistic.

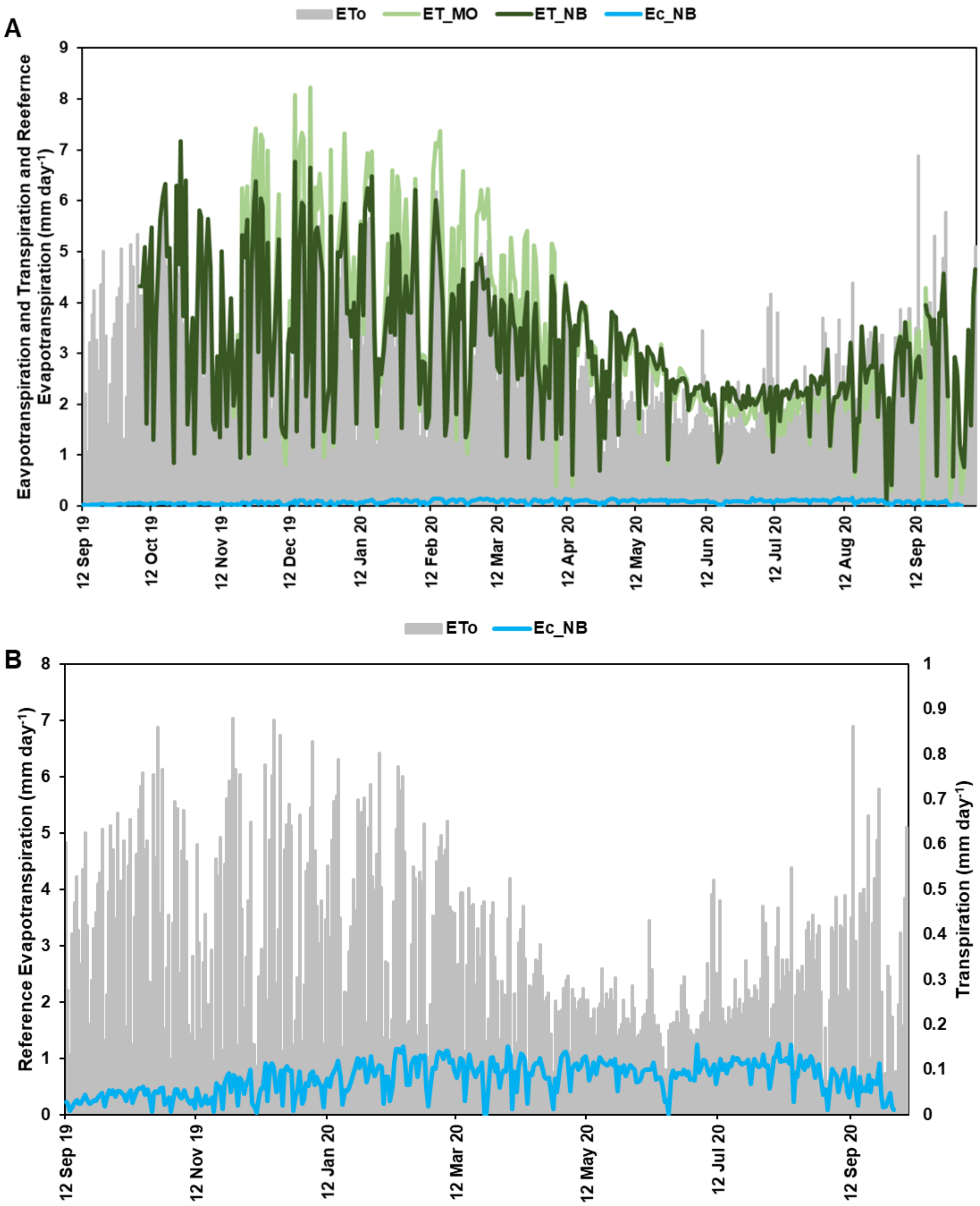


Figure 4.14: A) Reference evapotranspiration (ET_o) and evapotranspiration (ET) for the mature and non-bearing orchards and transpiration (E_c) for the non-bearing orchard and B) comparison between ET_o and E_c for the non-bearing orchard. In this graph note that the values are plotted on two different axes to illustrate the response of tree transpiration to evaporative demand.

Canopy size is therefore a major determinant of E_c in avocados, which is consistent with observations in a range of fruit tree crops including apple (Auzmendi et al., 2011, Li et al., 2002, Li et al., 2003), citrus (Marin and Angelocci, 2011, Villalobos et al., 2009, Villalobos et al., 2013) and olive (Orgaz et al., 2006, Orgaz et al., 2007, Paço et al., 2014). Water use reported for the three orchards in which ET measurements were made compare favourably to values reported by Hoffman and du Plessis (1999) for avocado water requirements of between 890 and 1020 mm per season for 7 year old trees at Burgershall. However, the measurements in the current study are much more robust and reflect the actual water use of the orchard. The difference in climates between the two sites should also be considered with Burgeshall likely to be hotter than Howick. These values provide a better guide for potential avocado water use, however, they reflect a fairly cool climate, as compared to many of the avocado growing regions in South Africa.

A more comprehensive evaluation of ET, E_s, rain and irrigation for the three study orchards in Howick is provided in Table 4.2. In this table E_s is estimated as a residual of ET and E_c and therefore includes evaporation from the soil, transpiration by the understory vegetation and at times evaporation from wet leaves. There was a definite seasonal variation in E_s in all three orchards, reflecting changing weather conditions, which lead to changes in available energy for evaporation, and changes in rainfall and therefore full surface wetting of the orchard. In the mature orchard E_s was between 6 and 22% of ET, with E_s being higher in summer and lower in winter (0.1 to 0.6 mm day^{-1}). As the trees in the mature orchard were very large, especially at the start of the season, a significant proportion of E_s (calculated as a residual of E_c and ET) could be evaporation of water from wet leaves, resulting from rainfall intercepted by the canopy. In the intermediate orchard E_s constituted a much greater percentage of total ET, varying from 53 to 77%. In this orchard, E_s ranged from 1.08 mm day^{-1} in winter to 3.15 mm day^{-1} in summer. As discussed above, in the intermediate orchard a significantly greater amount of solar radiation penetrated to the orchard floor between tree rows, resulting in a lush grass cover between rows, which would contribute significantly to evaporation from the orchard. This was also apparent in the non-bearing orchard, which had a low canopy cover and significant vegetation within the tree row and between the rows. In this orchard E_s contributed to between 95 and 98% of ET. In this orchard the highest rates of E_s were observed and they varied between 2.10 mm day^{-1} in winter and 3.63 mm day^{-1} in summer. This again emphasises the high non-beneficial consumptive water use in young orchards and that potential water savings could be made in these orchards by reducing this fraction of orchard ET.

Table 4.2: Details of evapotranspiration (ET) and evaporation (E_s) estimates, together with rainfall received and irrigation applied for the mature, intermediate and non-bearing avocado orchards in Howick. N = number of measurement days.

Orchard	Season	Average E_s (mm day^{-1})	Average ET (mm day^{-1})	%E_s of ET	Rain (mm)	Irrigation (mm)
Mature (N=540)	Spring	0.45	2.11	20	193	35#
	Summer	0.60	2.57	22	473	0
	Autumn	0.35	2.26	11	566	0
	Winter	0.11	1.58	6	106	130
Intermediate (N=622)	Spring	2.31	3.19	68	194	0
	Summer	3.15	4.28	77	784	0
	Autumn	1.94	3.01	68	595	1
	Winter	1.08	1.88	53	106	34
Non-bearing (N=393)	Spring	3.46	3.51	98	284	28
	Summer	3.63	3.71	98	458	0
	Autumn	2.93	3.03	97	279	0
	Winter	2.10	2.17	95	32	81

#The irrigation sensor in the intermediate orchard failed in November 2018

It should also be noted that rainfall in this region is quite high (average rainfall for the three seasons was 1090 mm) and although it is a summer rainfall region, some rain was still received in winter. This contributed significantly to water available for evaporation in the orchards, with E_s rates often being elevated following rainfall events in all three orchards (Figure 4.15). As a result of this high rainfall, very little irrigation occurs on this farm, with the majority of irrigation occurring during the dry winter months. In these months an increase in E_s is associated with irrigation events in the intermediate and non-bearing orchards. The same trend is not evident in the mature orchard, probably reflecting that the wetted area from the microsprinklers is within the area shaded by the trees. The seasonal variation in E_s is evident in all three orchards with higher rates in summer than winter.

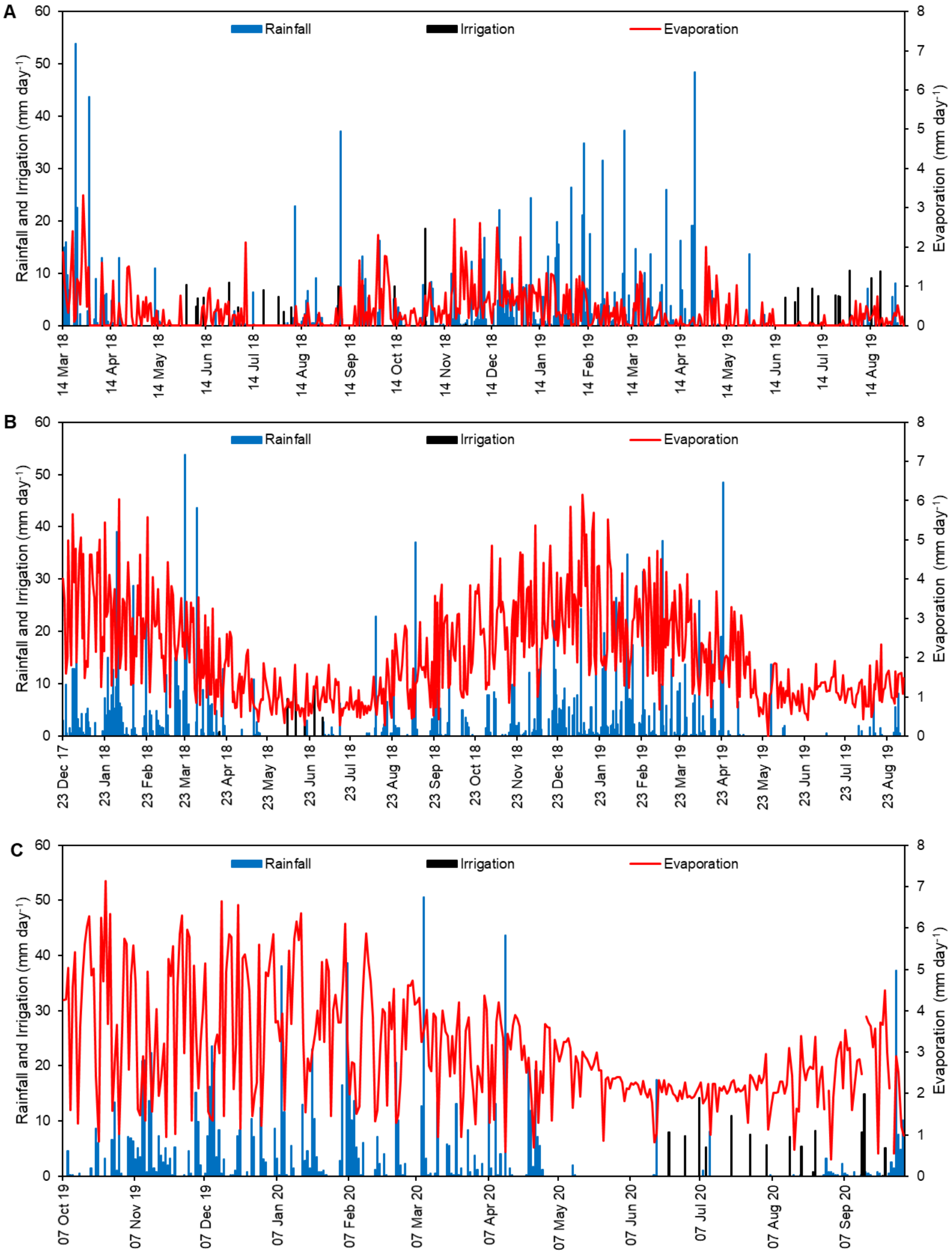


Figure 4.15: Evaporation, rainfall and irrigation in the A) mature avocado orchard B) the intermediate avocado orchard and in the C) non-bearing avocado orchard in Howick

Importantly, this is one of the first studies to determine transpiration volumes of avocado trees on a seasonal basis. Transpiration rates were fairly low with seasonal E_c ranging from 11.5 mm to 678 mm from the smallest trees to the largest trees. By comparing E_c with ET_o for the three orchards with larger trees, it is clear that E_c and ET_o do not always increase at the same rate, which implies that avocado E_c is not solely driven by atmospheric evaporative demand and that there may be some physiological control over transpiration, as seen for citrus (Taylor et al., 2015). It is therefore important to evaluate the response of avocado E_c to environmental variables in order to choose the most appropriate method to model avocado water use.

4.1.4 TRANSPIRATION RESPONSE TO ENVIRONMENTAL VARIABLES AND ECOPHYSIOLOGY

Gaining a clear understanding of the weather variables driving E_c of avocado is important for developing robust water use models and for irrigation research, but it is also important for aiding in site selection for new orchards, as E_c is intimately linked to dry matter production. Whilst there was research on plant water relations and gas exchange from the 1970s to early 1990s, there have been very few publications examining water use patterns of avocado trees, which is critical for managing water in avocado orchards. Current irrigation scheduling is based on evidence from studies looking at simple water balances and from general experience in the industry.

When examining the response of daily transpiration to daily weather conditions for three different orchards located in two different regions, it is evident that for many of the variables there was an initial linear increase of E_c with an increase in the variable, but at higher levels the rate of increase in E_c slowed relative to the increase in the variable (Figure 4.16). This was particularly noticeable for VPD and ET_o. As soil water was unlikely to be limiting during the study (as indicated by soil water measurements and predawn leaf water potential), this response indicates that E_c of avocado trees may regulate water loss under high evaporative demands, suggesting that it is more a supply-limited system than a demand-limited system. A supply-limitation implies that the rate of transport of water from the root to the leaves cannot match the rate of water loss from the leaves, as determined by the water potential gradient out of the leaf. As a result stomata start to close to limit water loss and prevent embolism formation (Campbell and Turner, 1990, Sperry et al., 2002). This has previously been reported for citrus (Taylor et al., 2015, Vahrmeijer and Taylor, 2018). The rate of increase of daily E_c decreased as daily VPD increased above 0.5-1.0 kPa for all three orchards. For ET_o, the change in the rate of increase of E_c occurred at approximately 2 mm day^{-1}. However, unlike VPD where the rate of increase decreased significantly after the threshold value, E_c still increased when ET_o was above 2 mm day^{-1}. The ratio between ET_o and E_c therefore varied with prevailing weather conditions and not just canopy size and this should be considered if a crop coefficient approach is used to estimate water use of avocado orchards. The response of E_c to increases in R_s and T_{air} was more consistent within the entire range of these variables, with E_c typically showing a steady increase as R_s and T_{air} increased. However, the response to these variables was more scattered, possibly indicating that at higher levels of both of these variables, they are not placing a limit on transpiration.

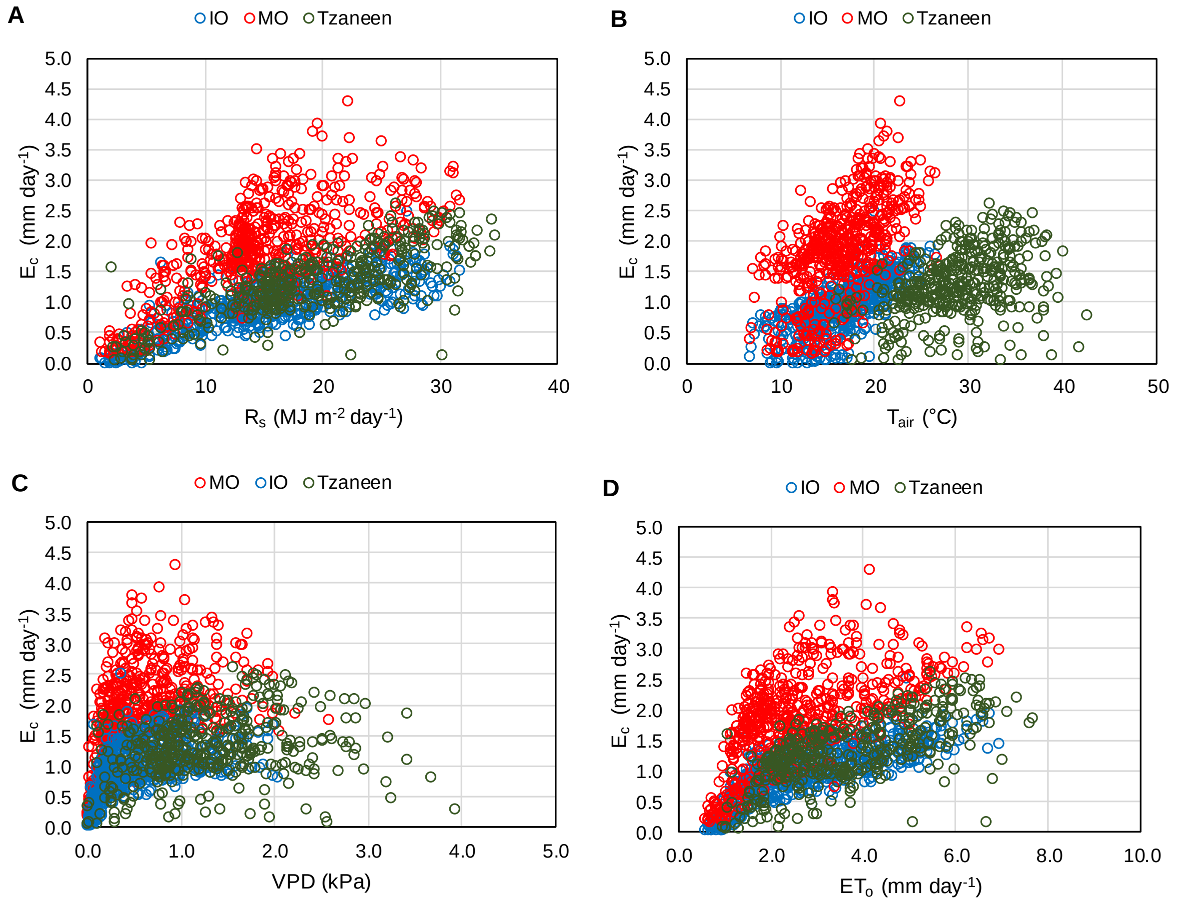


Figure 4.16: Relationship between daily transpiration (E_c) and (A) solar radiation (R_s), (B) air temperature (T_{air}), (C) vapour pressure deficit (VPD) and (D) reference evapotranspiration (ET_o), for the mature (MO) and intermediate (IO) avocado orchards in Howick and the orchard in Tzaneen.

Examining the daily response is important as water use modelling for irrigation scheduling is performed on a daily basis. However, as a daily average can hide the variation in these variables that determine E_c rates it is also important to evaluate hourly responses. Importantly, most canopy conductance models are run on an hourly basis in order to capture diurnal variation. Once again it is evident that E_c did not increase at the same rate as increases in VPD and ET_o and in the case of VPD it is clear that when considering maximum E_c values at each VPD level, there is a short initial increase in E_c, but at very low levels of VPD E_c starts to decrease with increasing VPD. The response to ET_o is particularly evident in the Tzaneen orchard, where significantly high values of hourly ET_o occurred. The threshold hourly ET_o value at which the rate of increase of E_c decreased was approximately 0.5 mm h^{-1}. This level was not reached in the orchard in Howick and therefore this could explain why the same decrease in E_c was not observed. A decrease in the rate of increase of E_c at R_s levels above approximately 4 MJ m^{-2} h^{-1} was observed in the orchard in Tzaneen. The clear responses to these variables suggests that the use of a canopy conductance model taking into account weather variables, such as Jarvis (1976), might provide reasonable estimates of transpiration in avocado orchards.

Furthermore, E_c responses to VPD_{air} and ET_{or} demonstrated that maximum E_c ($E_{c\ max}$) in all three orchards increased and decreased at varying rates in response to increases in the respective environmental parameters (Figure 4.18). Maximum E_c was achieved at the 0-1.0 kPa range in Howick, whilst in Tzaneen $E_{c\ max}$ was reached at the 1.5-2.0 kPa range. Maximum E_c in the IO was 2.51 mm day^{-1}, 4.31 mm day^{-1} in the MO and 2.63 mm day^{-1} in the orchard in Tzaneen, reflecting the differences in canopy size between the different orchards. A significant drop in $E_{c\ max}$ was noted in the mature orchard in Howick as VPD increased above 1.0 kPa. The response of $E_{c\ max}$ to increasing ET_o was much more variable than that to VPD. However, when examining the average response to increases in ET_o, it is evident that the initial rate of increase of E_c is not sustained and the rate of increase decreases as ET_o increases. This further suggests that avocado may be a supply limited system rather than a demand limited system. What is also noticeable from these responses is the differences in $E_{c\ max}$ between different orchards, which reflects differences in canopy size and emphasises the importance of accurate estimates of canopy size when estimating water use.

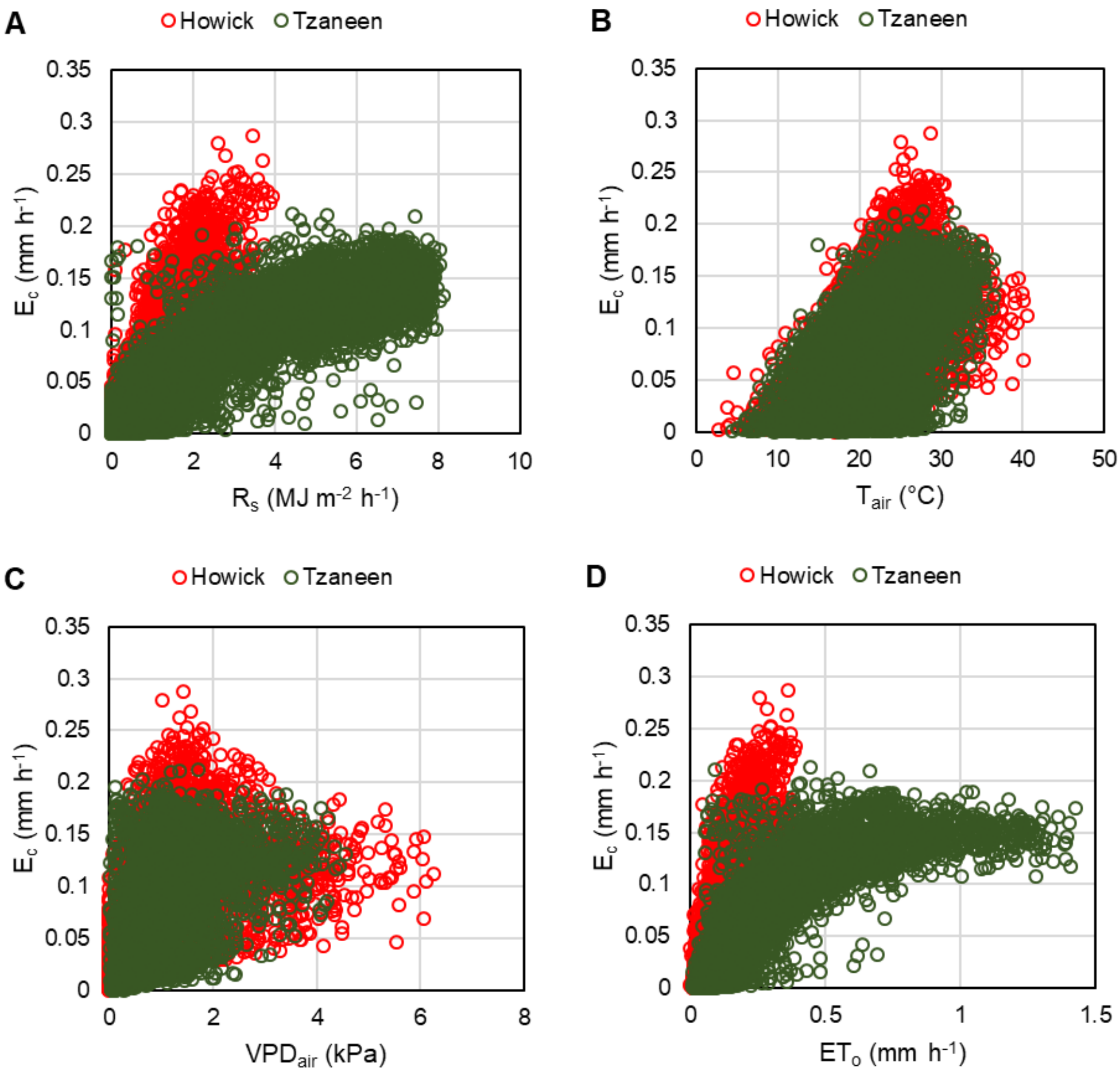


Figure 4.17: Relationship between daytime hourly transpiration (E_c) and (A) solar radiation (R_s), (B) air temperature (T_{air}), (C) vapour pressure deficit (VPD) and (D) reference evapotranspiration (ET_o) for the intermediate avocado orchard in Howick and the mature orchard in Tzaneen. Hourly variables for Howick were measured on the mast above the orchard, whilst for Tzaneen these hourly variables were measured at the weather station.

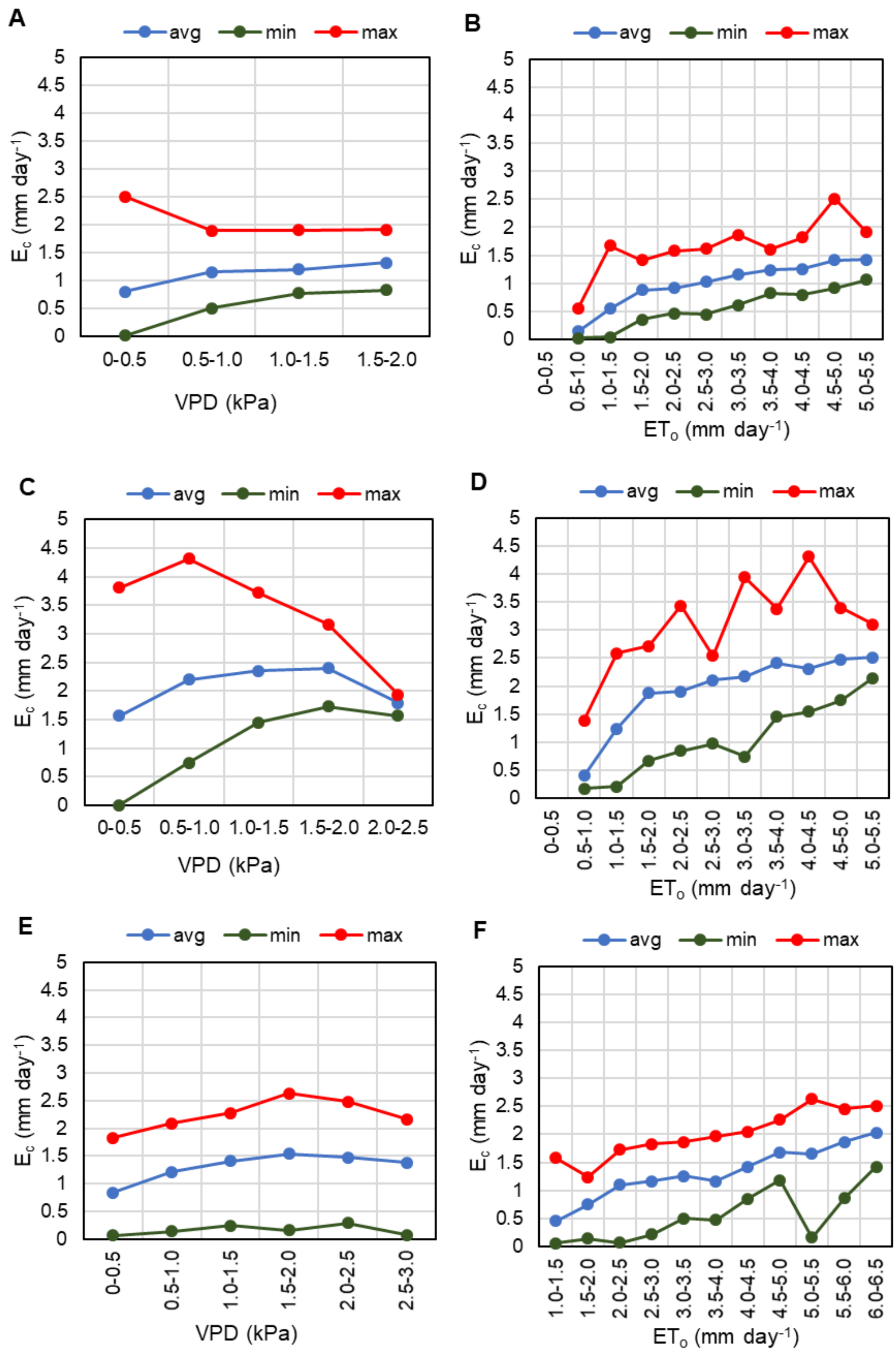


Figure 4.18: Average, maximum and minimum transpiration (*E_c*) of A & B) intermediate avocado trees in Howick, C & D) mature avocado trees in Howick, and E & F) mature avocado trees in Tzaneen in response to (A, C & E) vapour pressure deficit (VPD_{air}), and (B, D & F) reference evapotranspiration (ET_o) across two cropping seasons for the orchards in Howick and one cropping season for the orchard in Tzaneen

Importantly, water stress would have impacted the response of trees to environmental variables and E_c would typically be reduced under these conditions. In order to assess if the trees were water stressed during the course of the trial, predawn water potential (ψ_{pd}) measurements were taken at set intervals for the duration of the trial in the intermediate orchard (Figure 4.19). Average ψ_{pd} for the measurement period was -0.15 ± 0.09. Whilst there was a fair amount of variation in ψ_{pd}, it is unlikely that the orchard would have been stressed. Although no ψ_{pd} thresholds for stress in avocados have been established, previous studies suggest that stomatal conductance (g_s) is unaffected until leaf water potential (ψ_{leaf}) approaches -0.4 MPa, with g_s rapidly declining as ψ_{leaf} reaches -1.0 to -1.2 MPa (Bower, 1985, Bower et al., 1977, Whiley et al., 1988).

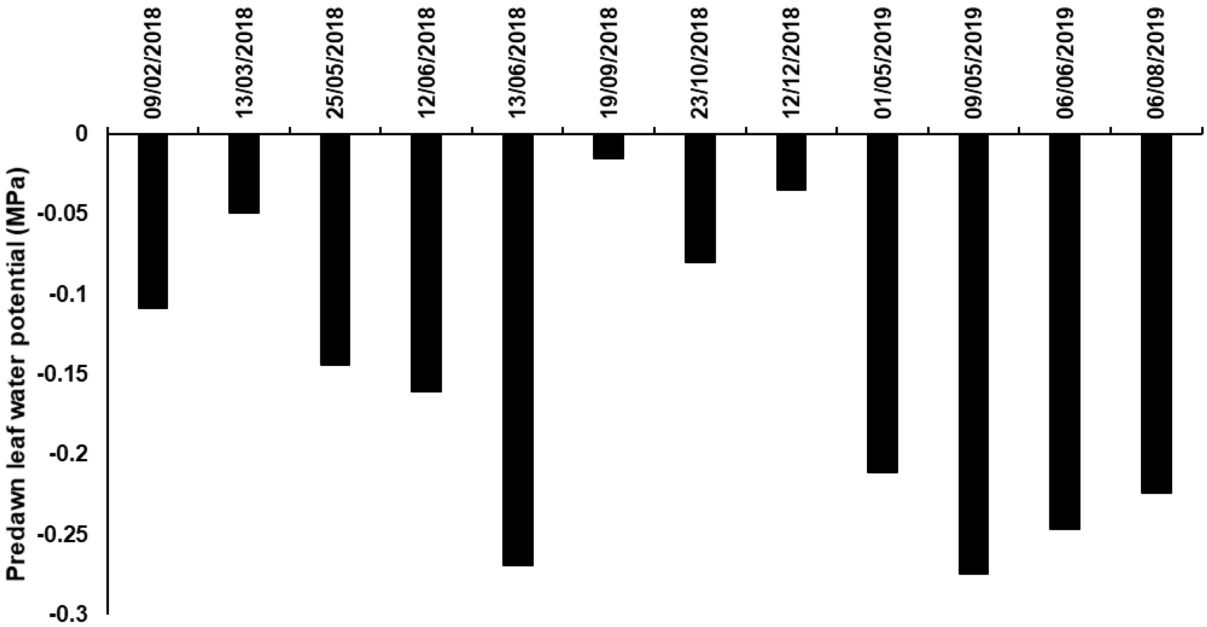


Figure 4.19: Predawn water potentials for the intermediate orchard in Howick across the measurement period

4.1.5 WATER USE EFFICIENCY AND WATER USE PRODUCTIVITY

The details of the gross sale price per carton for the different grades of avocado fruit are found in Table 4.3 for 2018 and 2019. The average price per carton and kg fruit was considerably higher in 2019 than in 2018, as is to be expected as 2018 was an "on" year for South Africa with high production volumes, whilst 2019 was an "off" year with lower production. Price was also highly dependent on the grade of fruit, which once again emphasises the need for growers to produce high quality fruit.

Table 4.3: Gross sale price per carton (R) and kg of avocado fruit for the 2018 and 2019 seasons

	2018		2019	
	Price \4 kg carton	**Price \ kg**	**Price \ 4 kg carton**	**Price \ kg**
Grade 1 (Export)	R124.63	R31.16	R212.17	R53.04
Grade 2 (Local)	R40.84	R10.21	R78.84	R19.71
Grade 3 (Factory)	R10	R2.50	R11.8	R2.95

In the intermediate orchard yield increased significantly from the 2017/2018 season (with reference to the period of water use measurements) to the 2018/2019 season from 12 857 kg to 18 658 kg (Table 4.4). However, the yield of first grade fruit did not differ much between the two seasons. There was significantly more second and third grade fruit in the second season. However, due to both the higher volumes of fruit and higher prices in 2018/2019, the gross profit per hectare increased from R331 245 to R611 217. The increase in yield in the 2018/2019 season could reflect the alternate bearing nature of avocado orchards, but as this orchard has not yet reached maturity, it could also reflect increased production as the trees grow.

Table 4.4: Yield per grade of fruit and income earned for the 2017/18 and 2018/19 seasons in an intermediate avocado orchard in Howick, based on gross price.

	2018		2019	
Grade	**Yield (kg/ha)**	**Price**	**Yield (kg/ha)**	**Price**
1	10400	R324 038.00	10366.08	R549 842.80
2	138	R1 408.98	2202.37	R43 408.71
3	2319.34	R5 798.35	6090.12	R17 965.85

Yield in the mature orchard in Howick was very similar to that of the intermediate orchard in the 2017/18 season, but the yield of grade 1 fruit was lower and as a result total gross profit from this orchard was R246 140, which was lower than from the intermediate orchard (Table 4.5). In the 2018/19 season yield was significantly lower in the mature orchard than the intermediate orchard, with a slightly higher percentage of first grade fruit in the intermediate (55%), as opposed to the mature orchard (51%). As a result, the gross profit in the 2018/19 season was lower in the mature orchard than the intermediate orchard.

Table 4.5: Yield per grade of fruit and income earned for the 2017/18 and 2018/19 seasons in a mature avocado orchard, based on gross price

	2018		2019	
Grade	**Yield (kg/ha)**	**Price**	**Yield (kg/ha)**	**Price**
1	7334.86	R228 535.90	6163.35	R326 919.41
2	627.10	R6 402.69	2175.30	R42 875.15
3	4480.55	R11 201.38	3746.35	R11 051.73

Evapotranspiration for the two seasons in the intermediate orchard was very similar (1087-1152 mm for the 12 month period from September to September). As a result of the increased yield in the second season, WUE_{ET} was higher in the 2018/2019 season (1.62 kg m^{-3}) than the 2017/2018 season (1.18 kg m^{-3}) (Table 4.6). Water use productivity was also higher in the second season as a result of the increased yield and higher prices for this season and varied from R30.47 m^{-3} to R53.06 m^{-3}. Interestingly, the amount of water evapotranspired for every kg of fruit produced was 845 L kg^{-1} in the first season and 617 L kg^{-1} in the second season. This is considerably lower than the 2000 L per kg reported in the popular press, but doesn't take into consideration all the water used in production, which includes water in the packhouse and for spray applications. In addition, if you consider an average fruit mass of 250 g, then it takes approximately 150-200 L to produce a single avocado in this orchard.

Table 4.6: Parameters used in the calculation of water use efficiency (WUE_{ET}) and water use productivity (WUP_{ET}) across two cropping seasons for the intermediate avocado orchard, based on evapotranspiration (ET) measurements.

	2017/2018 Season	2018/2019 Season
Total ET (mm)	1087	1152
Total ET (m^3)	10870	11520
Total Yield (kg ha^{-1})	12857	18659
Total Net Income (R ha^{-1})	R331 245.33	R611 217.37
WUE_{ET} (kg m^{-3})	1.18	1.62
WUP_{ET} (R m^{-3})	30.47	53.06

Based on a SAAGA production cost calculator for 'Hass' type cultivars where production costs were estimated at R42 062 per ha for year 5 and R45 746 per ha for year 6, adjusted WUP_{ET}, considering production costs, would be R26.60 m^{-3} for the 2017/18 season and R49.08 m^{-3} for the 2018/19 season.

Evapotranspiration in the mature orchard was 1009 mm for the 12 month period from September 2017 to September 2018 and 752 mm for the same period in 2018-2019. As a result of the slightly lower yield and lower ET, WUE_{ET} in the mature orchard was 1.23 kg m^{-3}, in the first season, which was marginally higher than the intermediate orchard (Table 4.7). However, due to the lower volume of grade 1 fruit from the mature orchard, WUP_{ET} was lower in the mature orchard, with a value of R24.39 m^{-3}. In the second season due to lower ET and only slightly lower yield, WUE_{ET} increased to 1.61 kg m^{-3} and due to better prices WUP_{ET} increased to R50.64 m^{-3}. To produce 1 kg of fruit 622-810 L of water was required, based on evapotranspiration. If you consider an average fruit size of 250 g, then it takes approximately 150-200 L to produce a fruit, which is the same as for the intermediate orchard.

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Table 4.7: Parameters used in the calculation of water use efficiency (WUE_{ET}) and water use productivity (WUP_{ET}) in a mature avocado orchard across two cropping seasons in 2017/2018 and 2018/2019. Values are calculated using evapotranspiration.

	2017/2018 Season	2018/2019 Season
Total ET (mm)	1009	752
Total ET (m^3)	10090	7520
Total Yield (kg ha^{-1})	12 442	12 085
Total Net Income (R ha^{-1})	R246 140	R380 846
WUE_{ET} (kg m^{-3})	1.23	1.61
WUP_{ET} (R m^{-3})	24.39	50.64

Based on a SAAGA production cost calculator for 'Hass' type cultivars where production costs for year 10 were estimated at R50 311 (oldest orchard estimate available), adjusted WUP_{ET}, considering production costs, would be R19.40 m^{-3} for the 2017/18 season and R43.95 m^{-3} for the 2018/19 season.

When considering WUE_T and WUP_T based on transpiration values during the 2018/19 season it was evident that the lower transpiration rates and slightly higher yields in the intermediate orchard resulted in much high WUE_T and WUP_T in this orchard when compared to the mature orchard (Table 4.8). In the intermediate orchard WUE_T was 5.2 kg m^{-3} was and WUP_T was R170.26 m^{-3}. This was compared to 1.78 kg m^{-3} and R56.17 m^{-3} in the mature orchard.

Table 4.8: Parameters used in calculation of transpiration water use efficiency (WUE_T) and water use productivity (WUP_T) in a mature avocado orchard across two cropping seasons in the 2018/2019 season. Transpiration volumes were used for these calculations.

	Intermediate Orchard	Mature Orchard
Total T (mm)	359	678
Total T (m^3)	3590	6780
Total Yield (kg ha^{-1})	12 442	12 085
Total Net Income (R ha^{-1})	R246 140	R380 846
WUE_T (kg m^{-3})	5.2	1.78
WUP_T (R m^{-3})	170.26	56.17

Water use efficiency (based on evapotranspiration) values reported for avocado in this study fall within the range of those reported in literature of between 0.7 and 3.2 kg m^{-3} (Aleemullah et al., 2001, Kurtz et al., 1992, Lahav et al., 1992) and that suggested by Carr (2013) of between 1 and 2 kg fruit m^{-3} (based on relatively low yields of between 9-10 t ha^{-1}). These reported values have largely been based on irrigation volumes and not on measured ET and thus the values reported in this study represent an important contribution to knowledge.

4.1.6 CONCLUSIONS

There have been very few systematic attempts to quantify water use of avocado orchards on a seasonal basis and for different sized canopies. This study represents a significant contribution to our understanding of avocado orchard water use. As with many other tree crops, E_c is largely dependent on canopy size. However, as with many other subtropical evergreen tree crops, weather variables also play a large role in determining orchard water use, but this relationship varies depending on how hot and dry it is. Preliminary data suggests that there is a threshold for VPD and ET_o at which the rate of increase of E_c with these variables starts to decrease, which possibly reflects physiological control over transpiration.

There were also significant periods during the study when ET and E_c measurements overlapped and this has provided great insight into the partitioning of ET into E_c and E_s in avocado orchard, which is also likely applicable to a wide range of orchards. When canopy cover is less than 70%, E_s composes a significant proportion of total ET, which will also increase depending on the vigour of the vegetation between the tree rows. Importantly in young orchards the vast majority of ET consists of evaporation from the soil and transpiration from the other vegetation in the orchard. Understanding the water balance in these orchards could go a long way to making water savings, especially during very dry years when water quotas are reduced.

Translating all this orchard specific information into water use models for various applications is critical to make this information useful to growers, consultants, grower associations and governmental departments. Models that are easier to use and provide information for strategic decisions need to considered, together with those models that provide accurate estimates on shorter time scales for tactical decision making.

4.2 MODELLING AVOCADO WATER USE

4.2.1 PARAMETERISATION AND VALIDATION OF A CROP COEFFICIENT MODEL

Crop coefficients (K_c) were determined for the orchards in Howick in which ET measurements were made (Figure 4.20). Despite differences in size between the three orchards, crop coefficients for the three orchards were very similar, as suggested by the very similar seasonal ET for the three orchards. However, the E_c component of ET differed substantially between the three orchards, suggesting that the E_s component also differed substantially. Using a single K_c for the three different orchards might result in fairly accurate estimates of ET, but this would not be suitable for irrigation scheduling. There was also more variation in K_c values (Figure 4.20) than K_t values (Figure 4.21 A & B), which possibly reflects the varying rate of E_s, which is influenced by surface wetting as a result of irrigation and rainfall. This is why Kool et al. (2014) proposed that modelling approaches should consider E_c and E_s separately.

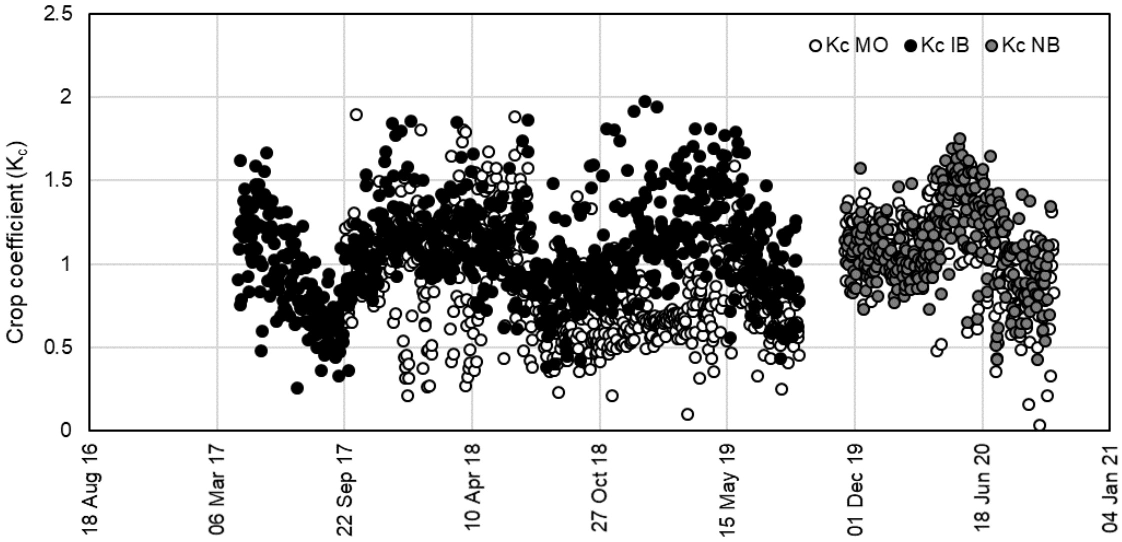

Figure 4.20: Crop coefficients (K_c) for the orchards in which evapotranspiration measurements were conducted in Howick. Mature orchard (MO), intermediate orchard (IO) and NB non-bearing orchard (NB)

Transpiration crop coefficients (K_t) were determined over two seasons in both the MO and IO orchards in Howick (Figure 4.21 A) and over one season in Tzaneen (Figure 4.21 B). In all three orchards values were typically higher in winter than in summer, which has been previously noted for citrus (Taylor et al., 2015). Importantly the trend was the same for all three orchards. Transpiration crop coefficients for the three orchards reflected differences in canopy size between the three orchards, but although the trees in Tzaneen had a larger canopy cover than the intermediate orchard in Howick the K_t values were very similar (Figure 4.21 C).

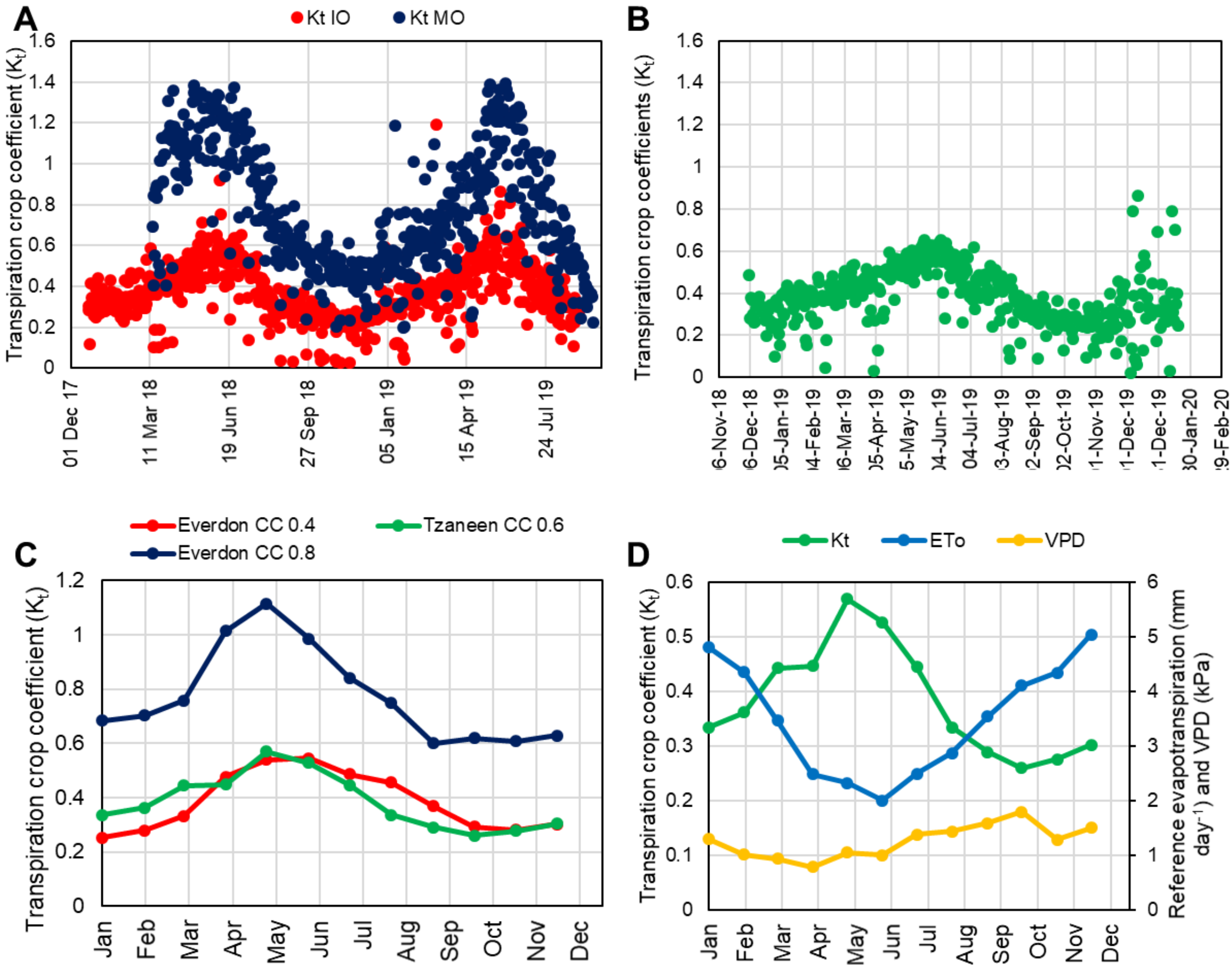

Figure 4.21: A) Transpiration crop coefficients (K_t) for the mature (MO) and intermediate orchard (IO) in Howick, B) K_t values for the orchard in Tzaneen, C) monthly comparison of K_t values for the three orchards and D) comparison of monthly K_t values for the orchard in Tzaneen with monthly vapour pressure deficit (VPD) and reference evapotranspiration (ET_o).

Monthly average K_t values for the mature orchard varied between 0.60 and 1.11, between 0.25 and 0.53 for the intermediate orchard and between 0.26 and 0.57 for the orchard in Tzaneen. The values for the two orchards with the lower canopy cover are comparable to values suggested by Carr (2013) of between 0.4 and 0.6, but these were suggested for mature orchards and were a K_c and not a K_t. The lack of agreement between different studies for crop coefficients is not surprising as these values are often orchard specific and vary according to canopy height, ground cover, tillage, leaf area index, method of estimating reference evapotranspiration, microclimate, irrigation method and frequency and method of measuring crop evapotranspiration (Naor et al., 2008, Snyder and O'Connell 2007). The reason for the higher K_t values during winter than summer is most probably related to the response of E_c to ET_o and VPD discussed in the previous section. It is evident from Figure 4.21 D that in Tzaneen, the highest values of K_t corresponded to the lowest values of ET_o and VPD and vice versa. This again suggests some kind of physiological control over transpiration and the method proposed by Allen and Pereira (2009) may be ideal for adjusting crop coefficients for different orchards.

As crop coefficients are usually orchard specific, it is critical to be able to determine a unique set of crop coefficients for each orchard. Allen and Pereira (2009) proposed a method to do this using fraction of ground cover and height. These authors also proposed a method for adjusting crop coefficients for crops exhibiting greater stomatal control over transpiration than most other agronomic crops, which was tested in citrus (Taylor et al., 2015), peaches (Paço et al., 2012) and apples (Mobe et al., 2020). Allen and Pereira (2009) suggested r_{leaf} (300 s m^{-1} for the initial and mid-season and 400 s m^{-1} for the end of the season) and M_L (2.0) values to use for avocado, together with orchard specific estimates of canopy height and fractional cover. When assessing these values, it was found that an M_L of 2.0 was too high and thus for all further applications, a value of 1.5 was used. When applying these values on a monthly basis to the avocado orchards in this study, it was evident that the method provided poor estimates of K_t for these orchards (Figure 4.22).

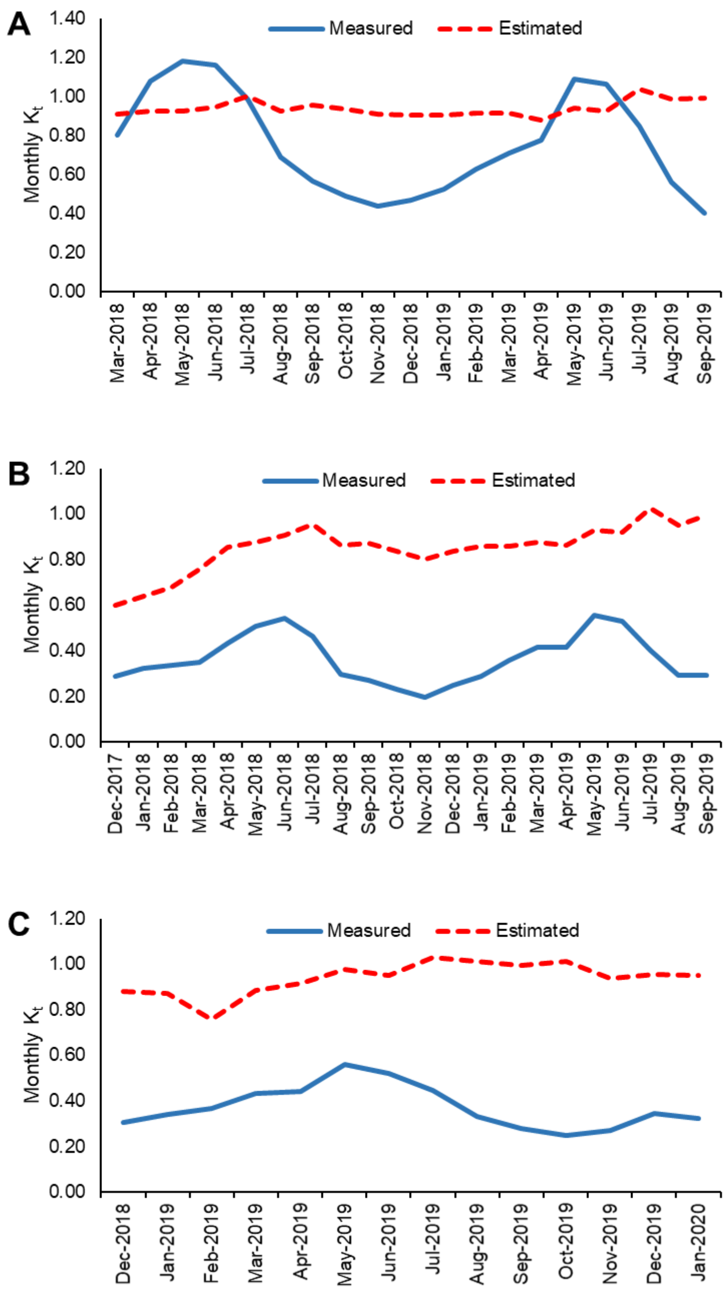

Figure 4.22: The estimation of monthly transpiration crop coefficients (K_t) in avocado orchards. A) Mature avocado orchard in Howick, B) intermediate avocado orchard in Howick and C) the avocado orchard in Tzaneen, using parameters suggested for avocado by Allen and Pereira (2009).

In the mature orchard K_t values were underestimated in winter, but overestimated in summer (Figure 4.22 A). When compared on a monthly basis these inaccuracies in K_t estimations using the parameters suggested by Allen and Pereira (2009) resulted in very poor estimates of transpiration as indicated by statistical parameters (MAE=67%, RMSE=38.4 mm and D=0.22) (Figure 4.23 A). If these K_t values were used over a year (April 2018 to March 2019) there would have been a 36% overestimation of transpiration. For both the orchards with an intermediate canopy cover (intermediate = 0.5, Tzaneen = 0.6) K_t values were overestimated throughout the study period (Figure 4.22 B & C) and this resulted in very poor estimations of monthly transpiration (Figure 4.23 B & C). In the intermediate orchard in Howick annual transpiration (January 2018 to December 2018) was overestimated by 144% and in the orchard in Tzaneen by 154% (January 2019 to December 2019). These poor estimations using a fixed estimate of r_{leaf} is perhaps not surprising as Taylor et al. (2015) demonstrated that a fixed estimate of r_{leaf} resulted in poor estimates of citrus water use. A similar need to adjust the r_{leaf} was found for apple orchards in the Western Cape Province of South Africa (Mobe et al., 2020). As a result, r_{leaf} was estimated in the three avocado orchards on a daily and monthly basis using measured transpiration, weather variables and canopy dimensions.

Following the estimation of r_{leaf} using average monthly data it was evident that r_{leaf} was typically significantly higher than the values of 300 s m^{-1} suggested for avocados by Allen and Pereira (2009), apart from late autumn and winter (April to July) in the mature orchard (Figure 4.24). In general, r_{leaf} values were higher in spring and summer than in winter, which reflects calculated K_t values, which were typically lower in summer than winter (Figure 4.22). Importantly, the same trend in r_{leaf} was found in all three orchards (Figure 4.24), which were located in two different regions and differed in canopy size and possibly reflects seasonal ET_o, as seen in the relationship between K_t values and ET_o in the orchard in Tzaneen (Figure 4.21 D). Seasonal and daily ET_o in summer were typically higher in Tzaneen than in Howick. A similar trend was also seen for VPD. This trend in r_{leaf} reflects the relationship between ET_o or VPD with E_c observed in Figure 4.16, where a plateau of E_c was reached at a threshold value of ET_o or VPD, suggesting some form of stomatal control over E_c. Although these calculated estimates of r_{leaf} could provide good estimates of K_t values and monthly transpiration in each of the respective orchards, it is the estimation of these values in orchards without measured transpiration that hinders the ease with which this approach can be used to accurately estimate transpiration for different avocado orchards.

As there seemed to be a good relationship between changing seasonal ET_o and r_{leaf} in the different avocado orchards and as a relationship between r_{leaf} and ET_o was used to derive estimates of r_{leaf} in citrus orchards (Taylor et al., 2015), a similar approach was evaluated in the avocado orchards in this study (Figure 4.25).

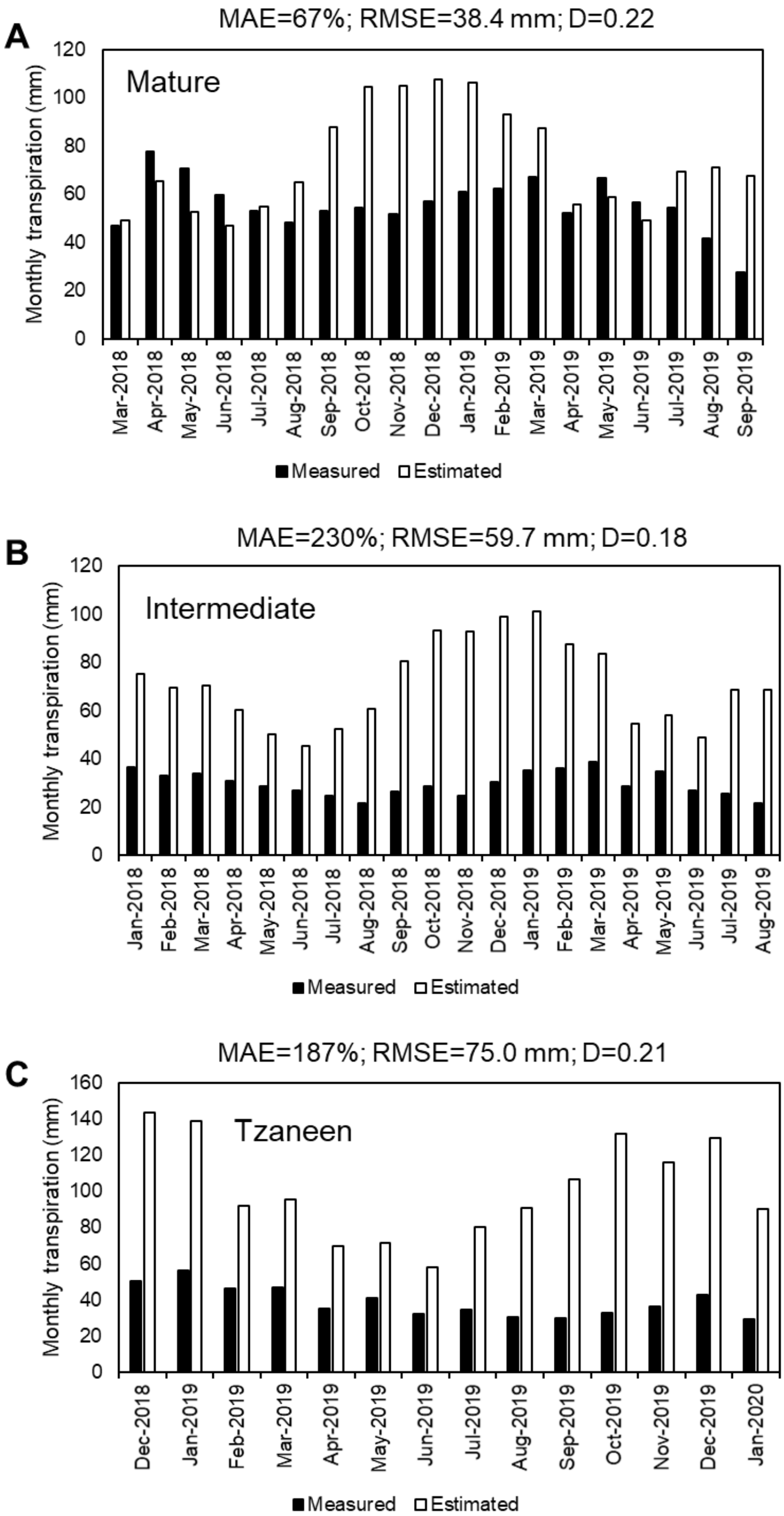

Figure 4.23: Monthly estimation of transpiration in the A) mature avocado orchard in Howick, B) intermediate avocado orchard in Howick and c) the avocado orchard in Tzaneen using the transpiration crop coefficient (K_t) values derived using the parameters suggested by Allen and Pereira (2009)

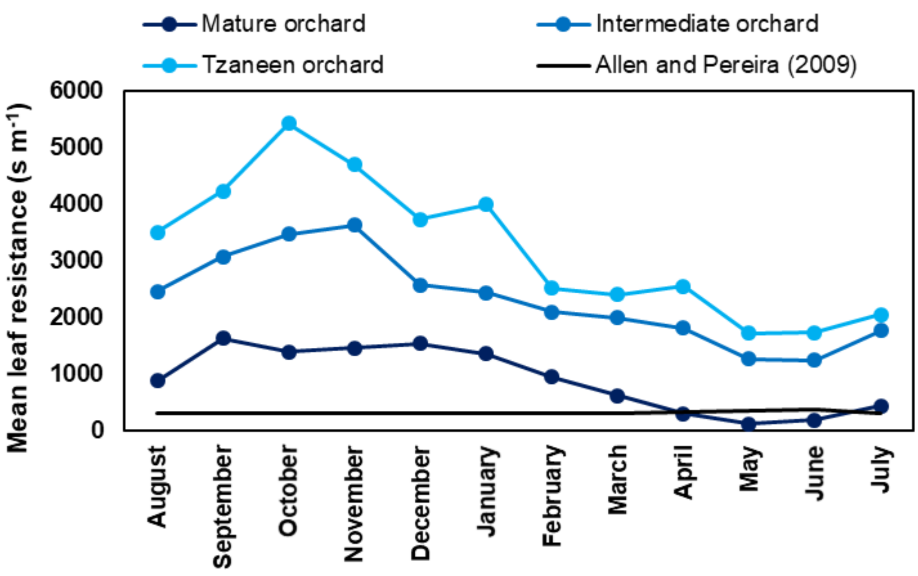

Figure 4.24: Monthly estimates of mean leaf resistance (r_{leaf}, s m^{-1}) from the three avocado orchards using the procedure outlined by Allen and Pereira (2009), compared with the value suggested by Allen and Pereira (2009) for avocado. Estimates were derived from monthly averages of the weather variables, canopy size and measured transpiration crop coefficients (K_t).

Unfortunately, this relationship was not consistent for the three orchards and only in the mature orchard was a relationship with a satisfactory R^2 value obtained (R^2=0.83). The slope of the line was very similar between the mature and intermediate orchards in Howick, but was fairly different for the Tzaneen orchard (Figure 4.25). In addition, the intercepts of these relationships were fairly different. This suggests that a single relationship derived from any orchard would not provide good estimates of r_{leaf} and therefore K_t in these orchards.

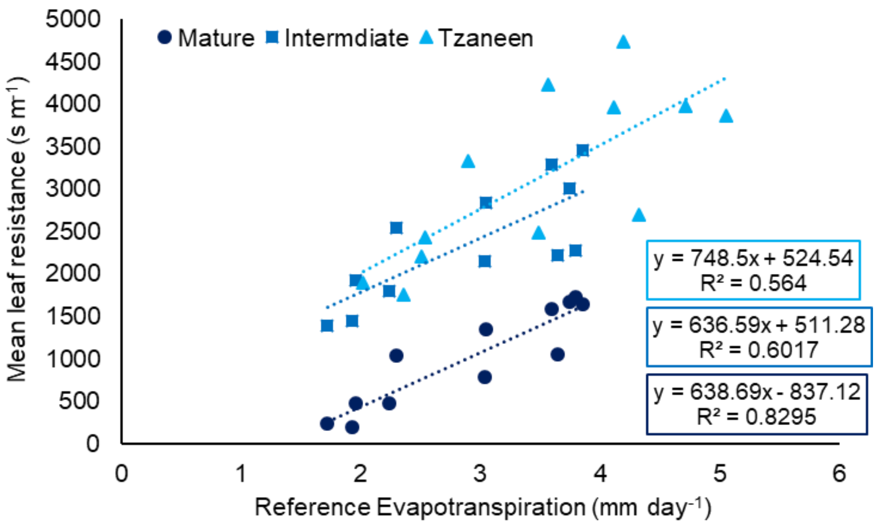

Figure 4.25: Relationship between monthly mean leaf resistance and reference evapotranspiration (ET_o) for the three avocado orchards

As the trend in r_{leaf} was similar for the different orchards, in order to try and provide improved seasonal estimates of water use, the $r_{leaf}/100$ term was replaced by $r_s/50$ for the F_r estimation in the two intermediate orchards, together with monthly r_{leaf} estimates from the mature orchard. Allen and Pereira (2009) suggest that for orchards where canopy cover is sparse (LAI<3 m^2 m^{-2}) the ratio $r_{leaf}/100$ can be replaced by $r_s/50$, where r_s is the estimated bulk canopy resistance for the full cover conditions. Although this approach provided better estimates of both K_t and as a result transpiration, the estimates in both intermediate orchards did not meet the statistical criteria for reasonable model performance (MAE>20% and D<0.8) (Figure 4.26). However, unsurprisingly monthly estimates of r_{leaf} from the mature orchard provided reasonable estimates of monthly transpiration across 19 months in this orchard, with a MAE of 17% and D=0.84 (Figure 4.26 A & B). Using this approach, transpiration over a single year was underestimated by 11% in the mature orchard and overestimated by 11% in the intermediate orchard in Howick and 34% in the orchard in Tzaneen. This approach therefore could not account for the differences between the three orchards. As the two intermediate orchards were of similar size, the monthly r_{leaf} values from the intermediate orchard in Howick were evaluated in the orchard in Tzaneen, in order to assess if a r_{leaf} based on fractional canopy cover could lead to better estimates of K_t values for improved seasonal estimates of transpiration required for planning purposes.

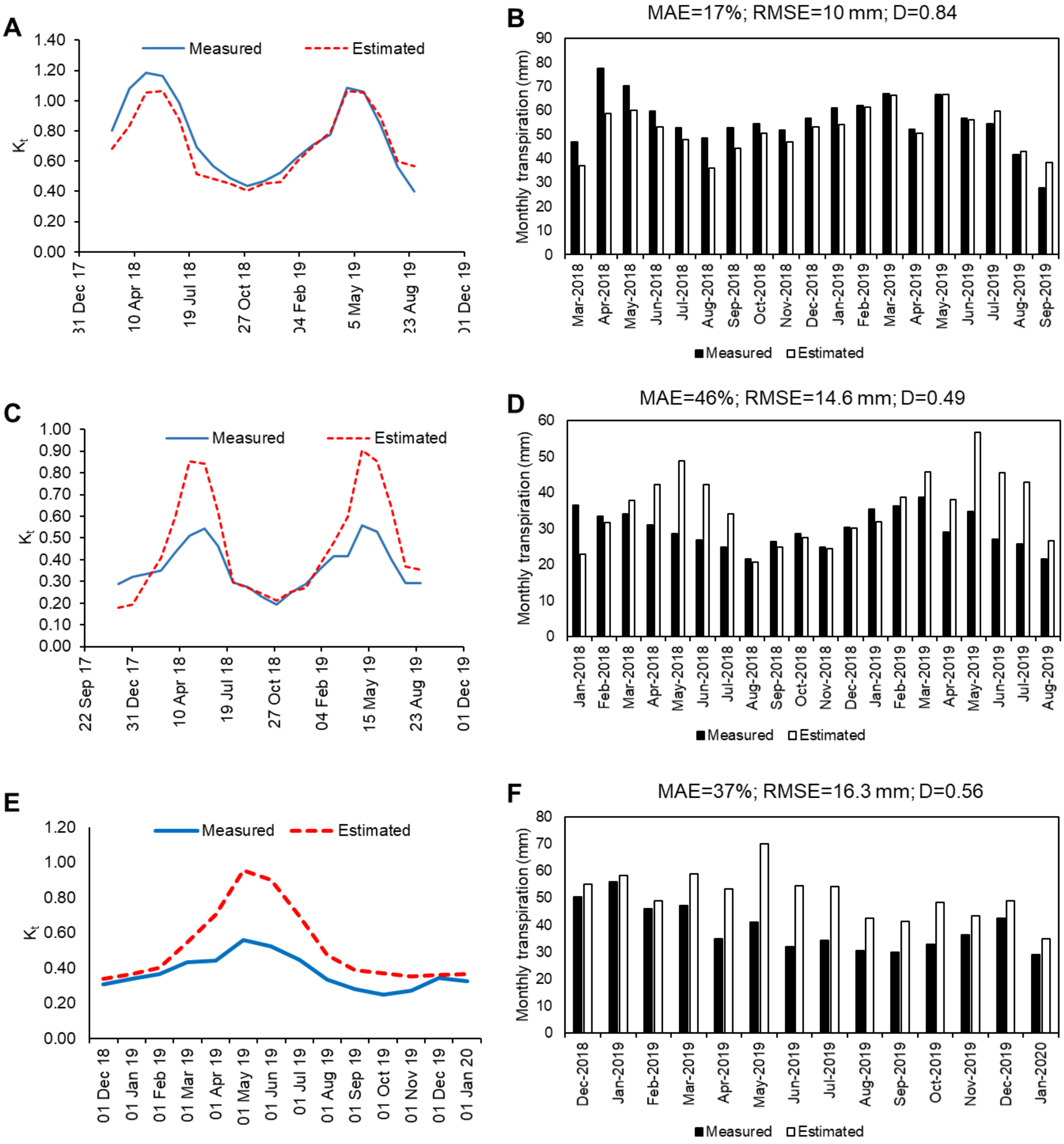

Figure 4.26: A, C and E) Monthly estimates of transpiration crop coefficients (K_t) and B, D, F) monthly estimates of transpiration using the K_t values calculated using monthly mean leaf resistance (r_{leaf}, s m^{-1}) values for the mature orchard and replacing $r_{leaf}/100$ by $r_s/50$ in the calculation of F_r for the intermediate orchard and Tzaneen orchard. A and B) Mature avocado orchard in Howick, C and D) intermediate avocado orchard in Howick and E and F) the avocado orchard in Tzaneen.

Estimates of monthly E_c were greatly improved in both the intermediate orchard in Howick and the orchard in Tzaneen, when using monthly estimates of r_{leaf}, determined in the intermediate orchard in Howick (Figure 4.27). Statistics indicated adequate model performance in the intermediate orchard in Howick, however, the performance of the model in the Tzaneen orchard just failed to meet the stipulated criteria for acceptable model performance. Annual transpiration (January 2018 to December 2018) was underestimated by 10% (34 mm) in the intermediate orchard in Howick and 18% (85 mm) in the Tzaneen orchard.

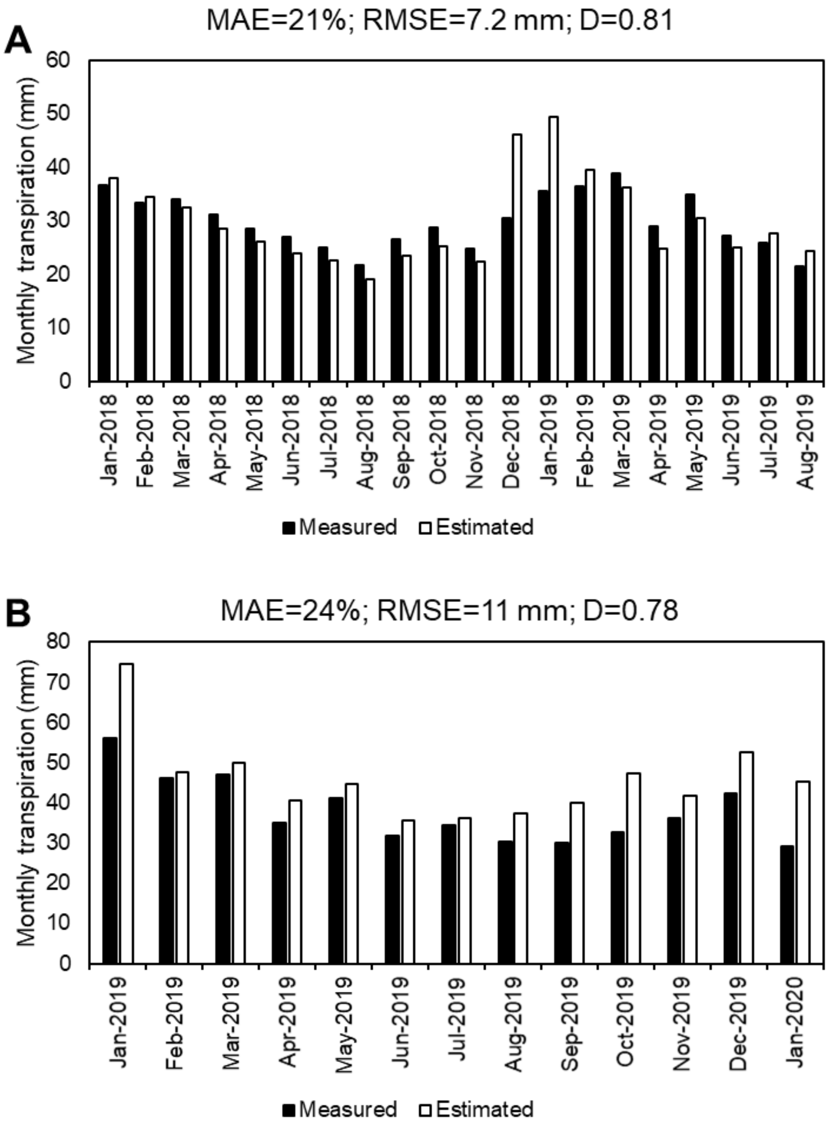

Figure 4.27: Monthly transpiration estimates for the A) intermediate orchard in Howick and B) orchard in Tzaneen using mean monthly estimates of mean leaf resistance (r_{leaf}, s m^{-1}) for the intermediate orchard in Howick.

Whilst still not sufficiently accurate to provide accurate estimates across all avocado orchards, this approach represents a significant improvement on previously suggested crop coefficients for avocado orchards provided in FAO-56 (Allen and Pereira, 2009, Allen et al., 1998) (Figure 4.28). The values provided in Table 4.9 can provide a starting point for seasonal transpiration estimates for avocado orchards with full or intermediate canopy cover that can assist with better planning for irrigation purposes.

Table 4.9: Values for monthly mean leaf resistance (r_{leaf}, s m^{-1}) and transpiration crop coefficients (K_t) to be used for orchards with close to full fractional canopy cover (f_c) and those orchard with a canopy cover (f_c) of 0.4-0.6

Month	r_{leaf} for f_c>0.85 (s m^{-1})	K_t	r_{leaf} for f_c=0.50 (s m^{-1})	K_t
January	1730	0.56	2272	0.33
February	1055	0.52	2226	0.32
March	779	0.45	2152	0.30
April	474	0.41	1796	0.27
May	193	0.45	1451	0.32
June	238	0.46	1397	0.37
July	471	0.60	1919	0.35
August	1039	0.69	2541	0.40
September	1348	0.81	2839	0.46
October	1586	1.06	3286	0.53
November	1645	1.06	3458	0.53
December	1673	0.89	3002	0.43

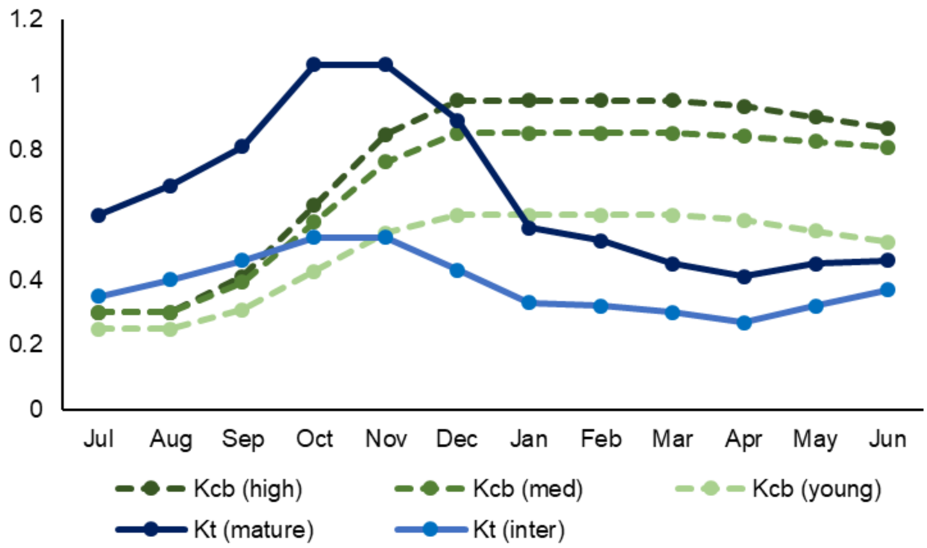

Figure 4.28: Comparison of transpiration crop coefficient (K_t) values determined for mature and intermediate orchards as compared to basal crop coefficients (K_{cb}) suggested for avocado orchards by Allen and Pereira (2009), with high canopy cover (K_{cb} high), medium canopy cover (K_{cb} med) and for young orchards (K_{cb} young).

The inability of this approach to derive appropriate K_t values for different orchards based on the estimation of r_{leaf} for avocado orchards is perhaps not surprising, as Allen and Pereira (2009) caution that the estimation of r_{leaf} using their procedure contains artefacts of the K_t measurements, weather data error and the constructs of equations estimating $K_{t\ full}$ and F_r.

However, what the approach does demonstrate is the important controlling role of leaf or canopy resistance in determining the transpiration rates of avocado trees, especially during the hot and dry spring and summer months. An approach able to provide better estimates of canopy conductance might therefore allow for better estimates of avocado transpiration.

4.2.2 PARAMETERISATION AND VALIDATION OF A CANOPY CONDUCTANCE MODEL

4.2.2.1 Estimates of E_c using a canopy conductance model in conjunction with the Penman-Monteith equation

In order to successfully estimate transpiration using the Penman-Monteith equation, reliable estimates of g_c and g_a are required, together with weather data. Whilst g_a can be estimated using windspeed and tree characteristics, such as height, it is the estimation of g_c that is more challenging. Jarvis (1976) proposed a method for estimating stomatal conductance by determining a maximum conductance and scaling this according to functions for solar radiation, VPD, air temperature and soil moisture content, which vary from 0-1. The usefulness of this approach to estimate g_c can be seen in Figure 4.29, where g_c of trees in the intermediate orchard is seen to vary in response to a number of factors. On days with lower solar radiation and VPD (20 January 2018), g_c is slightly higher, whilst diurnal transpiration and g_c respond clearly to changes solar radiation. On days with higher VPD it is evident that g_c is lower than on days with lower VPD (18 March 2018 and 25 July 2018). It is also evident that g_a is significantly higher than g_c, which results in a decoupling factor closer to 0, implying that the canopy is well coupled to the atmosphere.

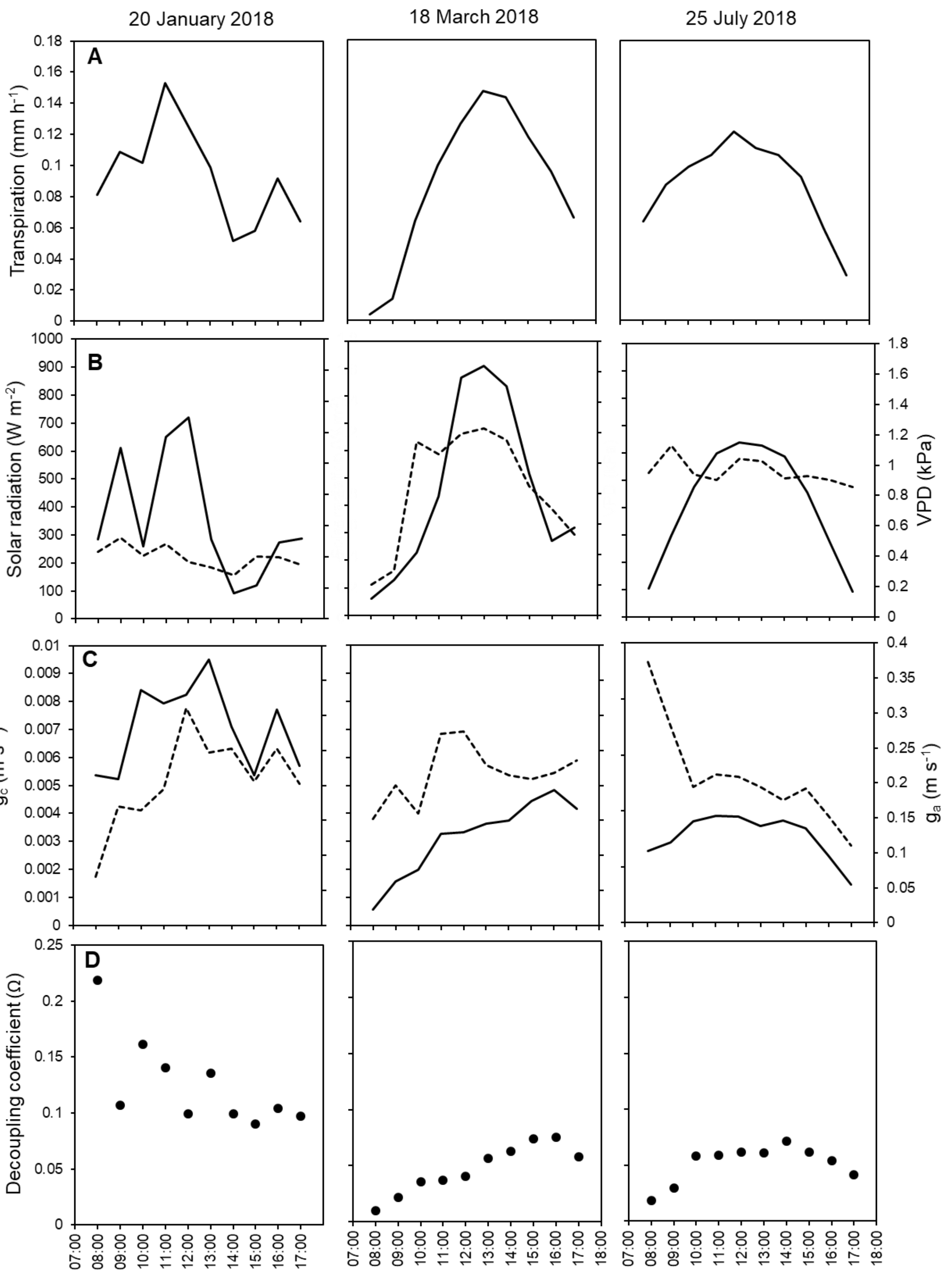

Figure 4.29: Diurnal variations in A) transpiration, B) solar radiation (solid line) and vapour pressure deficit (VPD, dotted line), C) canopy conductance (g_c, solid line) and aerodynamic conductance (g_a, dotted line) and D) the decoupling coefficient (Ω) in the intermediate orchard on three days 20 January 2018, 18 March 2018 and 25 July 2018

Calculated g_a, throughout the duration of the trial, yielded a daytime (08:00-17:00) average value of 426 ± 233 mm s^{-1} in the MO, 219 ± 98 mm s^{-1} in the IO and 22 ± 7.2 mm s^{-1} in the orchard in Tzaneen. The difference in values between orchards in Howick and Tzaneen possibly reflects the difference in windspeed measurements, with windspeed measured by sonic anemometers above the canopy in the orchards in Howick, whilst in Tzaneen windspeed above the canopy was calculated from AWS data where windspeed was measured at 2 m. The AWS was also 2.5 km from the orchard. It could also reflect differences in canopy height and the two different environments. Average daytime (08:00 to 17:00) g_c, calculated by inverting the Penman-Monteith equation was 6.50 ± 9.14 mm s^{-1} in the MO, 6.13 ± 5.12 mm s^{-1} in the IO orchard and 1.98 ± 2.16 mm s^{-1} in the Tzaneen orchard. Following the parameterisation of the Jarvis-type g_c model (Equation [31]) it was determined that maximum g_c ($g_{c\ max}$) in the intermediate orchard was 45.1 mm s^{-1} (Table 4.10). This was higher than the measured $g_{c\ max}$ in the mature (37.4 mm s^{-1}) and intermediate orchards (29.9 mm s^{-1}), but was very similar to the measured $g_{c\ max}$ in the orchard in Tzaneen (43.8 mm s^{-1}). This suggests that $g_{c\ max}$ obtained through least squares regression analysis in the intermediate orchard may not be a fair measure of maximum g_c and that this approach could not quite explain the variation in g_c as a result of changing weather conditions in the orchards. Alternatively, it is possible that the maximum possible g_c did not occur in the orchards due to a limiting weather variable. This is perhaps not surprising as a considerable amount of hourly weather data from the EC systems was missing. However, the estimates of g_c appear to be reasonable and are slightly higher than those for citrus and olive (1.6-2.2 mm s^{-1}) and a range of deciduous tree crops (5.4-8.1 mm s^{-1}) (Villalobos et al., 2013). These values were higher than those estimated for macadamias in this current study, where average g_c was 0.7 mm s^{-1} in the mature orchard and 0.3 mm s^{-1} in the intermediate orchard. This reflects lower transpiration values in the macadamia orchards in this study when compared to the avocado orchards. This is perhaps not surprising considering the region of origin for both crops. Whilst both are understorey forest species (Carr, 2013; Carr, 2013), macadamias likely evolved in a slightly drier environment, especially in winter. As a result, macadamias are likely to have drought tolerance mechanisms that allow the survival for a fairly long dry period. One such mechanism could be a quicker stomatal closure to increasing VPD.

When assessing the performance of the Jarvis-Steward approach to estimate g_c in the various orchards, not all the statistical criteria were met for good model performance (Figure 4.30). Whilst D>0.8 for the intermediate orchard in Howick, MAE was greater than 20% and R^2 was <0.8. In the other two orchards none of the statistical criteria were met, indicating poor performance of the model to estimate g_c on an hourly basis. Importantly, at VPD>3 kPa, negative values for g_c were simulated. These high hourly values for VPD were outside the dataset used for parameterisation in the intermediate orchard in Howick and demonstrates the limitations to this approach and the importance of a good data set for model parameterisation. Accuracy on such a short time step is perhaps not expected from such a model. When comparing on a monthly basis, simulated g_c compared more favourably to simulated g_c, except in the mature orchard in Howick, where g_c was underestimated by the model (Figure 4.31). This is not surprising as the trees in the mature orchard were significantly bigger than the trees in the intermediate orchard, especially for the first few months of measurements before the major pruning events in this orchard. Importantly seasonal variation in measured g_c was also observed, with higher g_c in the winter months than summer months in the intermediate orchard in Howick and the orchard in Tzaneen. A similar seasonal trend was not observed in the mature orchard, with large variation in measurements in early summer. This can be attributed to missing weather data during these periods and significant changes in canopy size throughout the measurement period as a result of pruning.

Table 4.10: Optimised parameters for Equations [31] to [34] used to model canopy conductance (g_c). Parameters were generated through non-linear least squares regression analysis using data from the intermediate avocado orchard in Howick.

Parameter	Value
$g_{c\ max}$ (mm s^{-1})	45.088
k_{D1} (kPa)	-0.273
k_{D2} (kPa)	-2.774
k_T (^oC)	26.597
k_R (W m^{-2})	84.966
R^2	0.289

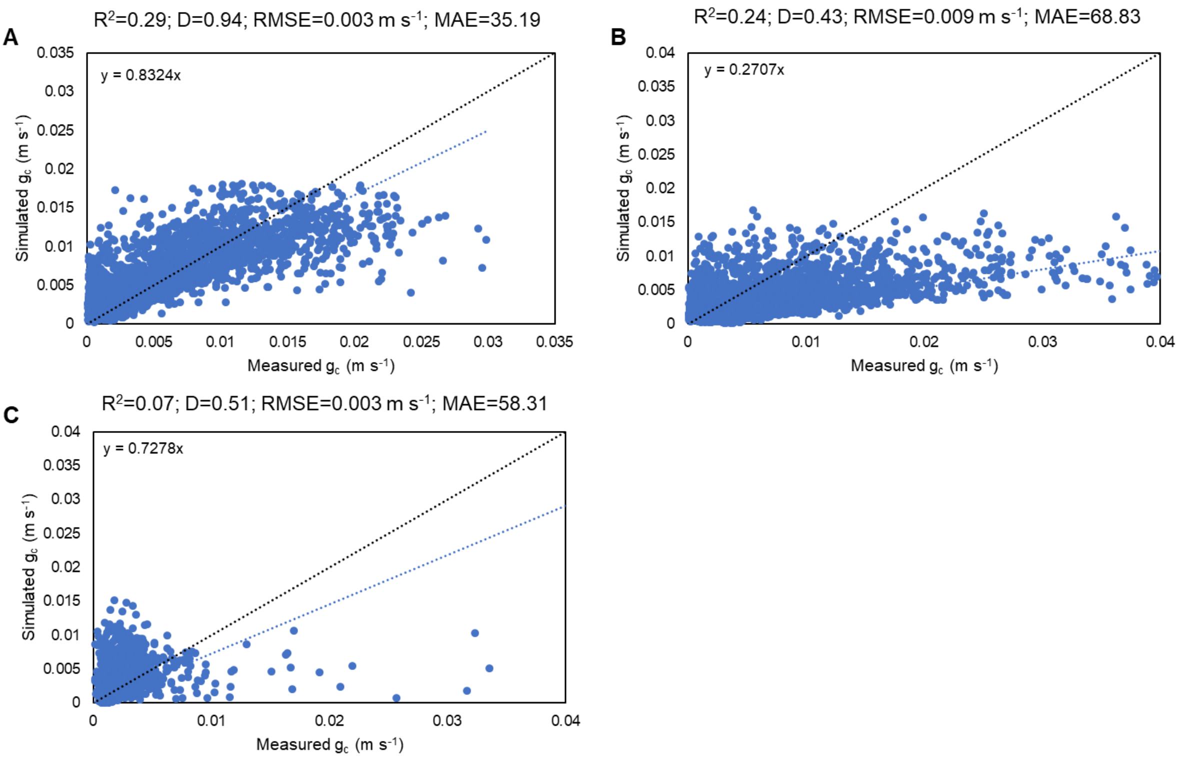

Figure 4.30: Hourly measured (calculated by inverting the Penman-Monteith equation) and simulated (using Equation [31]) canopy conductance (g_c) for the A) intermediate orchard and B) mature orchard in Howick and C) the orchard in Tzaneen, using parameters for the Jarvis-Steward model derived during parameterisation in the intermediate orchard in Howick. The black dotted line is the 1:1 line. The blue line is the best fit linear regression line.

Using these hourly estimates of g_c to determine daily transpiration values, it is evident that in the parameterisation orchard (intermediate orchard) daily estimates of transpiration were fairly good (D=0.93, RMSE = 0.139 mm day^{-1} and MAE=21.4). For the period used for parameterisation the total measured E_c in the intermediate orchard was 231 mm and estimated E_c was 237 mm (Figure 4.32). In keeping with the underestimation of g_c in the mature orchard, E_c was underestimated on a daily basis, with none of the statistical criteria met during the validation period in this orchard. During this time frame total measured E_c was 398 mm, whilst estimated was 150 mm. In the orchard in Tzaneen, E_c was overestimated in the hotter months (summer, spring and autumn), but was fairly well estimated in winter. Although D=0.82, MAE was greater than 20% and RMSE=0.353 mm day^{-1}. Over the period used for model validation total measured E_c was 377 mm, whilst total estimated E_c was 423 mm. Thus, although canopy size was very similar in the two orchards, parameters derived for the orchard in Howick resulted in the overestimation of E_c in Tzaneen, which cautions the use of the model outside of the range of conditions in which it was parameterised. Importantly some of the discrepancies in model performance could be explained by changes in canopy size over the measurement period, as a result of the vegetative growth flushes and pruning. Pruning in the mature orchard was significant and this needs to be considered when estimating g_c.

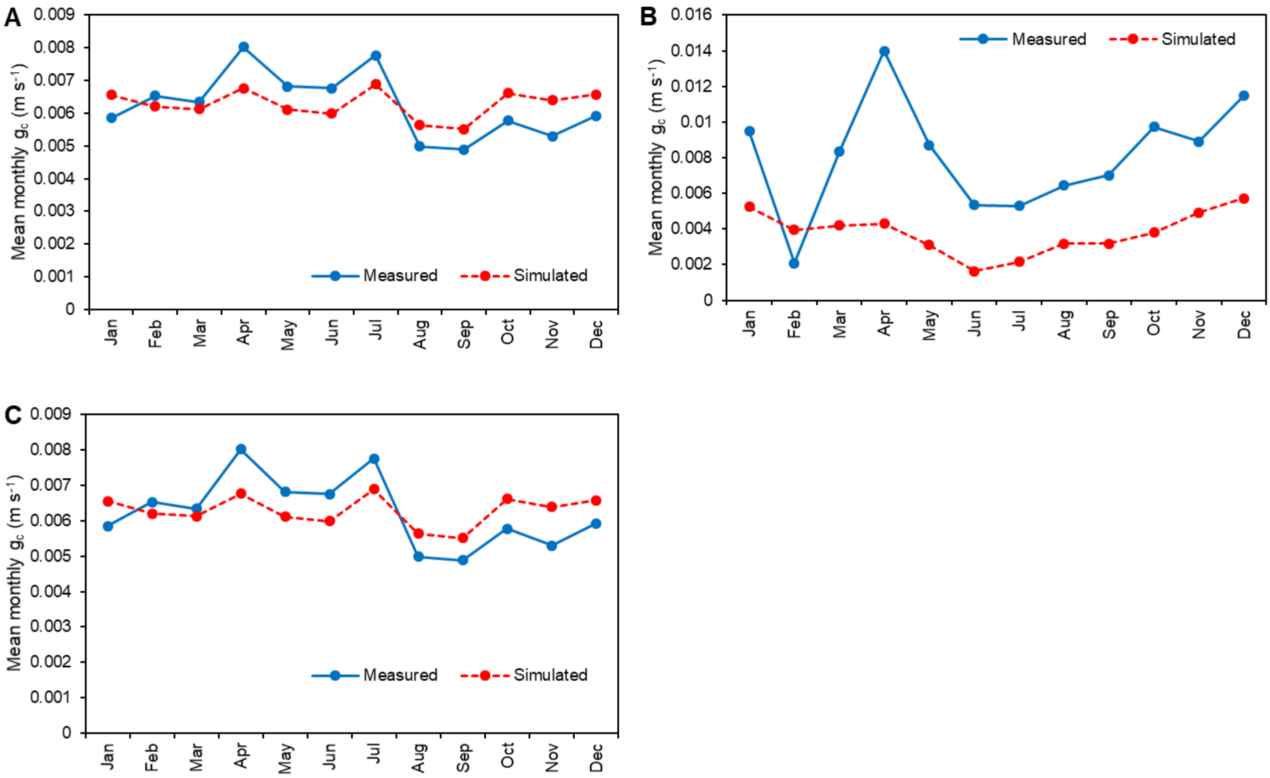

Figure 4.31: Mean monthly measured (calculated by inverting the Penman-Monteith equation) and simulated (using Equation [31]) canopy conductance (g_c) for the A) intermediate orchard and B) mature orchard in Howick and C) the orchard in Tzaneen, using parameters for the Jarvis-Steward model derived during parameterisation in the intermediate orchard in Howick

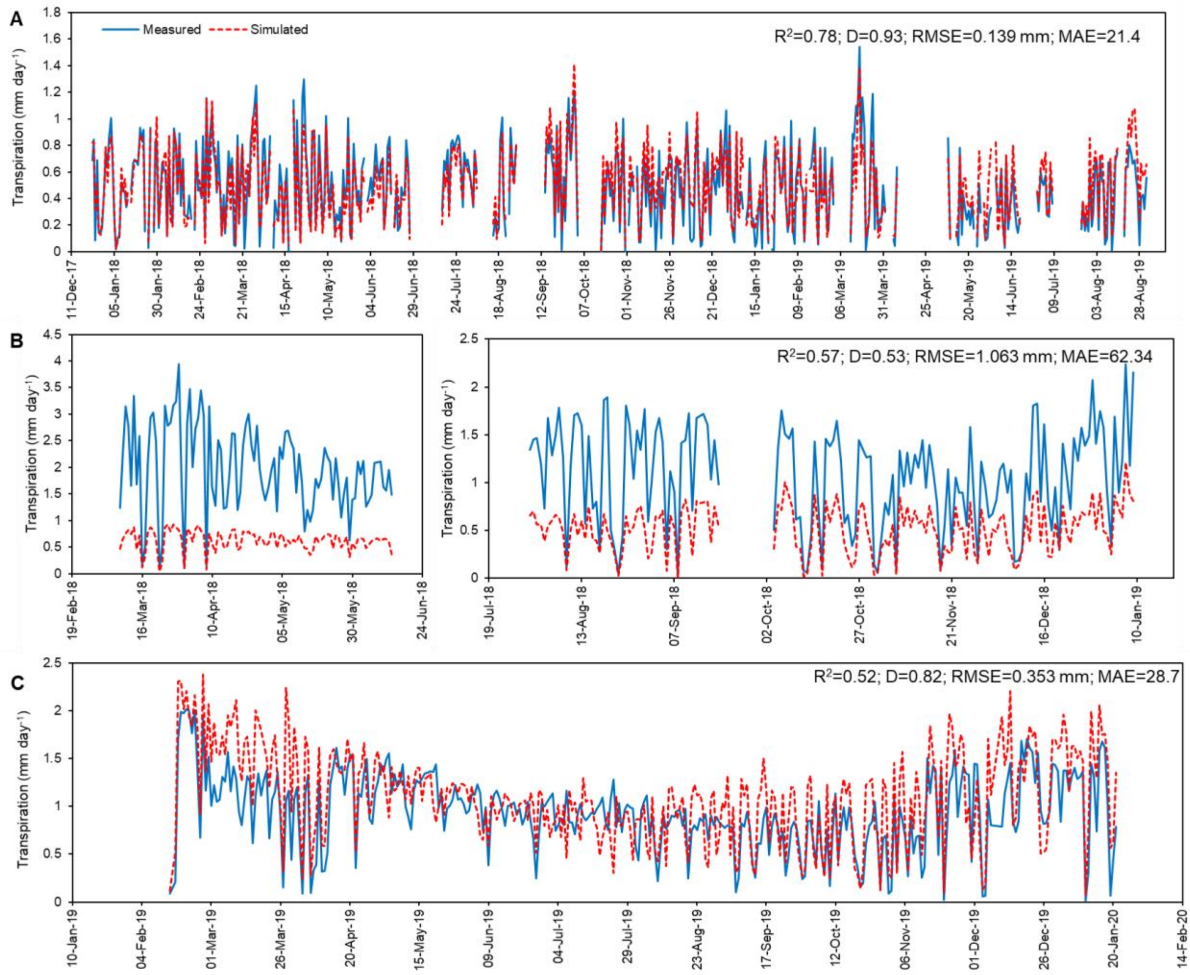

Figure 4.32: Comparison between hourly measured and simulated transpiration (E_c) totalled on a daily basis for the A) intermediate orchard and B) mature orchard in Howick and C) the orchard in Tzaneen, using g_c estimated using the Jarvis-Steward equation. Missing data is due to missing weather data from the eddy covariance system or AWS.

The underestimation of g_c in the mature orchards most likely stems from the underestimation of $g_{c\ max}$ for this orchard, when using the value optimised for the intermediate orchard. Seasonal variations in $g_{c\ max}$, as a result of variations in leaf area have also been observed in olive (Testi and Villalobos, 2009). Average LAI in the intermediate orchard was 2.79 $m^2\ m^{-2}$ at the start of the study, whilst it was 3.96 $m^2\ m^{-2}$ in the mature orchard, a ratio of approximately 1.4. A $g_{c\ max}$ value of 0.1 m s^{-1} (adjusted for LAI) gave improved estimates of both g_c and E_c in the mature orchard, especially after June 2018, where model performance met all statistical criteria (Figure 4.33). Poor estimates from March to June 2018 could be linked to a number of issues, including measurement errors and missing weather data. The large month to month variation in measured g_c from January through to May could represent measurement errors, as this value would be influenced by both weather variables and g_a estimates. However, without measured LAI the determination of an appropriate $g_{c\ max}$ for this approach is problematic and hinders the use of this approach for estimating water use of a wide range of avocado orchards.

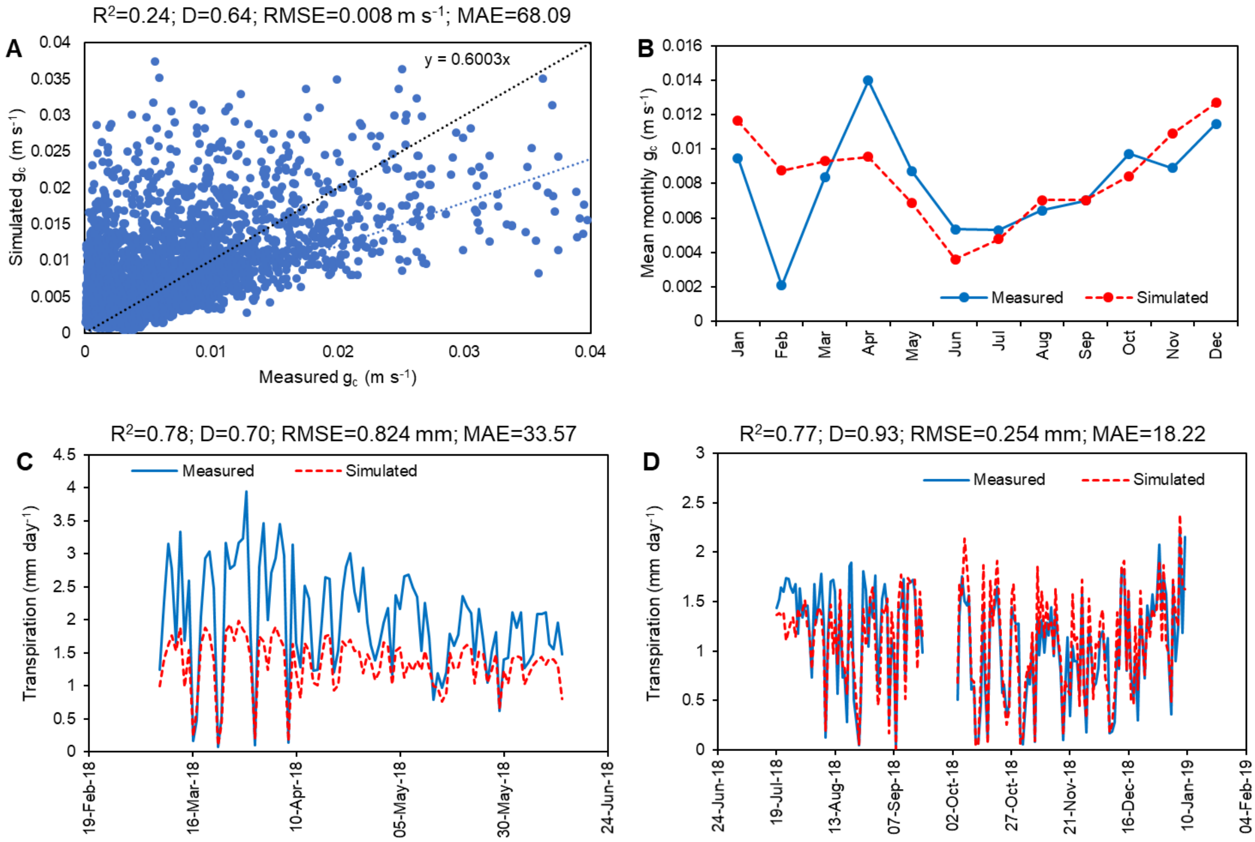

Figure 4.33: Comparison of measured and simulated A) hourly canopy conductance, B) mean monthly conductance, C) transpiration from March to June 2018 and from D) July 2018 to January 2019, using a $g_{c\ max}$ of 0.1 m s^{-1}

Although fairly accurate estimates of E_c could be achieved in three avocado orchards using the Penman-Monteith equation (Monteith and Unsworth, 1990), it required accurate estimates of both g_c and g_a. In addition, for reasonable estimates of g_c, using the Jarvis (1976) model in orchards varying in canopy size, $g_{c\ max}$ needed to be adjusted for canopy size. The ease with which LAI measurements can be made to adjust $g_{c\ max}$ could hinder the widespread use of this approach. In addition, the model still needs to be parameterised with a data set covering a greater range of conditions, to ensure the model performs adequately over a range of conditions. Although estimates of g_a were fairly high in this study, they were not unreasonably high compared to average g_a estimated in a range of forest canopies (de Aguiar et al., 2017, Mallick et al., 2016). It is, however, important to note that without accurate estimates of above canopy windspeed, the accuracy of the Penman-Monteith method may be compromised. This requirement could potentially be circumvented as McNaughton and Jarvis (1983) suggested that in well-ventilated canopies, such as orchards, the role of g_a is far less critical than g_c in determining E_c. Villalobos et al. (2000) and Orgaz et al. (2007) found supporting evidence for this in olive, where estimates of E_c, in well coupled olive orchards, were not sensitive to changes in g_a. Orgaz et al. (2007), however, noted that the sensitivity of E_c to changes in g_a would increase substantially in orchards which are decoupled from the atmosphere, which commonly occurs at low windspeed, largely because boundary layer conductance has a significant effect on g_c and small changes in g_a would have a substantial effect on E_c in these crops. As the average decoupling coefficient for the mature orchard was 0.06, for the intermediate orchard 0.10 and for the orchard in Tzaneen 0.24, it implies that avocado canopies are generally well coupled to the atmosphere and g_a would not have a dominating effect on E_c. An alternative approach to modelling E_c, which takes this into account, is the model proposed by Whitley et al. (2009), which uses a modified Jarvis-Steward approach to estimate E_c rather than g_c.

4.2.2.2 Estimates of E_c using a using a modified Jarvis steward type model as proposed by Whitley et al. (2009)

The simplified approach of Whitley et al. (2009) is based on the Jarvis-Steward approach but instead of estimating g_c, E_c is estimated directly from weather data. The model assumes that there is a maximum rate of E_c, which is only achieved under optimal environmental conditions. It also assumes that the crop is well coupled to the atmosphere and that stomata exert strong control over transpiration. Average seasonal values for the decoupling coefficient (Ω) in the three study orchards suggest that avocado transpiration is well coupled to the atmosphere, as values were close to 0 (mature = 0.06, Intermediate = 0.1, Tzaneen = 0.24). This method therefore circumvents the need to estimate g_c and g_a, which could eliminate some error associated with these calculations. However, it is still an empirical approach and therefore it might not apply outside the calibration area.

The model was parameterised on daily data in the intermediate orchard in Howick, as model performance was best in this orchard as indicated by model statistics. Daily data was used as this is the format of weather data that is most often available to growers. The optimised parameters are provided in Table 4.11. Parameterisation through non-linear least squares regression analysis yielded a maximum E_c ($E_{c\ max}$) rate of 125 L day^{-1} or 4.5 mm day^{-1}. This was higher than the maximum daily rate of E_c measured in the orchard of 70 L day^{-1} (2.5 mm day^{-1}), which suggests that the model may tend to overestimate orchard transpiration. During this parameterisation phase, most of the statistical criteria were met, except for R^2 which was 0.77 (Figure 4.34 A) and thus daily transpiration was simulated fairly accurately. Transpiration was generally slightly underestimated in the summer months, where the model failed to simulate the higher transpiration rates with a high degree of accuracy (Figure 4.35 A). Overestimation of transpiration was observed in winter in the second season of measurements. Despite this shortcoming, for the first year of measurement (23 December 2017-22 December 2018) E_c was only underestimated by 4.6 mm.

Table 4.11: Optimised parameters for Equation [37] used to model transpiration (E_c). Parameters were generated through non-linear least squares regression analysis using daily data from the intermediate avocado orchard in Howick.

Parameter	**Value**
$E_{c\ max}$ (L h^{-1})	124.81
K_{e1} (kPa)	1.962
K_{e2} (kPa)	1.435
k_T (°C)	44.38
k_R (W m^{-2})	2.369
R^2	0.77

When the parameters derived from the intermediate orchard were applied to other two measurement orchards, the results were not as good, which is not unexpected. In the mature orchard in Howick both R^2 and MAE did not meet the statistical criteria (Figure 4.34 B). This was after $E_{c\ max}$ was adjusted for canopy cover by a factor of two (the canopy cover in the mature orchard was twice that of the intermediate orchard at the start of measurements). Despite this adjustment for canopy size, E_c was underestimated at the start of the season (Figure 4.35 B). At the end of the season E_c was, however, overestimated, which could be a result of changes in canopy size as a result of pruning. This stresses the importance of good estimates of canopy size to estimate E_c accurately. Over the duration of the first year of measurements, total E_c was underestimated by 47 mm, which is not unreasonable.

When applying the parameters from the intermediate orchard to the orchard in Tzaneen, daily E_c was not well estimated, despite also accounting for differences in canopy size in the $E_{c\ max}$ parameter (Figure 4.34 C). Even when the Whitley et al. (2009) model was parameterised using data from the Tzaneen orchard, model performance did not meet all the statistical criteria (Figure 4.34 D). This poor performance of the model was particularly noticeable at the start of the season (Figure 4.35 C), when solar radiation was estimated from temperature data, as the AWS was only installed in February 2019. Whilst removing this period of data from the statistical analysis improved model performance the defined criteria for good model performance were still not met. Annual E_c (4 December 2018-3 December 2019) was underestimated by 58 mm, which is fairly similar to the mature orchard. This emphasises the need for caution when applying empirical models outside of the region in which they were parameterised and suggests that more mechanistic approaches are required for accurate estimates of E_c across a wide range of climatic zones. In addition, the scaling of $E_{c\ max}$ for orchards varying in canopy size should be explored further using more robust estimates of canopy size, that can account for pruning practices that reduce leaf area more than canopy volume.

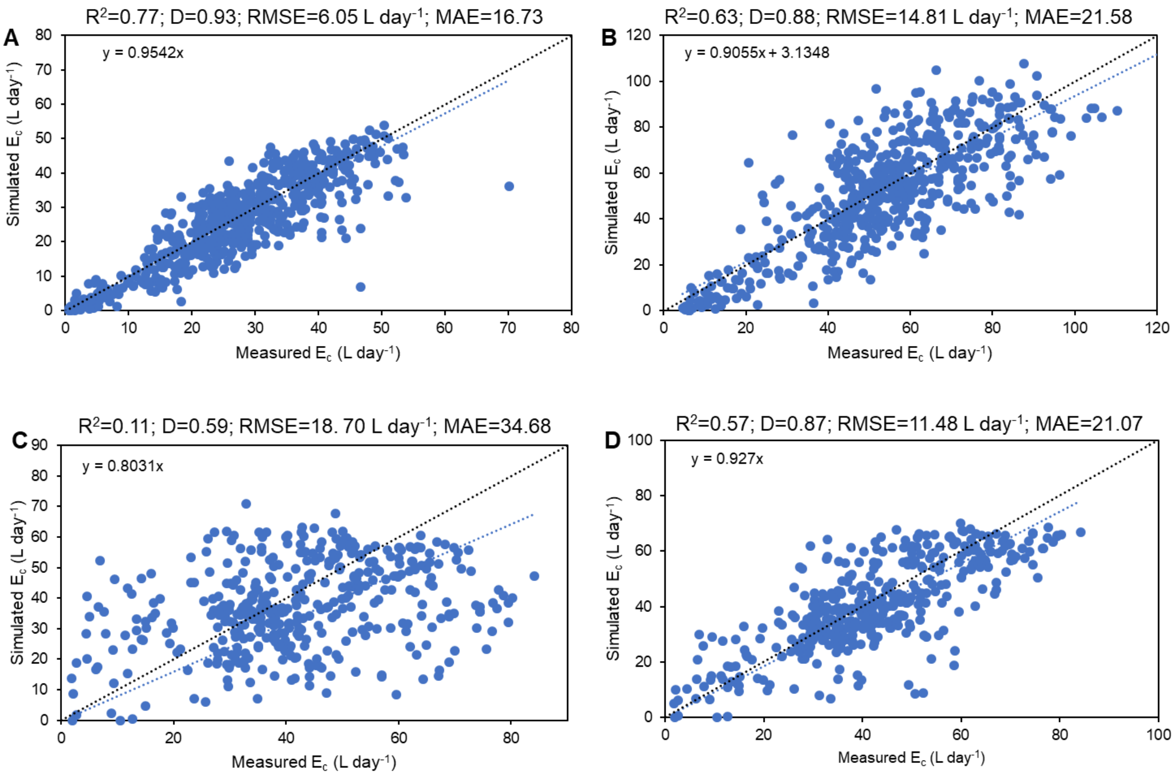

Figure 4.34: Daily measured and simulated (using Equation [37]) transpiration for the A) intermediate orchard and B) mature orchard in Howick and C) the orchard in Tzaneen, using parameters for the Whitley et al. (2009) model derived during parameterisation in the intermediate orchard in Howick and D) simulated and estimated transpiration during parametrisation in the Tzaneen orchard. The black dotted line is the 1:1 line. The blue line is the best fit linear regression line.

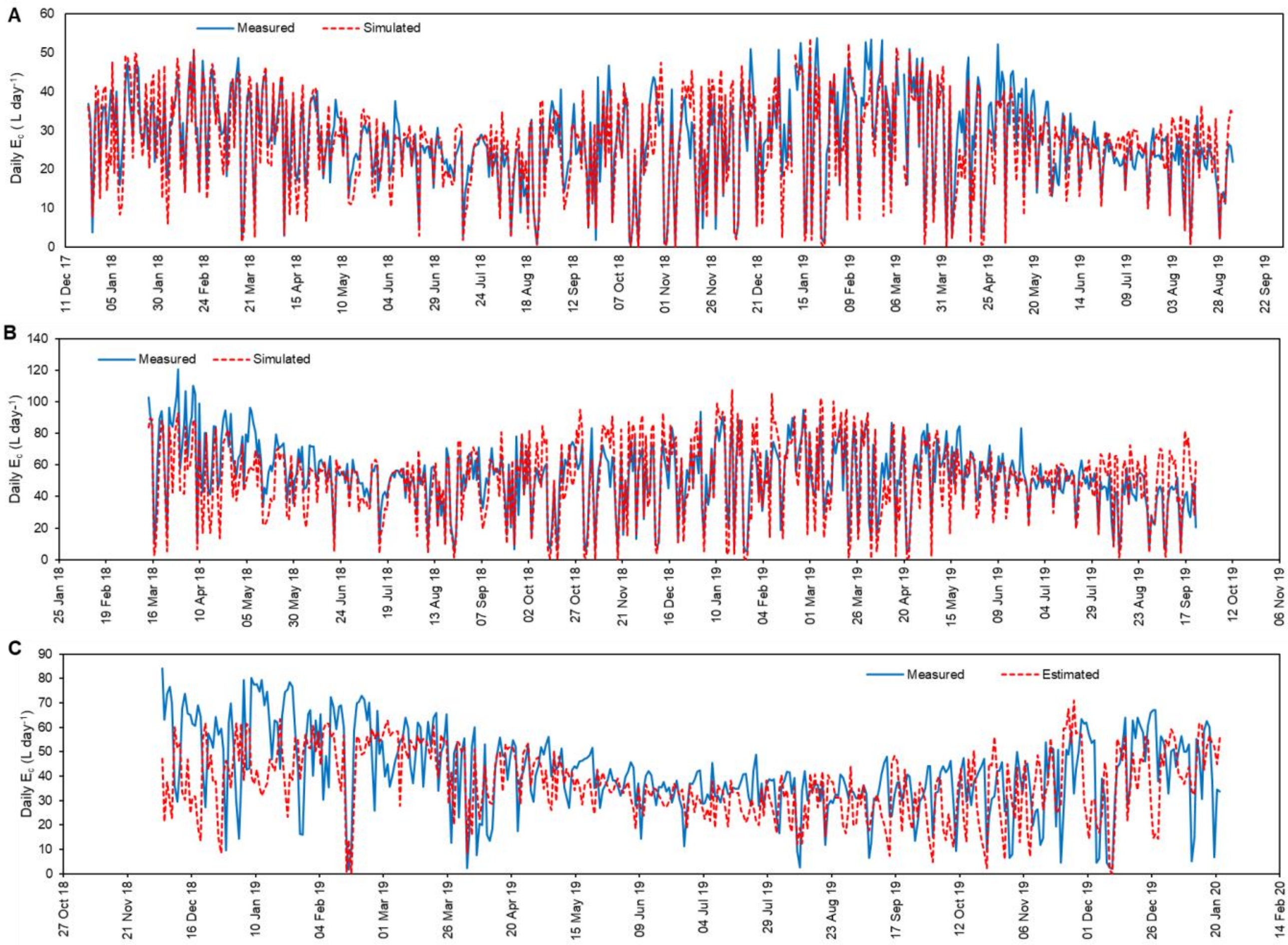

Figure 4.35: Comparison between daily measured and simulated transpiration (E_c) for the A) intermediate orchard and B) mature orchard in Howick and C) the orchard in Tzaneen, using E_c estimated using the approach by Whitley et al. (2009) and parameters for the intermediate orchard

The question remains if this approach can be used for irrigation scheduling and it would seem that this approach might be useful for retrospective adjustment of applied irrigation volumes on a weekly basis (Figure 4.36). Weekly total E_c was well estimated in both the mature and intermediate orchard (Figure 4.36 A & B), but once again weekly estimates were not as accurate in the Tzaneen orchard, especially for the first few weeks of measurement (Figure 4.36 C). However, the model showed promise for weekly estimates for the rest of the period of measurements, although compensatory errors may have occurred during his period. Importantly, this is a step in the right direction, as avocado orchard water use has not been previously quantified over prolonged periods and under different climatic conditions. This is the first report of this type of modelling in avocado orchards and is a good start for the estimation of E_c of a wide range of orchards.

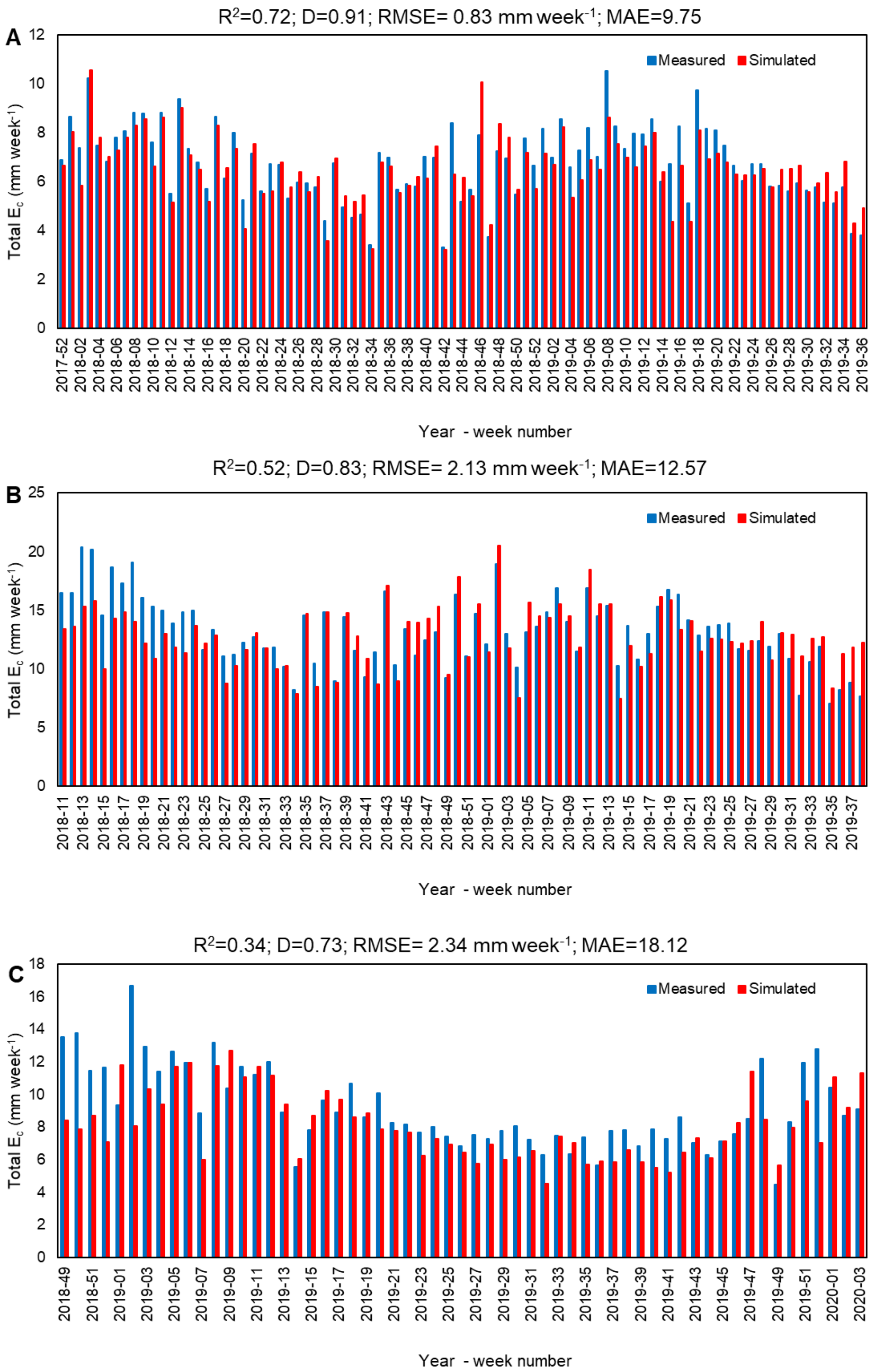

Figure 4.36: Comparison between weekly measured and simulated transpiration (E_c) for the A) intermediate orchard and B) mature orchard in Howick and C) the orchard in Tzaneen, using E_c estimated using the approach by Whitley et al. (2009) and parameters for the intermediate orchard in Howick

4.2.3 CONCLUSIONS

Three modelling approaches for estimating E_c in avocado orchards were evaluated in this study. These included a crop coefficient approach (Allen and Pereira, 2009), the Penman-Monteith equation using canopy conductance estimated using a Jarvis approach and an empirical Jarvis-type approach by Whitley et al. (2009), where transpiration is estimated directly. The focus was on E_c modelling as this is the component of orchard ET that is unique to an avocado tree. In addition, this modelling was focussed on the two orchards with an intermediate canopy size and the mature orchard.

Transpiration crop coefficients followed the same trend in all three orchards but varied in magnitude due to differences in canopy cover. Monthly average K_t values for the mature orchard varied between 0.60 and 1.11, between 0.25 and 0.53 for the intermediate orchard and between 0.26 and 0.57 for the orchard in Tzaneen. The shape of the avocado K_{cb} curve suggested by Allen and Pereira (2009) did not apply to the study orchards and therefore this study has provided better estimates of K_t values for a crop coefficient curve which can be used for the estimation of seasonal water use of avocado orchards. Allen and Pereira (2009) also suggested parameters for avocado that can be used to determine orchard specific K_t values, if tree height and canopy cover are known. These parameters provided poor estimates of K_t for the three orchards, which would have resulted in a significant overestimation of transpiration in each orchard. It was evident that the r_{leaf} value of 300 s m^{-1} was too low for these orchards and that r_{leaf} should be dynamic and change throughout the season, with higher values in spring and summer and lower values in winter. Monthly r_{leaf} was estimated for the orchards by back calculating using measured transpiration and whilst reasonable E_c estimates could be obtained using the r_{leaf} values derived for each orchard, no single set of r_{leaf} estimates could provide reasonable monthly estimates in all three orchards. Reasonable seasonal estimates could be obtained and thus this method represents a significant improvement of currently existing crop coefficients for avocado orchards and could be used with reasonable confidence for seasonal estimates of E_c for planning purposes. This approach also clearly highlighted the importance of leaf resistance or alternatively canopy conductance for accurate estimates of E_c.

As a result, the next modelling approach evaluated was the use of the Penman-Monteith equation with estimates of g_c derived using a Jarvis approach (Jarvis, 1976). Parameters for the Jarvis approach were optimised in the intermediate orchard and then applied to the mature orchard in Howick and intermediate orchard in Tzaneen. When comparing hourly estimates of g_c with hourly measured g_c, estimates did not meet all the model criteria in any of the orchards, however, on a monthly basis g_c estimates were reasonable in the two intermediate orchards. Using these g_c values in the Penman-Monteith equation, daily estimates of E_c were reasonable in the two intermediate orchards. Estimates of both g_c and E_c were improved for the mature orchard, when the size of the canopy was considered and $g_{c\ max}$ was adjusted accordingly. However, it is the adjustment of $g_{c\ max}$ that is important to ensure accurate estimates of E_c and an appropriate, end-user friendly method of doing this still needs to be determined.

As a result of the Penman-Monteith approach requiring a number of variables which are not easy to measure, the approach of Whitley et al. (2009) was evaluated, which uses a modified Jarvis-Steward model to estimate E_c directly. Transpiration was modelled on a daily basis and was parameterised with reasonable accuracy in the intermediate orchard in Howick. However, when these parameters were applied to the other two orchards, E_c was poorly estimated. This is not surprising as canopy cover of the mature orchard was almost double that of the intermediate orchard. When this was considered, estimated E_c in the mature orchard improved considerably. However, estimates for the Tzaneen orchard did not meet statistical criteria. This was attributed to the empirical nature of the approach and as a result the response of E_c to the different environmental variables may differ between the two regions. Although estimates were not accurate on a daily basis for all orchards, when considering fortnightly E_c fairly good estimates of water use were obtained for all three orchards. This approach could therefore be used to retrospectively assess irrigation schedules for the previous two weeks and to adjust accordingly.

Whilst these modelling approaches are not promising for tactical decision making on a day to day basis, they do cater for more strategic decision needed for planning purposes. Although much work still needs to be done on avocado water use modelling, this study represents a significant step in the right direction, as there have been no previous reports on modelling of E_c of avocado orchards. Future modelling exercises should also focus on modelling of soil evaporation,

4.3 IMPACT OF WATER STRESS AT DIFFERENT PHENOLOGICAL STAGES ON YIELD AND QUALITY OF AVOCADOS

4.3.1 WEATHER VARIABLES

Minimum temperatures for the spring and summer of 2018/19 were significantly ($P < 0.001$) lower than for 2019/20 (Figure 4.37 A). The maximum temperatures for the two years did not differ significantly ($P = 0.68$; Figure 4.37 A). Since the actual difference in minimum temperatures between the two years was not substantial (~2°C), it is not expected that minimum temperatures would have caused differences in growth and development between the two years. In general, VPD for the 2019/20 season was lower than for the 2018/19 season (Figure 4.37 B), indicating drier atmospheric conditions during the 2018/19 season compared to the 2019/20 season. In terms of solar radiation, there were no substantial differences between seasons, but variation in solar radiation was substantially more during spring, summer and autumn compared to winter, due to variation caused by cloudy conditions in this summer rainfall region (Figure 4.37 D). Rainfall for the spring and summer of 2018/19 was lower (447 mm) than for the spring and summer of 2019/20 (568 mm) (Figure 4.37 E), indicating that the spring and summer of 2019/20 was wetter than the spring and summer of 2018/19. Variation in ET_o was greatest in spring, summer and autumn, with maximum values recorded in mid-summer. Reference evapotranspiration exceeded rainfall substantially during early spring (September and October) for both 2018/19 and 2019/20 (Figure 4.38), which coincided with the fruit set period. During the summer of both 2018/19 and 2019/20 the difference between reference evapotranspiration and rainfall was much smaller, with rainfall exceeding ET_o during some months (Figure 4.38).

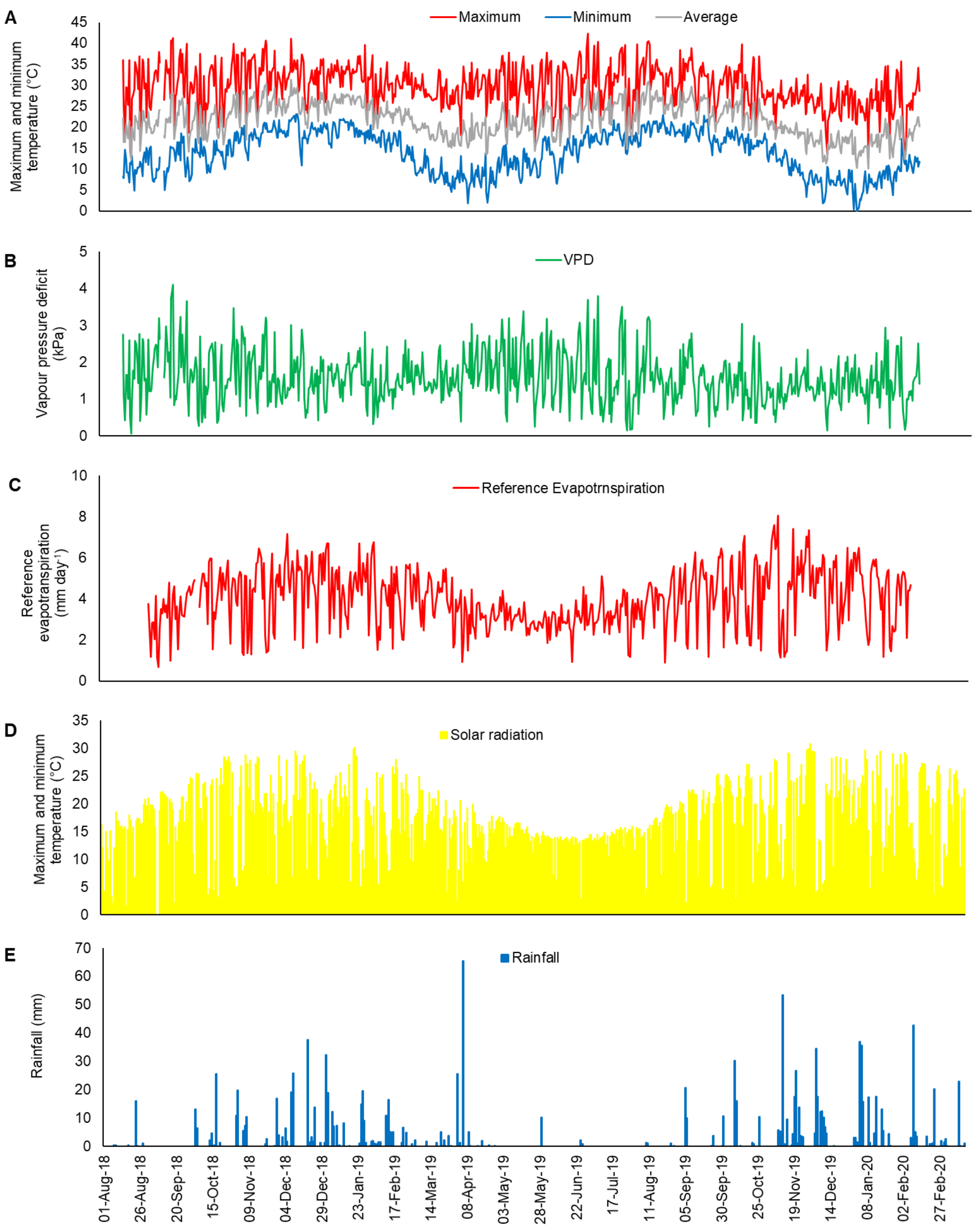

Figure 4.37: Maximum, minimum and mean air temperature (°C), (B) air vapour pressure deficit (VPD_{air}) (kPa), (C) reference evapotranspiration (mm day^{-1}), (D) solar radiation (MJ m^{-2} day^{-1}) and (E) total daily rainfall (mm) obtained from an automatic weather station located close to the orchard over a three season period (1 August 2018 to 15 September 2020)

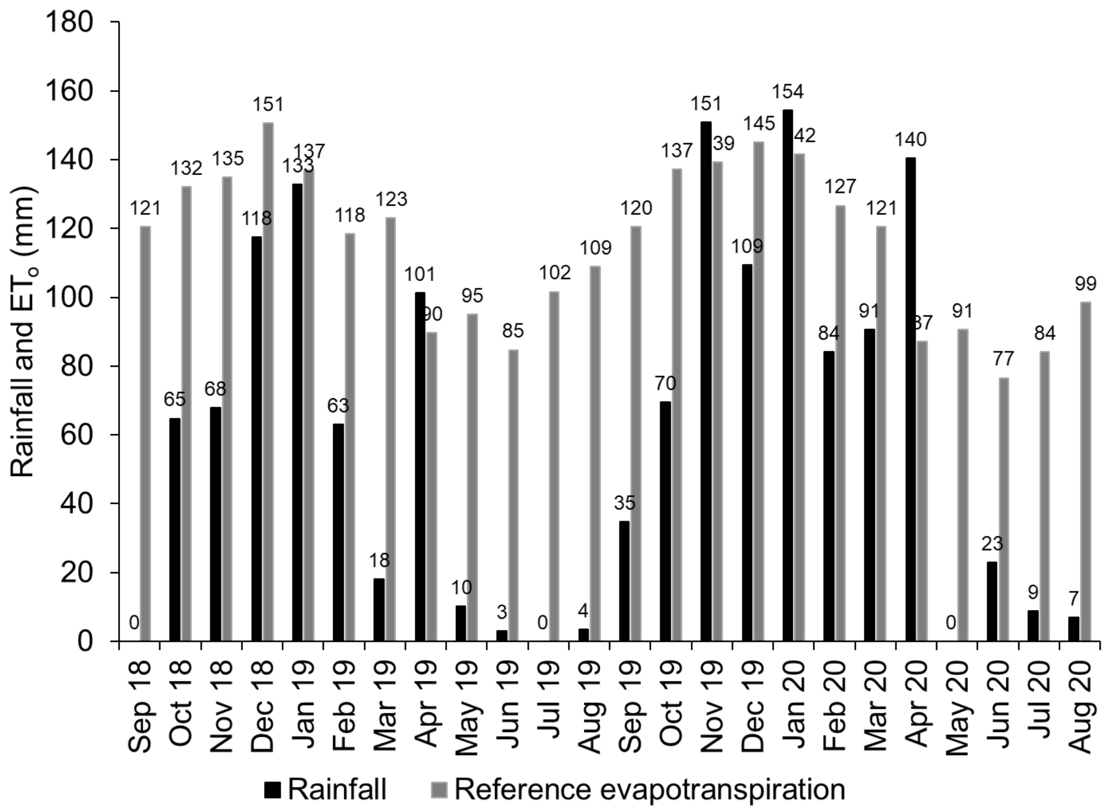

Figure 4.38: Total monthly rainfall and reference evapotranspiration (ET_o) for the ARC TSC experimental site

In terms of phenological stages, the flowering period for 2020/21 was significantly colder and wetter than the flowering period in the 2019/20 season (Table 4.12), which could have affected flowering intensity. For the fruit set stage, conditions were cooler and wetter for 2019/20 compared to 2018/19, which could have impacted fruit set. Weather conditions during fruit growth were similar for the 2018/19 and 2019/20 seasons (Table 4.12). Conditions during fruit maturation were once again cooler and wetter during the 2019/20 season compared to the 2018/19 season (Table 4.12). Rainfall for the autumn and winter of 2020 was also higher (270 mm for March to August) compared to the autumn and winter of 2019 (143 mm for March to August) (Figure 4.38), creating the wetter conditions as mentioned for fruit maturation for the 2019/20 season compared to the 2018/19 season, as well as for the flowering period of 2020/21 compared to the flowering period of 2019/20. In addition, for each month during the autumn and winter of 2019 and 2020, with the exception of April for both 2019 and 2020, total monthly reference evapotranspiration exceeded total monthly rainfall (Figure 4.38), suggesting the possible need for supplementary irrigation to possibly prevent water stress. During April, in both 2019 and 2020, the majority of the total rainfall received during the month fell in a single severe thunderstorm activity with strong winds and flash floods (5 April 2019 and 14 April 2020). Very little of this rainfall would have been effective, as runoff was likely to be considerable during each event.

Table 4.12: Average weather conditions during each phenological stage for the ARC TSC experimental site for the duration of the current study. T_{air} – air temperature, R_s – solar radiation, VPD – vapour pressure deficit, ET_o – reference evapotranspiration

Phenology	**Year**	**Date**	**Timespan** (days)	**T_{air} (°C)** (Av ± Std)	**$T_{air\ min}$ (°C)** (Av ± Std)	**R_s (MJ m^{-2} day^{-1})** (Av ± Std)
Flowering	2018/19	N/A#	-	-	-	-
	2019/20	16 May-24 Sep	132	19.47 ± 0.24	9.80 ± 0.28	14.71 ± 0.34
	2020/21	9 May-28 Sep	143	16.91 ± 0.24	7.95 ± 0.26	14.72 ± 0.34
Fruit set	2018/19	14-28 Sep	14	23.97 ± 0.92	14.28 ± 0.63	17.44 ± 1.33
	2019/20	20 Sep-4 Oct	15	20.03 ± 0.86	11.73 ± 0.77	19.12 ± 1.95
Fruit growth	2018/19	28 Sep-15 Feb	141	24.00 ± 0.30	16.77 ± 0.30	19.23 ± 0.60
	2019/20	4 Oct-26 Feb	146	24.74 ± 0.25	18.16 ± 0.19	19.94 ± 0.62
Fruit maturation	2018/19	16 Feb-29 May	103	23.68 ± 0.28	16.40 ± 0.38	16.10 ± 0.45
	2019/20	27 Feb-19 May	83	21.89 ± 0.29	15.18 ± 0.30	15.76 ± 0.58

Phenology	**Year**	**Date**	**VPD_{air} (kPa)** (Av ± Std)	**ET_0 (mm)** (Av ± Std)	**Rain** (mm)	**ET_0 – Rain** (mm)
Flowering	2018/19	N/A#	-	-		-
	2019/20	16 May-24 Sep	1.75 ± 0.06	3.27 ± 0.08	51	380.4
	2020/21	9 May-28 Sep	1.38 ± 0.05	2.91 ± 0.07	51	327.5
Fruit set	2018/19	14-28 Sep	2.24 ± 0.29	4.37 ± 0.34	0	85.9
	2019/20	20 Sep-4 Oct	1.73 ± 0.20	4.28 ± 0.40	15	49.2
Fruit growth	2018/19	28 Sep-15 Feb	1.63 ± 0.06	4.44 ± 0.12	428	197.6
	2019/20	4 Oct-26 Feb	1.58 ± 0.06	4.60 ± 0.13	556	115.6
Fruit maturation	2018/19	16 Feb-29 May	1.53 ± 0.04	3.54 ± 0.10	149	216.9
	2019/20	27 Feb-19 May	1.28 ± 0.06	3.26 ± 0.12	233	37.4

4.3.2 PHENOLOGY OF THE 'HASS' AVOCADO TREES

For 'Hass' avocado trees at the ARC TSC experimental farm, flower initiation takes place during late autumn (end of May) when temperatures drop. This is followed by inflorescence development during the winter (July to August) (Figure 4.39). Full bloom occurs at the end of winter and is followed by fruit set during early spring (end of September to mid-October)

(Figure 4.39). Fruit growth takes place throughout the entire period the fruit is on the tree, which is from spring until early autumn (Figure 4.39), however, rapid fruit growth usually occurs from October to December. During rapid fruit growth, a natural fruit abscission period, termed "November drop" occurs at the end of November (Figure 4.39). From February fruit growth slows down considerably, but some growth still takes place until harvest. Fruit moisture content also starts to decrease from February, whilst the oil content increases. The period from mid-February until harvest is therefore termed fruit maturation for the purpose of this study. The fruit reaches harvest maturity (moisture content level below 77%) during May (Figure 4.39).

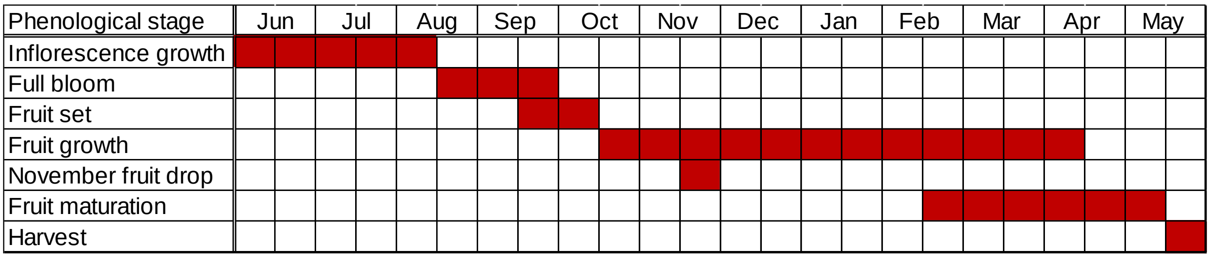

Figure 4.39: Phenology of 'Hass' avocado trees at the ARC TSC experimental site

4.3.3 STRESS APPLIED DURING FRUIT SET

For the 2018/19 season, fruit set occurred for a two-week period between 14 and 28 September 2018 at the ARC TSC experimental site in Nelspruit. For the 2019/20 season, fruit set also took place over a two-week period, but was approximately one week later (20 September 2019 to 4 October 2019) than in the 2018/19 season. For both the 2018/19 and 2019/20 season the soil matric potential for the fully irrigated treatment was kept above the threshold matric potential of -40 kPa (Figure 4.40 A & B) to ensure well-watered conditions and to prevent stress. For the stress treatment the aim was to dry out the soil to below -40 kPa to induce stress. During the 2018/19 season, the top-soil was dried out during the last week of fruit set to approximately -60 kPa (Figure 4.40 A), whilst both the top and sub-soil were drier than -40 kPa for the entire fruit set stage during 2019/20 (Figure 4.40 B). It is therefore expected that conditions were more stressful during 2019/20 than 2018/19. Unfortunately, midday stem xylem water potential did not follow a clear relationship with drying soil conditions. For the 2018/19 season, midday stem xylem water potential was significantly lower during the last week of fruit set and was clearly related to the drier soil conditions (Figure 4.40 A). However, during the 2019/20 season, there was no clear relationship between soil matric potential and midday stem xylem water potential (Figure 4.40 B), with no significant differences between the fully irrigated and stress treatment, though soil conditions were dramatically drier for the stress treatment.

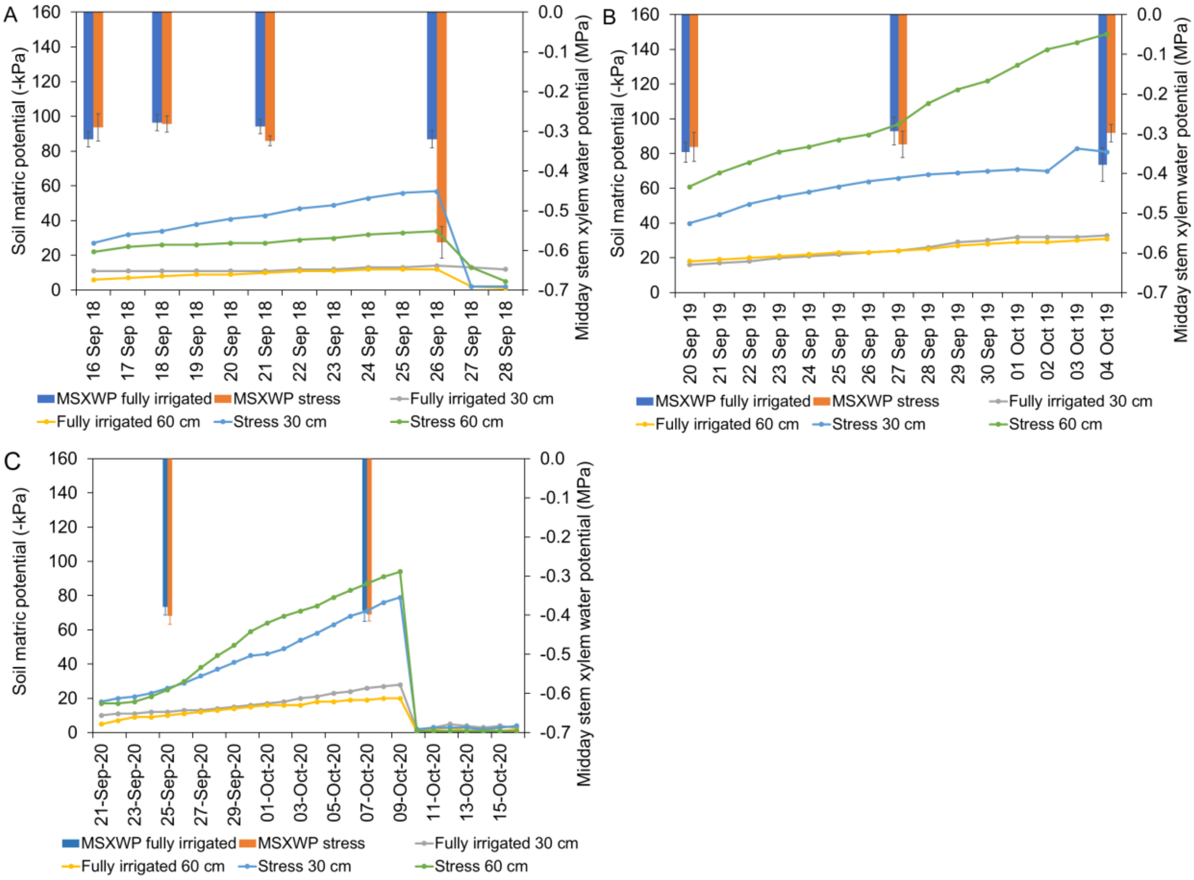

Figure 4.40: Soil matric potential and tree midday stem xylem water potential for the period during which water stress was applied during fruit set for the Nelspruit experimental site for the A) 2018/19 season, B) 2019/20 season and C) 2020/21 season

Fruit set was expressed as the mean number of fruit that set per inflorescence and is depicted in Figure 4.41. The drier soil conditions of the water stress treatments caused a significant (P = 0.01) reduction in fruit set for both seasons. Fruit set was lower during the 2019/20 season (P-value for season = 0.006) when the soil matric potential was substantially more negative compared to the 2018/19 season (Figure 4.41). In addition, the 2019/20 season was a low yielding ("off") season and it was therefore expected that fruit set would be lower than the 2018/19 season, which was a high yielding ("on") season. The implementation of water stress resulted in a 34% and 56% decrease in fruit set for the 2018/19 and 2019/20 seasons, respectively.

These results imply that even a short period of water stress during fruit set results in considerable crop losses, whilst water stress during the entire fruit set period may result in severe crop losses, with the possibility that 50% of the crop could be lost during this period. It is therefore crucial that water stress is avoided during fruit set to prevent crop losses. As rainfall is still low during the fruit set period (Figure 4.38) and temperatures and VPD are relatively high (Figure 4.37 A to C and Table 4.12), conditions for water stress would be easily created if water is withheld. Application of sufficient supplementary irrigation is therefore crucial during this stage to avoid crop losses.

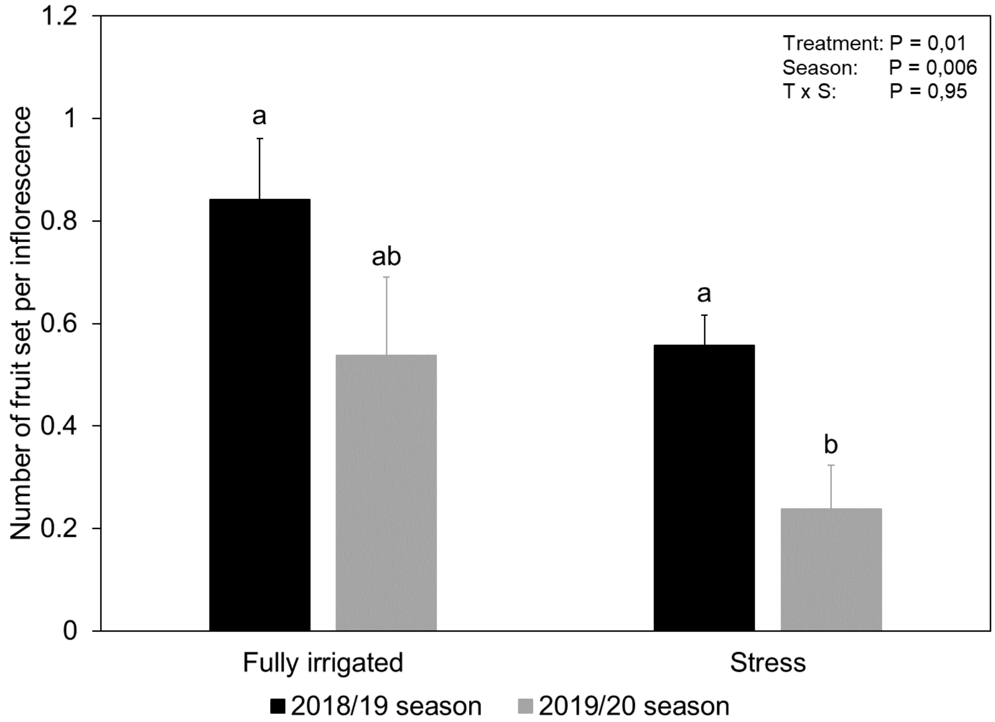

Figure 4.41: The effect of water stress on fruit set of 'Hass' avocado trees grafted on 'Duke 7' rootstock for the 2018/19 and 2019/20 seasons

Spring vegetative growth coincides with fruit set. However, it is not evident from the results if the drier soil conditions during fruit set affected spring vegetative growth significantly (Figure 4.42). This was most likely because the irrigation resumed in this treatment after fruit set and before extension phase of the spring vegetative flush had ended. Spring vegetative growth was, however, significantly less vigorous during the 2019/20 season compared to the 2018/19 season. Given that fruit set was also lower during the 2019/20 season ("off" year) compared to 2018/19 ("on" year), this could possibly be linked to the availability of energy reserves, as suggested during fruit set. Avocado is known for its alternate bearing behaviour in which case alternate cycles of high yields ("on" years), are followed by low yields ("off" years). During "on" years, trees are usually depleted of carbohydrate reserves, especially during the crucial stages of fruit set, causing the low yields for the following year ("off" season). During the "off" year the tree "recovers" again, while accumulating sufficient carbohydrate reserves for a high crop load the following year, thereby repeating the entire alternate bearing cycle (Davie et al., 1995). It is therefore expected that the spring vegetative growth would also be less vigorous during an "off" year.

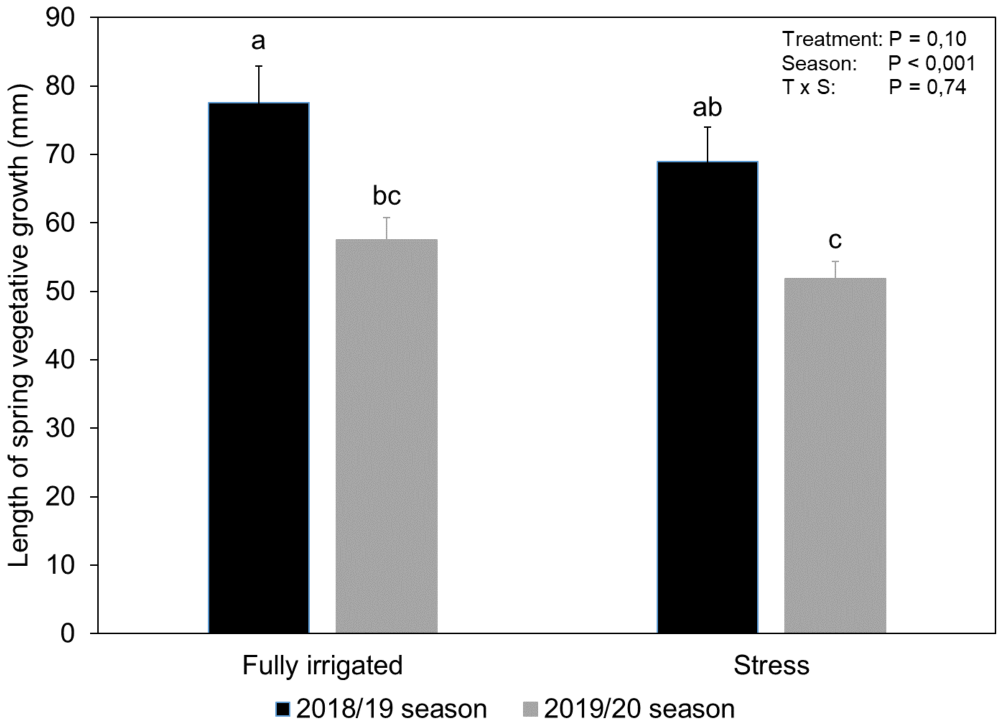

Figure 4.42: The effects of water stress on spring vegetative vigour of 'Hass' avocado trees grafted on 'Duke 7' rootstock for the 2018/19 and 2019/20 seasons

4.3.4 STRESS APPLIED DURING FRUIT GROWTH

During the early stages of fruit growth, a distinct natural fruitlet abscission period occurs, which is termed "November drop" in South Africa. This fruitlet abscission event occurs, regardless of any stress factor and the underlying mechanism is not fully understood. In this study, the fruit that dropped was found to be between 15 and 60 g in mass and was characterized by an aborted seed testa when cut open (Figure 4.43). Removing the embryos and staining them with a 1% tetrazolium solution, revealed that the embryos of the fruit that dropped were still alive when the fruit dropped.

Figure 4.43: Fruit that dropped during the November fruitlet abscission period were characterized by an aborted seed testa (top right), compared to the live seed testa of fruit that remained on the tree (top left). However, the embryos of both the fruit that remained on the tree (bottom left) and dropped fruit (bottom right) were alive

A significant correlation was obtained between fruitlet abscission and crop load, with fruitlet abscission tending to increase with increased crop load (Figure 4.44). A larger proportion of fruit also abscised during the “off” (low cropping) season of 2019/20, compared to the “on” (high cropping) seasons of 2018/19 and 2020/21 (Figure 4.44). A strong relationship was found between starch levels in individual ovaries during flowering and eventual fruit retention (Alcaraz et al., 2013). In this instance the higher the starch levels in the ovary, the higher the probability that the fruit will reach maturity. Large variation also occurred between individual flowers, indicating that some flowers compete more strongly for available starch reserves. In addition, no significant correlation (r^2 = 0.04) was found between starch levels in the wood of the main stem and fruitlet abscission during the 2020/21 season. Based on this, it is currently hypothesized that those fruit that set from flowers which had a lower ability to compete for carbohydrate reserves, will eventually be the fruit that abscise. In a separate study, it was shown that fruit that abscised had higher levels of ABA than fruit that remained on the tree (Garner and Lovatt, 2016). In terms of alternate bearing, fruitlet abscission was most likely also related to the levels of carbohydrate reserves (Davie et al., 1995). The competition between fruit for water, nutrients and carbohydrates and its relationship with fruitlet abscission and ABA levels needs more detailed investigation, especially under conditions of water stress.

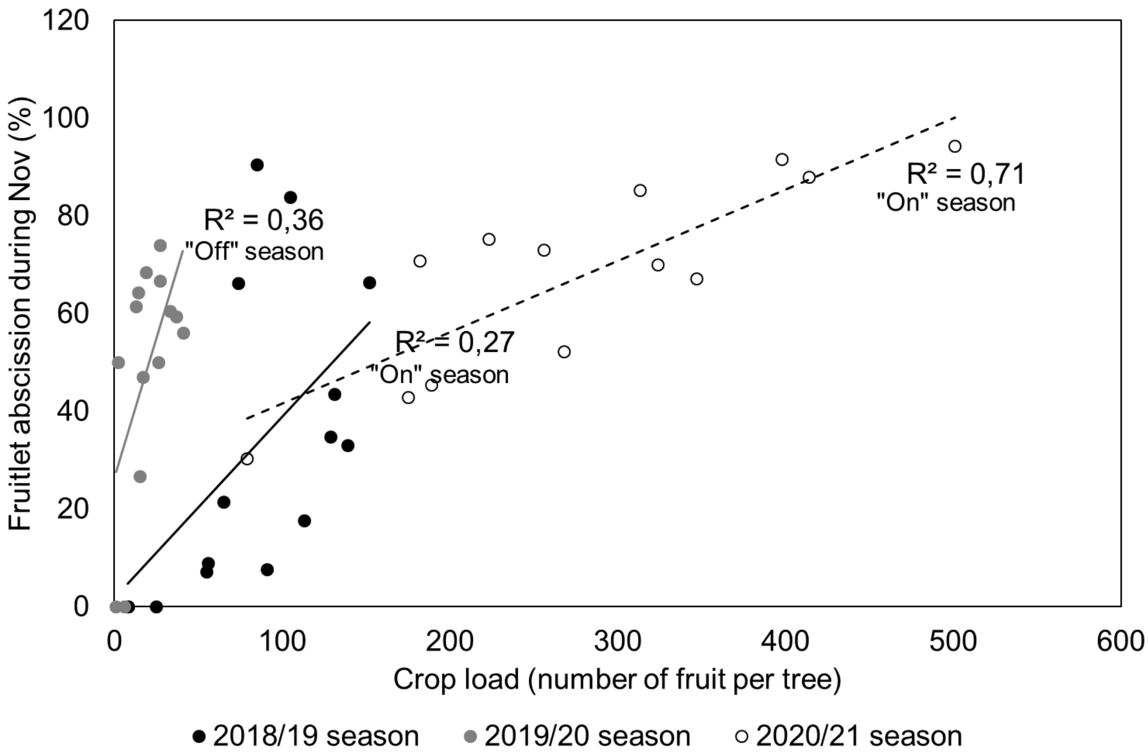

Figure 4.44: The effect of crop load on fruitlet abscission during the "November fruit drop" period for the 2018/19, 2019/20 and 2020/21 seasons

With higher rainfall received during the fruit growth period (428 mm in 2018/19 and 555 mm in 2019/20) it was more challenging to dry out the soil below the threshold level of -40 kPa, even though plastic sheets were used to exclude rainwater from the drip area of the trees. For the 2018/19 season, the topsoil for the water stress treatment was dried out below -40 kPa for a one month period between mid-November and mid-December 2018 (Figure 4.45 A). For the 2019/20 season, the top soil for the water stress treatment was dried out below -40 kPa for a one month period in November 2019 and again for a short period during the beginning of February 2020 (Figure 4.45 B). The soil for both the fully irrigated and water stress treatments was therefore relatively wet during both the 2018/19 and 2019/20 seasons and it is unlikely that significant water stress occurred for the water stress treatment. There were also no significant differences between the midday stem xylem water potential values at all measurement dates between the different treatments for both the 2018/19 and 2019/20 season (Figure 4.45 A & B). The midday stem xylem water potential values were relatively high (above -0.5 MPa), indicating that stressful conditions were not successfully implemented during this phenological stage for both seasons. During November and December, rainfall was lower for the 2020/21 season compared to the other two seasons (see Figure 4.38), resulting in the soil of the stress treatment being dried out significantly more than for the fully irrigated treatment (Figure 4.45 C). In this instance, both the top and sub-soil were drier than -100 kPa, which implies removal of all plant available water and stress conditions should therefore have been created. Unfortunately, midday stem xylem water potential values did not differ substantially between the fully irrigated and stress treatments.

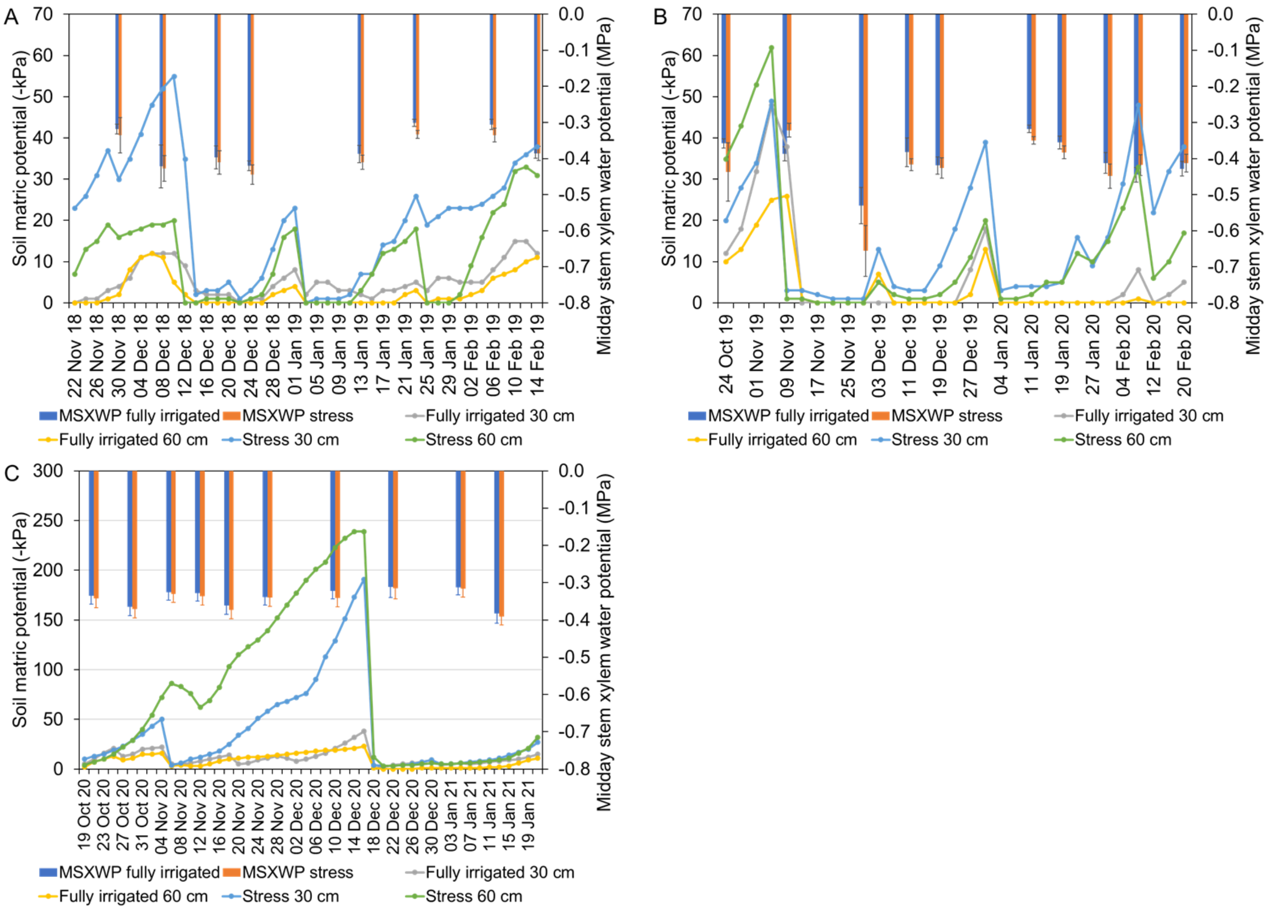

Figure 4.45: Soil matric potential and tree midday stem xylem water potential for the period during which water stress was applied during fruit growth for the Nelspruit experimental site for the A) 2018/19 season, B) 2019/20 season and C) 2020/21 season

Application of water stress during the 2020/21 season resulted in a tendency for higher fruitlet abscission (statistically non-significant) (Figure 4.46). There is therefore some indication that water stress may increase fruitlet abscission. Water stress, however accelerated fruitlet abscission as it was documented that fruitlet abscission started two weeks earlier for the stress treatment, compared to the fully irrigated treatment. As the soil for the water stress treatment could not be dried out sufficiently, no significant treatment effect was obtained for fruitlet abscission (Figure 4.46). A significant seasonal effect was also obtained with a larger proportion of the fruit that abscised during the “off” season of 2019/20 compared to the “on” seasons of 2018/19 and 2020/21 (Figure 4.46). Possible reasons for the higher fruitlet abscission during the 2019/20 season include altered tree carbohydrate levels during “on” and “off” years as explained above.

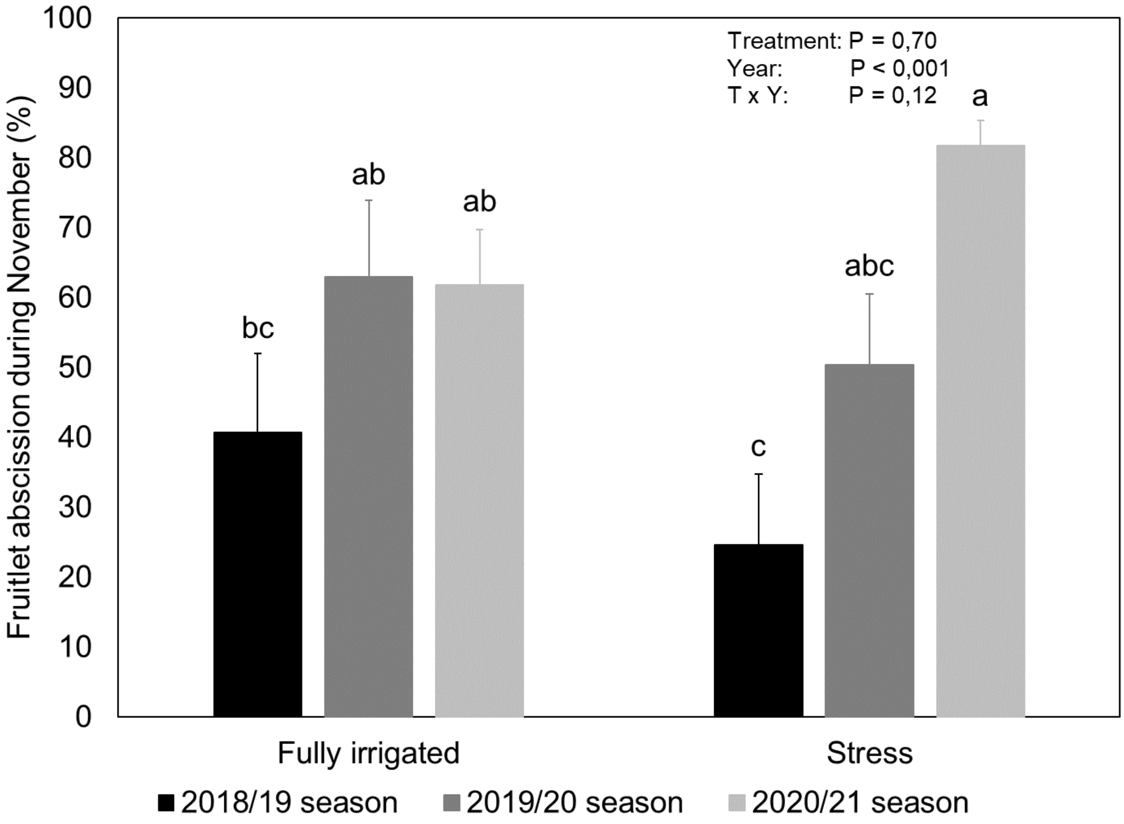

Figure 4.46: The effects of water stress on fruitlet abscission during the “November fruit drop” period for the 2018/19, 2019/20 and 2020/21 seasons.

4.3.5 STRESS APPLIED DURING FRUIT MATURATION

For the 2018/19 season, both the top and sub-soil was dried out below -40 kPa for a one-month period between March and April 2019 (Figure 4.47 A). For the remainder of the fruit maturation period the soil was relatively wet. The exposure of trees to water stress conditions during this phenological stage was therefore relatively short for the 2018/19 season. For the 2019/20 season, soil water was depleted below -40 kPa for almost a two-month period (mid-February to April 2020) (Figure 4.47 B). Unfortunately, some soil matric potential data was lost for April 2020 due to the COVID-19 lockdown when the batteries of the logger failed. It is, however, unlikely that the soil would have dried out substantially during the period of data loss due to the high rainfall that was received during April 2020 (140 mm for the month, with two events of 55 mm and 45 mm, Figure 4.38). Nevertheless, soil conditions for the water stress treatment were drier for the 2019/20 season than for the 2018/19 season and the likelihood of water stress was therefore higher during 2019/20. It is also evident during the 2018/19 season the midday stem xylem water potential was lower for the stress treatment when compared to the fully irrigated treatment during the period the soil was much drier for the stress treatment, which was at the end of March 2019 (Figure 4.47 A). During the remaining period of fruit maturation for 2018/19, midday stem xylem water potential did not differ between the treatments (Figure 4.47 A). Unfortunately, for the 2019/20 season the number of measurements carried out for midday stem xylem water potential was limited by the COVID-19 lockdown period (Figure 4.47 B).

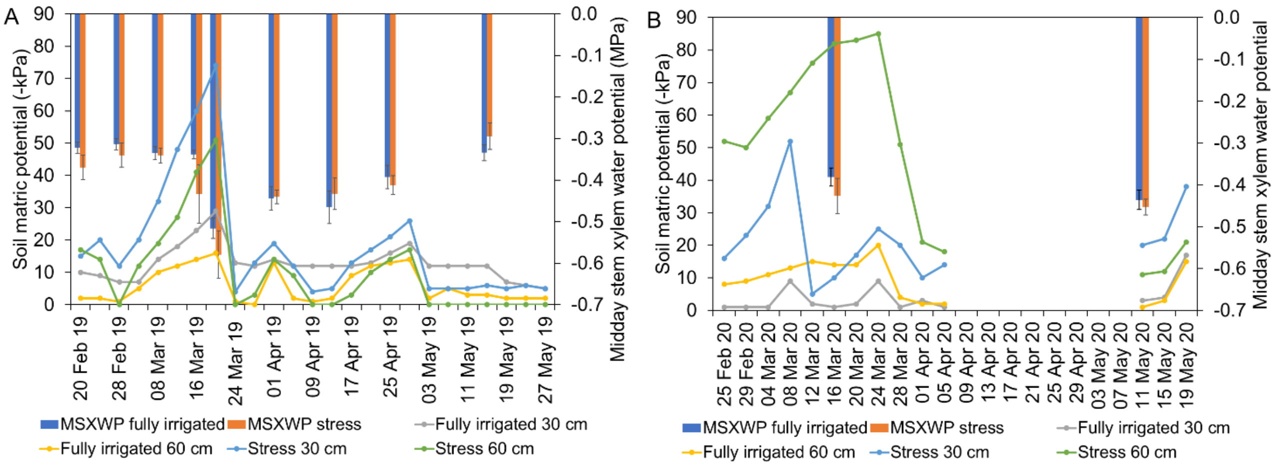

Figure 4.47: Soil matric potential and tree midday stem xylem water potential for the period during which water stress was applied during fruit maturation for the Nelspruit experimental site for the A) 2018/19 season and B) 2019/20 season

During the early stages of fruit maturation, significant fruit growth still occurs and water stress during the early stages of fruit maturation may still negatively impact final fruit size. The relatively short period of water stress during early fruit maturation for 2018/19 had no significant impact on fruit size. However, the much drier soil conditions during the early stage of fruit maturation for the 2019/20 season had a negative impact on final fruit size with fruit from the water stress treatment being approximately 26% smaller than fruit from the fully irrigated treatment (Figure 4.48).

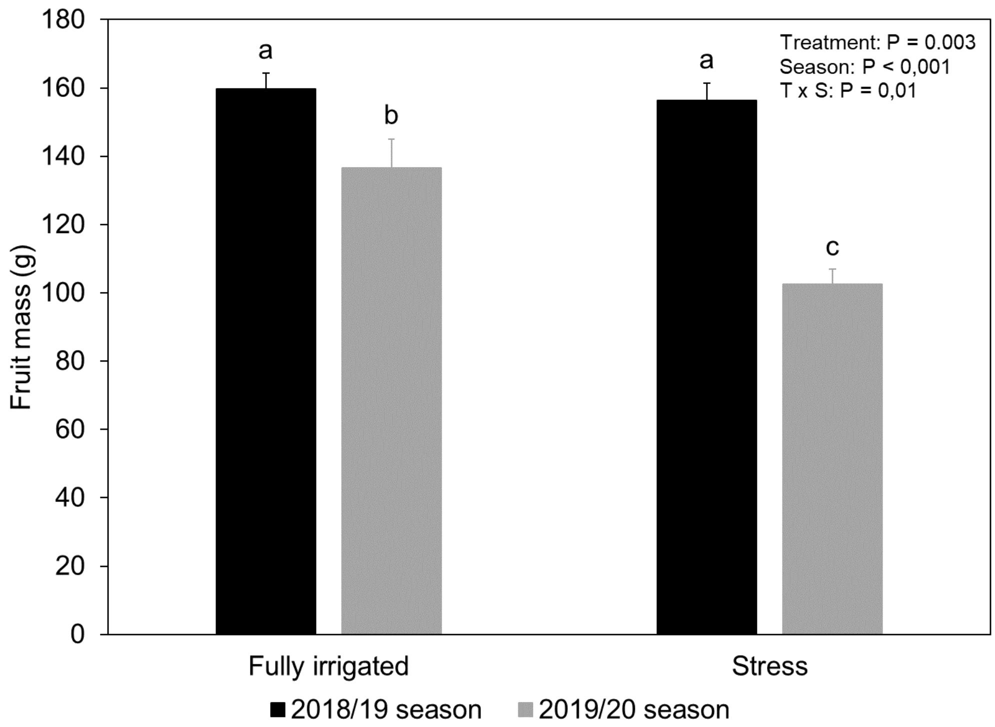

Figure 4.48: Effects of water stress applied during fruit maturation on fruit size of 'Hass' avocado fruit during the 2018/19 and 2019/20 seasons

Avocado fruit, as with many other commodities, lose moisture during extended cold storage periods. It can be seen from Figure 4.49 that moisture loss was gradual during both seasons. When the different treatments were compared, moisture loss for both the fully irrigated and stress treatments were similar for the first 8 to 10 days of storage at 5.5°C (Figure 4.49). Thereafter, fruit from the fully irrigated treatment lost more water than fruit from the water stress treatment at fruit maturation until removal from cold storage. Total fruit moisture loss was significantly more for the 2019/20 season compared to the 2018/19 season for both fully irrigated and water stress treatments (Figure 4.49). Fruit for the 2019/20 season was only cold-stored for 26 days and not for 28 days because the cold room broke down and fruit had to be removed before the entire 28 day cold storage period.

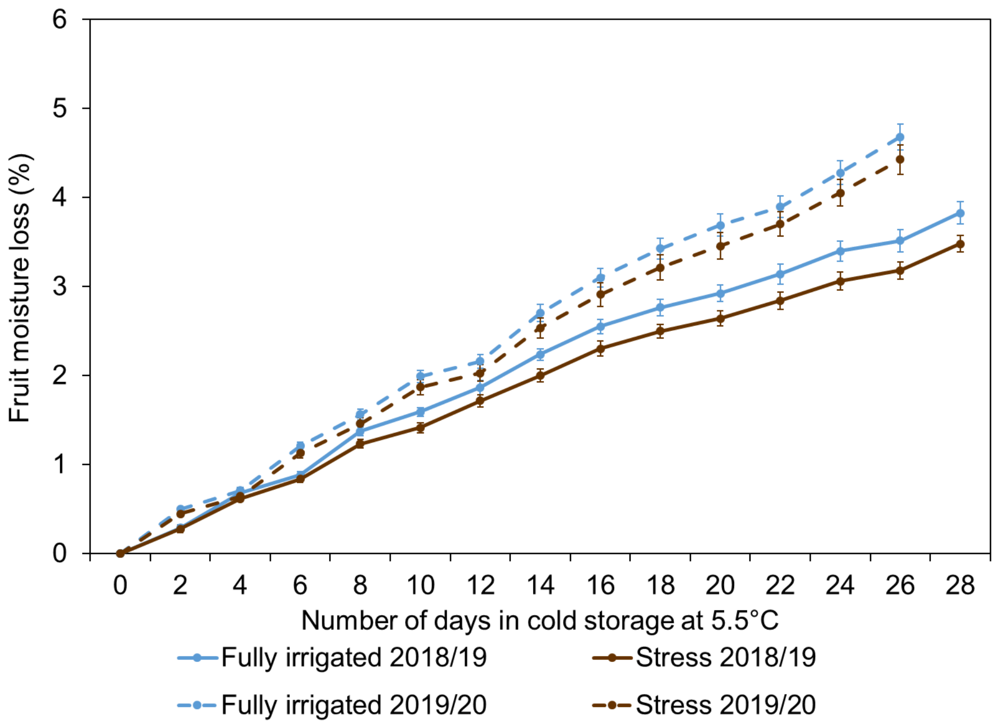

Figure 4.49: Fruit moisture loss during cold storage at 5.5°C of fruit from fully irrigated and water stressed (during fruit maturation) 'Hass' avocado trees grafted on 'Duke 7' rootstocks for the 2018/19 and 2019/20 seasons

In terms of internal fruit quality, application of water stress had no significant effect on the incidences of fungal rots (Table 4.13). In general, infection of fruit with both stem-end-rot and body rots was low and of no real economic importance. The incidence of both vascular browning and vascular staining was significantly higher in the water stress treatments when compared to the fully irrigated treatment (Table 4.13). Vascular staining was mostly confined to the micropyle area in the mesocarp and was therefore not of much concern. In addition, the drier soil during 2019/20 caused a higher incidence of vascular staining during 2019/20, compared to 2018/19 when soil was wetter. The incidence of both postharvest physiological disorders was therefore strongly linked to pre-harvest stress factors, in this instance, water stress. Diffuse mesocarp discoloration was absent from both treatments during both seasons.

Table 4.13: The effects of water stress at fruit maturation on quality of 'Hass' avocado fruit

Year	Treatment	Stem-end-rot (% of fruit infected)	Body rot (% of fruit infected)	Vascular browning (% of fruit infected)	Vascular staining (% of fruit infected)
2018/19	Fully irrigated	1.3 ab[#]	0.7 a	0.0 b	2.5 c
	Stress	1.4 a	2.9 a	2.5 a	10.6 b
2019/20	Fully irrigated	0.0 b	6.7 a	0.0 b	0.0 c
	Stress	0.0 b	6.7 a	2.1 a	12.9 a
Treatment		$P = 0.75^{NS}$	$P = 0.53^{NS}$	$P = 0.005^{**}$	$P < 0.001^{**}$
Year		$P = 0.01^{**}$	$P = 0.47^{NS}$	$P = 0.99^{NS}$	$P = 0.34^{NS}$
T x Y		$P = 0.01^{**}$	$P = 0.53^{NS}$	$P = 0.99^{NS}$	$P = 0.50^{NS}$

[#]Means followed by different letters differ significantly at P < 0.05

4.3.6 STRESS APPLIED DURING FLOWERING

Flowering data was first collected during the 2019/20 season, but not during the 2018/19 season. This is because the trial at the Nelspruit site started at the beginning of fruit set for the 2018/19 season. During the 2019/20 season, soil was relatively wet during the flowering period for both the fully irrigated and stress treatments, with the exception of the first month during flowering when the top-soil of the stress treatment was dried out to be below -40 kPa (Figure 4.50 A). During the 2019/20 season soil was wet due to the farm staff regularly irrigating and ignoring instructions given for correct scheduling. During the 2020/21 season, the soil of the water stress treatment was dried out sufficiently with both the top and sub-soil being generally drier than -40 kPa (Figure 4.50 B). During flowering, midday stem xylem water potential did not differ significantly between the treatments, even during the periods when the soil of the stress treatment had been depleted significantly (Figure 4.50 A & B). It would therefore appear as if midday stem xylem water potential may not be a strong indicator of water stress in avocado. Schaffer and Whiley (2003) suggested that stomatal conductance is a more reliable indicator of the early onset of water stress. The strict control of leaf water potential, as a result of stomatal closure could be why midday xylem leaf water potential is not a good indicator of water stress in avocados. Whiley and Schaffer (1994) cited a number of publications from the late 1970s and early 1980s where a decline in stomatal conductance was reported when leaf water potential dropped below -0.4 MPa.

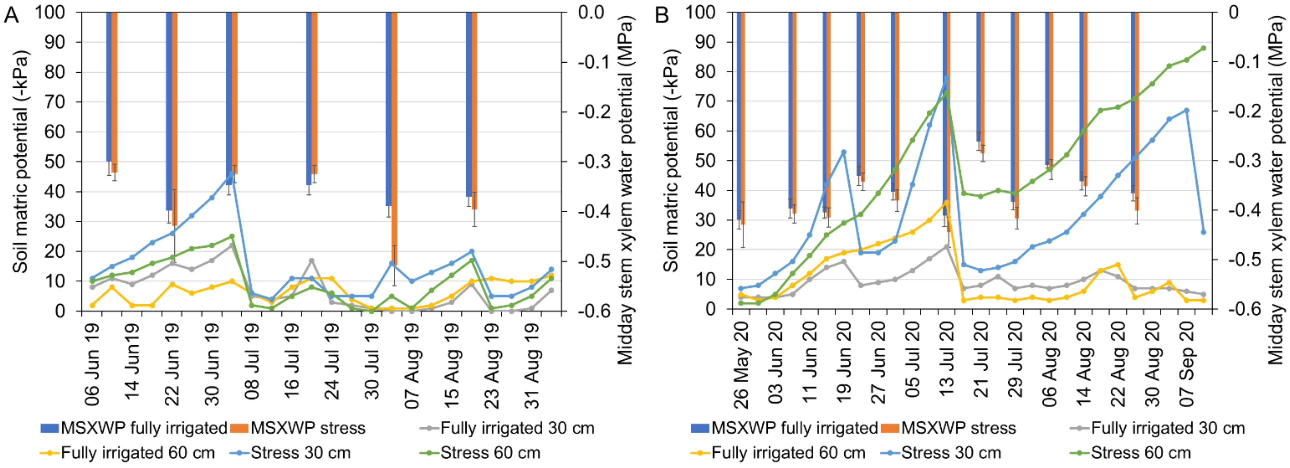

Figure 4.50: Soil matric potential and tree midday stem xylem water potential for the period during which water stress was applied during flowering for the Nelspruit experimental site for the A) 2018/19 season and B) 2019/20 season

The application of water stress had no significant effect on flowering intensity, as flowering in the stress treatments did not differ significantly from the control in either season (Figure 4.51). An earlier study confirmed these results, as Chaikiattiyos et al. (1994) concluded that water stress does not affect flowering, but flowering in avocado is rather triggered by low temperatures during late autumn to early winter. A significant season effect was observed, where trees flowered more profusely during the 2020/21 season compared to the 2019/20 season (Figure 4.51). As mentioned earlier, the autumn and winter in 2020 was significantly colder than in 2019, which could have triggered heavier flowering during the 2020/21 season, compared to the 2019/20 season. In addition, tree carbohydrate levels could also be higher, since the flowering of the 2020/21 season occurred after an “off” year and that could also have contributed to more profuse flowering in the 2020/21 season.

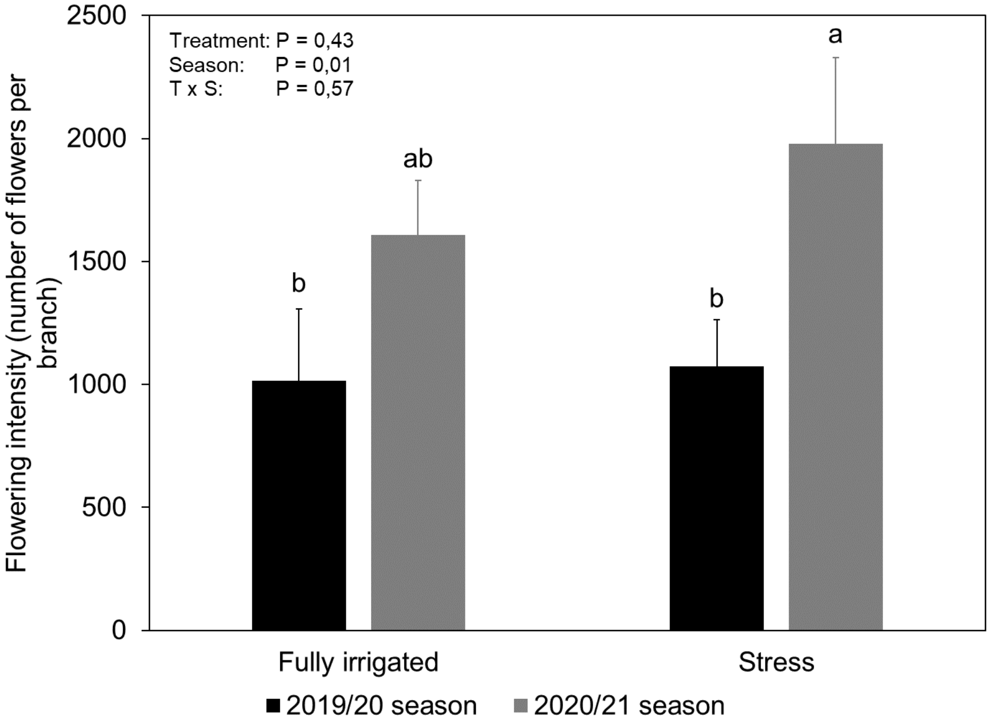

Figure 4.51: Effect of water stress applied during flowering on flowering intensity of ‘Hass’ avocado trees grafted on ‘Duke 7’ rootstocks

4.3.7 THE EFFECT OF WATER STRESS AT DIFFERENT PHENOLOGICAL STAGES YIELD

Water stress implemented during different phenological stages had a significant effect (P = 0.02) on yield (Figure 4.52), with water stress decreasing yield. The yield reduction was most prominent when water stress was applied at fruit set (Figure 4.52). Applying a water stress at other phenological stages had a less dramatic effect on yield, although it should be noted that during the course of the study the same level of stress was not achieved during all phenological stages from fruit growth to fruit maturation. It is evident that water stress during fruit set likely causes the largest reduction in yields, indicating that this is a critical stage at which water stress should be avoided. Season had a highly significant (P < 0.001) effect on yield. Yield for the 2018/19 season was significantly higher than for the 2019/20 season. This can be ascribed to the alternate bearing behaviour of trees in this orchard, in which case 2018/19 was a high cropping season (“on season”), while 2019/20 was a low cropping season (“off season”). It is expected that for this orchard 2020/21 will be an “on season” again. It should also be noted that the yield for 2019/20 had to be estimated as a result of theft during the COVID-19 lockdown.

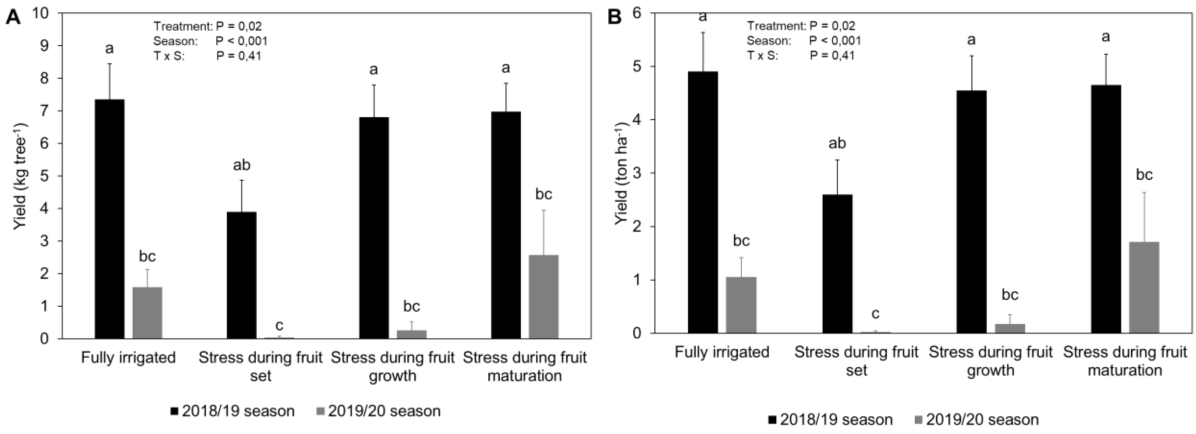

Figure 4.52: The effect of water stress at different phenological stages on yield of 'Hass' avocado trees in terms of A) kg tree^{-1} and B) t ha^{-1}.

4.3.8 MIDDAY STEM XYLEM WATER POTENTIAL AS AN INDICATOR OF WATER STRESS FOR AVOCADO

The application of water stress had no significant effect on mean midday stem xylem water potential for any of the phenological stages (Table 4.14). Even though fruit set was negatively affected by the drier soil conditions during both 2018/19 and 2019/20, mean midday stem xylem water potential was very similar for the fully irrigated and water stress treatments for both seasons.

Table 4.14: The effect of water stress on midday stem xylem water potential of 'Hass' avocado trees

Year	Treatment	Fruit set	Fruit growth	Fruit maturation	Flowering
2018/19	Fully irrigated	-0.33 a$^{\#}$	-0.37 a	-0.38 a	-0.38 a
	Stress	-0.35 a	-0.39 ab	-0.40 a	-0.37 a
2019/20	Fully irrigated	-0.33 a	-0.41 bc	-0.40 a	-0.37 a
	Stress	-0.32 a	-0.43 c	-0.41 a	-0.37 a
Treatment		P = 0.57 ^{NS}	P = 0.09 ^{NS}	P = 0.14 ^{NS}	P = 0.75 ^{NS}
Year		P = 0.21 ^{NS}	P < 0.001**	P = 0.38 ^{NS}	P = 0.60 ^{NS}
T x Y		P = 0.38 ^{NS}	P = 0.95 ^{NS}	P = 0.89 ^{NS}	P = 0.82 ^{NS}

$^{\#}$Means followed by different letters differ significantly at P < 0.05, means are for midday stem xylem water potential at each phenological stage, measured in MPa.

For the fruit growth stage, midday stem xylem water potential values were slightly more negative for the 2019/20 season compared to the 2018/19 season. For both fruit maturation and flowering, midday stem xylem water potential values were similar for both seasons and for both the fully irrigated and water stress treatments. As mentioned above this could suggest that midday stem water potential is not the best indicator of water stress in avocado trees.

A relatively strong and significant linear correlation was obtained between midday leaf transpiration rate and midday stem xylem water potential (Figure 4.53). For this correlation, the midday transpiration rate decreased with decreasing midday stem xylem water potential. In Figure 4.53 values can be grouped into two distinct groups. Relatively high transpiration rates occurred when midday stem xylem water potential was above -0.5 MPa, whilst lower transpiration rates occurred when midday stem xylem water potential values were below -0.5 MPa. It was also noted that stomatal conductance decreased when midday stem xylem water potential dropped below -0.5 MPa (data not shown), indicating that stomatal closure below -0.5 MPa started to occur, which may indicate the onset of water stress. The correlation between midday stem xylem water potential and photosynthesis was non-linear (Figure 4.54). In this instance there was a tendency that the rate of photosynthesis peaked at midday stem xylem water potential values of between -0.40 and -0.50 MPa, where after it decreased by approximately 50% at -0.70 MPa. There were unfortunately not many readings above -0.35 MPa for photosynthesis and further work is necessary to establish a proper relationship between midday stem xylem water potential and the rate of photosynthesis. When considering midday stem xylem water potential measurements during the various phenological stages when stress was imposed, it is evident that values seldom fell below -0.5 MPa and it is therefore unlikely that stomatal conductance and photosynthesis would have been impacted. This reaffirms the finding that despite withholding irrigation to the trees during each phenological stage, sufficient stress was not induced in the treatments for a sufficient period of time.

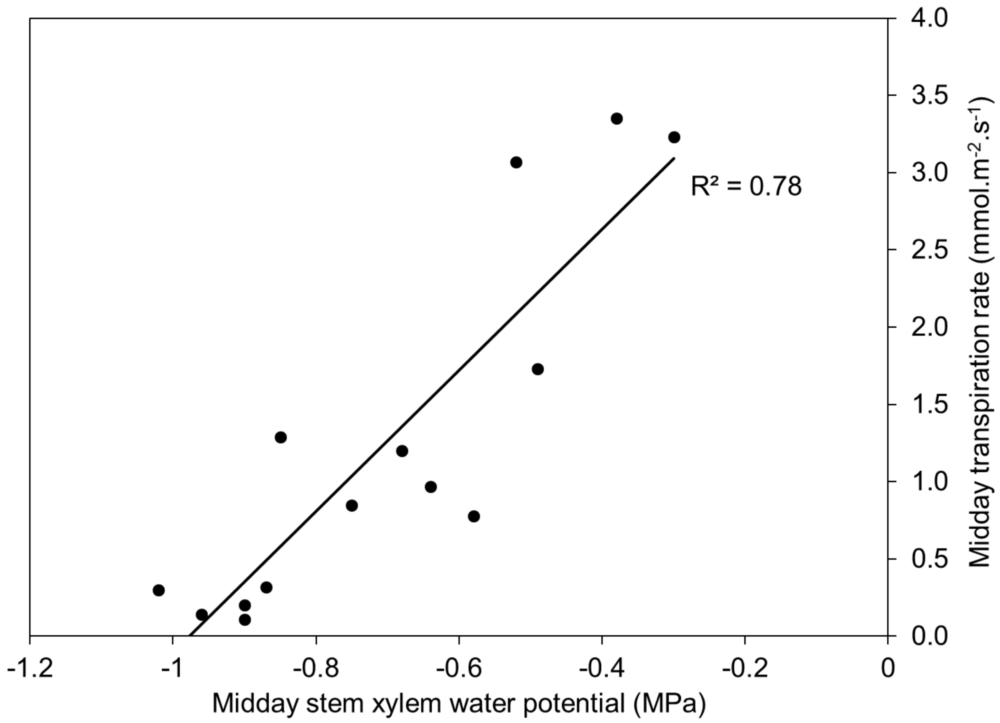

Figure 4.53: Relationship between midday transpiration rate and midday stem xylem water potential of 'Hass' avocado trees grafted on 'Duke 7' rootstocks

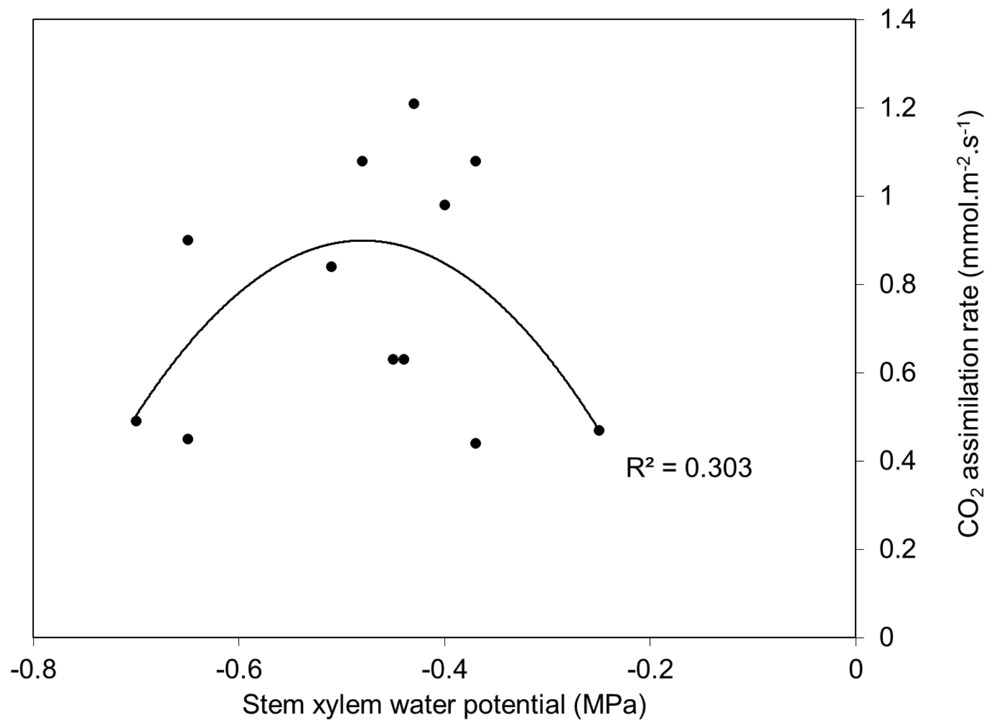

Figure 4.54: Relationship between midday photosynthesis rate and midday stem xylem water potential of 'Hass' avocado trees grafted on 'Duke 7' rootstocks

A strong and significant non-linear correlation was obtained between midday stem xylem water potential and soil matric potential of the sandy-clay soil of the experimental site (Figure 4.55). In this instance, midday stem xylem water potential decreased with decreasing soil matric potential. This was expected as increased xylem tension is associated with an increase in soil drying. However, the changes in midday stem xylem water potential were relatively small (-0.25 MPa) over a wide range of soil matric potentials (0 to -70 kPa). This helps explain why there were no significant differences in mean midday stem xylem water potential values between the control and stress treatment for each phenological stage (Table 4.14), even though the soil in the stressed treatment was significantly drier than the fully irrigated control. Similar results were presented in an earlier study on avocado (Sharon et al., 2001), where little change in leaf turgor pressure was recorded, even under conditions of drastic soil water depletion. In the study by Sharon et al. (2001), it was also shown that leaf water potential values rarely dropped below -1.3 MPa, which is much higher than for most other crops. This was ascribed to high elasticity of the leaves. It is therefore possible that the tree can already experience water stress, with the effects of this water stress being manifested in production and growth, as demonstrated in this study, without midday stem xylem water potential values dropping significantly from unstressed trees. It is, however, evident that a significant drop in midday stem xylem water potential occurred when soil matric potential fell below -40 kPa, indicating the possibility of a stress response. However, this decrease is not drastic and was approximately 0.1 MPa (Figure 4.55). Midday stem xylem water potential on its own is therefore not a reliable indicator of water stress in avocado, regardless of the fact that it correlated strongly with soil matric potential. Other plant indicators should therefore be investigated for avocado and possibly be used in conjunction with midday stem xylem water potential to indicate water stress.

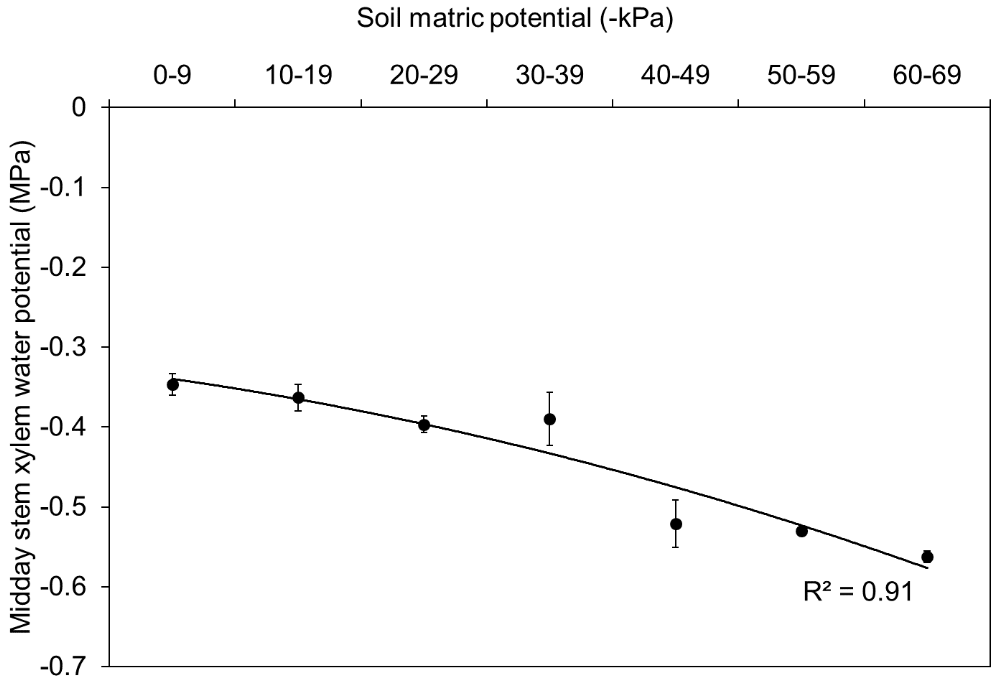

Figure 4.55: Relationship between midday stem xylem water potential of ‘Hass’ avocado trees grafted on ‘Duke 7’ rootstocks and soil matric potential of a sandy-clay soil

4.3.9 CONCLUSIONS

This study has shown that avocado trees and therefore yields are sensitive to water deficits, even if water deficits are moderate or only occur for relatively short periods of time. Water deficits resulted in stress that led to a negative impact at every phenological stage (with the exception of flowering) during which a water deficit stress was applied. The fruit set stage is especially sensitive, as fruit set occurs during early spring when conditions are generally hot and dry, with very high VPD and low rainfall. If orchards are not adequately irrigated during fruit set, crop losses of even more than 50% could potentially occur. The fruit growth stage is less critical as fruit growth typically takes place during the summer when rainfall is high. The probability for water stress during fruit growth is therefore low in years with “normal” rainfall, as was evident from challenges to dry the soil sufficiently to induce water stress during this study. However, it was shown in this study, when rainfall is low during summer, fruitlet abscission during the fruit growth period may be accelerated. It is therefore important to monitor soil water conditions, even during the summer when rainfall is high, to prevent excessive drying that may lead to water stress. Irrigation should therefore be applied strategically during periods to ensure that soils do not dry out to stressful levels. During fruit maturation, fruit growth decreases significantly, while the moisture content of fruit decreases until the fruit reaches harvest maturity. This stage occurs during late summer and autumn when rainfall generally declines and soil may dry out to levels where water stress may occur. Water stress, even for relatively short periods during fruit maturation may lead to higher incidences of postharvest physiological disorders, lowering the marketability of the fruit. When dry soil conditions occur early during fruit maturation, when significant fruit growth still takes place, fruit may even be smaller thereby further affecting the marketability of the fruit. Water stress, however, had no effect on flowering. Water deficit stress therefore negatively affects production, fruit size and quality, which will eventually negatively affect marketability and farm income. Irrigation must therefore be optimized, using proper measurement, monitoring and scheduling tools in order to avoid water stress. From this study results indicate that when the soil was dried out to a matric potential of lower than -40 kPa, negative impacts on yield and quality were noted. A reliable plant physiological indicator, which should aid in optimizing irrigation scheduling, should be investigated further, as results from this study showed that midday stem xylem water potential on its own was not a reliable indicator of water stress for avocado trees.

5. GENERAL DISCUSSION AND CONCLUSIONS

This study has provided comprehensive measurements of evapotranspiration (ET) and transpiration (E_c) over a number of seasons, in a number of different sized orchards, across two climatic regions (Table 5.1). Average ET for the three orchards in Howick were very similar and ranged between approximately 1000 to 1150 mm per season or 10 000 to 11 500 m^3 per season. Transpiration was, however, dependent on canopy size and ranged from 30 mm per season for a young non-bearing orchard to 680 mm in a mature orchard. Thus, while newly planted orchards have fairly low water requirements, it is important to make provision for when orchards are mature and will require significantly higher volumes of water to sustain growth and productivity. The large variation in day to day E_c and ET was a result of changing weather conditions, with E_c of avocado trees shown to be driven largely by solar radiation and vapour pressure deficit (VPD). However, E_c did not always increase at the same rate as VPD increased and after a strong initial positive response, E_c tended towards a plateau value as ET_o and VPD passed a certain threshold value. This suggests that E_c of avocado trees is not demand limited but at times could be limited by the rate at which the tree is able to transport water from the roots to the leaves. This needs to be taken into account when modelling water use, as the crop coefficient approach is a demand limited model.

Table 5.1: Summary of tree water use of the avocado orchards in Howick and Tzaneen (ND-not determined)

	Mature orchard		Intermediate orchard		Non-bearing orchard		Tzaneen orchard	
	L	**Mm**	**L**	**mm**	**L**	**mm**	**L**	**mm**
Annual E_c	18 984	678	10 052	359	840	30	15 232	476
Max E_c per day	121	4.31	70	2.51	4.4	0.16	84	2.63
Avg. E_c per day	53	1.90	27	0.98	2.3	0.08	42	1.31
Annual ET	21 056	752	32 256	1152	31 472	1124	ND	
Max ET per day	207	7.40	225	8.02	201	7.17	ND	
Avg. ET per day	67	2.41	81	2.89	87	3.11	ND	
Canopy cover	0.90		0.56		0.16		0.58	
WUE (kg m^{-3})#	1.23	1.61	1.18	1.62	ND		ND	
WUP (R m^{-3})#	24.39	50.64	30.47	53.06	ND		ND	

#values are for the 2017/18 season and 2018/19 season

By estimating evaporation (E_s) as a residual of ET and E_c measurements it was possible to assess variation of this component of the water balance between different orchards. It was evident from these estimations that canopy cover had a significant influence on E_s rates in various orchards. The mature orchard with the largest canopy cover had the lowest rates of E_s, with E_s constituting 15% of ET on average over the measurement period. This fraction increased to 66% in the intermediate orchard and 97% in the non-bearing orchard. This clearly illustrates that in younger orchards evaporation makes up a considerably greater proportion of ET, which is considered non-productive or non-beneficial consumptive water use. As a result, when the tree canopy is still relatively small and shades only a small percentage of the orchard floor there is considerable opportunity to reduce evaporation and make water savings. Such strategies may include, mulches and reducing the area of surface wet by irrigation.

As these values are specific to a single orchard for a single year, a number of models were evaluated to make these values applicable to a wide range of orchards in different climatic regions. Although, improvements are still required to the crop coefficient approach, this study has contributed to much better estimates of both K_c values and K_t values for avocado orchards (Figure 5.1), which can be used to estimate seasonal water use for planning purposes. Crop coefficient values were fairly similar for all three orchards where ET measurements were conducted. Values tended to be lowest in early spring and highest in early winter, with an average of 1.0 for all three orchards for the duration of the study. This indicates that total orchard water use was very similar to ET_o on a yearly basis. However, these K_c values are likely to be very specific to this region, especially for the orchards with lower canopy cover and will reflect the regularity of surface wetting by rainfall and irrigation which impact evaporative losses from the orchard floor. Importantly, K_t values are likely to be more similar between orchards and will largely depend on canopy size. Values for K_t for orchards with different canopy covers are provided in Table 5.2 and these represent an improvement on the values suggested for avocado by Allen and Pereira (2009). This is because this study clearly demonstrated lower K_t values in summer than winter. In order to predict K_t values for orchards differing in canopy size to those in Table 5.2, a fairly simple approach to estimate orchard specific crop coefficients was evaluated in this study and was found to provide reasonable estimates of K_t for different orchards, provided estimates of ET_o, canopy cover and tree height are available,

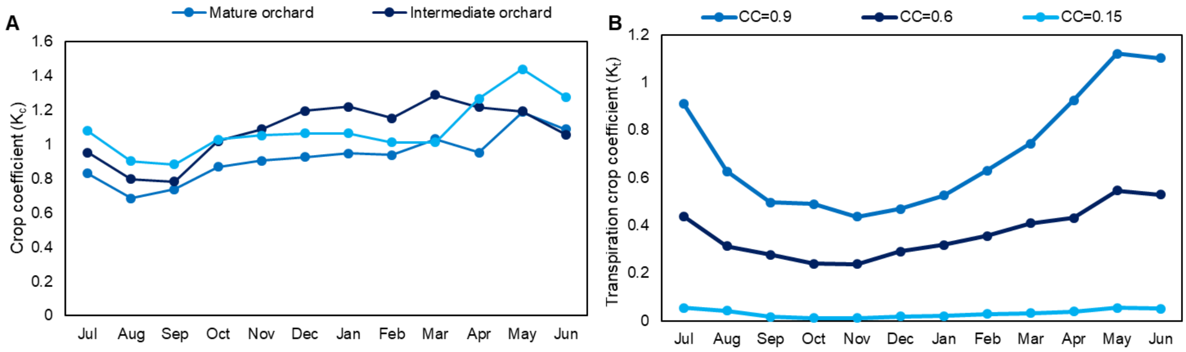

Figure 5.1: A) Crop coefficients (K_c) and B) transpiration crop coefficients (K_t) for orchards with varying canopy covers (CC)

Table 5.2: Values for transpiration crop coefficients (K_t) for avocado orchards with a range of canopy covers (CC)

Month	CC=0.9	CC=0.6	CC=0.15
July	0.91	0.44	0.05
August	0.63	0.31	0.04
September	0.50	0.28	0.02
October	0.49	0.24	0.01
November	0.44	0.24	0.01
December	0.47	0.29	0.02
January	0.53	0.32	0.02
February	0.63	0.36	0.03
March	0.74	0.41	0.03
April	0.93	0.43	0.04
May	1.12	0.55	0.06
June	1.10	0.53	0.05

Alternatively, if hourly weather data is available, together with estimates of LAI, then the Jarvis approach together with the Penman-Monteith equation should provide reasonable estimates of g_c, which in turn should provide good estimates of daily and monthly E_c. This model was, however, parameter intensive and required reasonable estimates of both g_c and g_a, which can be difficult to obtain. The estimation of g_c through the Jarvis approach is also fairly empirical and did not simulate g_c in the Tzaneen orchard with the same degree of accuracy as the orchards in Howick. As the study orchards were well coupled to the atmosphere, it is possible to consider that g_a is not limiting to E_c rates and therefore an alternative approach was assessed where E_c was estimated directly. This less data intensive modified Jarvis-Steward approach provided reasonable direct estimates of E_c, which can be used with good confidence on a fortnightly basis to estimate E_c. Once again canopy size needed to be considered to provide reasonable estimates of E_c and because this is also an empirical approach, the model did not perform as well when used for the Tzaneen orchard. Although all the models performed better on a fortnightly or monthly basis than on a daily basis, this study still represents significant progress in the modelling of avocado water use, that can be used for planning purposes.

This study also determined the impact of water stress at different phenological stages on yield and quality of avocado orchards, where it was demonstrated that avocado trees, and therefore yields, are sensitive to water deficits, even if water deficits are moderate or only occur for relatively short periods of time. Stress during times of low rainfall seemed to be particularly harmful to final yield and this typically occurred during the fruit set stage. At this stage there is the potential for more than 50% of the crop to be shed under stressful conditions. The probability for water stress during fruit growth is low in years with "normal" rainfall. However, irrigation should be applied strategically during dry periods to ensure that soils do not dry out to stressful levels, as fruit growth can decline during these periods. Water stress, even for relatively short periods during fruit maturation may lead to higher incidences of postharvest physiological disorders, lowering the marketability of the fruit. Irrigation must therefore be optimized, using proper measurement, monitoring and scheduling tools in order to avoid water stress and to make the most of available rainfall.

6. RECOMMENDATIONS

This study represents the first step in determining water use of avocado orchards and whilst measurements were made in a number of orchards varying in canopy size in two climatic zones, some questions still remain, largely because the performance of water use models was not always acceptable in the different orchards. More robust ways of estimating canopy size need to be evaluated as it was clearly evident in this study that transpiration was dependent on canopy size. Remote sensing techniques to determine canopy volume and radiation interception models, which account for changes in leaf area density as a result of pruning practices need to be tested and parameterised for avocado orchards. This will allow for improved water use modelling in orchards with different canopy sizes. The relatively poor performance of the Jarvis approach to estimate canopy conductance suggests that more mechanistic approaches should be investigated for the estimation of canopy conductance. In this respect the approach suggested by Villalobos et al. (2013) should be evaluated. In addition, in order to understand constraints within the plant to water use, more detailed ecophysiological studies for avocado under a range of conditions need to be performed. This should include diurnal and seasonal variation in gas exchange and water relations and the manner in which crop load impacts these processes. Understanding the partitioning of evapotranspiration between soil evaporation and transpiration is important as transpiration should ideally be maximised in orchards, whilst evaporation should be minimised. Modelling of evaporation needs to be done to account for changes in wetting patterns of irrigation and by rainfall in relation to changes in canopy size and shading of the orchard floor. This should allow for scenario testing by growers in order to try and minimise this component in orchards, thereby allowing for water savings.

Whilst two seasons of water stress treatments were completed in this study, there were stages when it was very difficult to implement water stress due to high rainfall. As a result, the impact of continuous mild water stress during these stages is still largely unknown. These stages typically occurred in summer. In addition, more research on the thresholds at which stress is experienced by avocado trees could contribute significantly to our knowledge of how to schedule irrigation for avocado trees. This could help answer the question of at what soil water depletion level irrigation should be implemented. The combined determination of predawn and midday stem water potentials together with gas exchange, could help determine suitable plant-based indicators of water stress, which could then be matched to soil water depletion levels.

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7. CAPACITY BUILDING

7.1 DEGREE PURPOSES

One student has graduated from this section of the project – Ms Letisha Govender BSc (Hons) Hydrology. However, two students are in the process of completing their PhDs and one student will submit his MSc dissertation shortly.

Ms Evidence Mazhawu PhD (busy with thesis writing)
"Modelling water use of avocado orchards" Ms Mazhawu is registered for her PhD at the University of KwaZulu-Natal. Her studies focus on the water use and modelling of avocado orchards of different ages.

"Water is a key component for agricultural production success. Determining the exact water requirements help improve water use efficiency and avoid loss of already scarce water resources. With agriculture being the greatest consumer of available water resources in South Africa, it is imperative to determine the exact water requirements of any given crops. Water needs of avocado orchards are met through irrigation, hence knowledge of water use is vital for continual growth and expansion of the industry. The main objective of the study was to determine the unstressed water use of avocado trees under South African conditions. Measurements were conducted in three orchards at Everdon Estate, Howick, KZN Midlands varying in canopy size. Orchards were microsprinkler irrigated and managed according to the industry standards. Precise estimation of actual evapotranspiration (ET) and transpiration are vital for orchard water management. Evapotranspiration in both orchards was determined using Eddy covariance systems. Transpiration rates were estimated using the heat ratio method (HRM) of the heat pulse velocity technique. Reference evapotranspiration was calculated from the weather parameters recorded by an automatic weather station on the farm. Additional measurements included stomatal conductance, predawn leaf water potential, volumetric water content and leaf area index (LAI). These field-scale ET data and crop coefficients will be critical for irrigation management of avocado orchards and are the first water use results in South Africa using eddy covariance method."

Mr Nico Roets PhD (busy completing the last season of data collection)
"The impact of water stress at different phenological stages on avocado yield and quality" Mr Roets will be registering in 2021 at the University of Pretoria. Mr Roets has assessed the impact of water stress at different phenological stages on avocado yield and quality.

“Many South African avocado producing regions are regularly facing drought conditions where water allocations are reduced. Understanding which phenological stages are most sensitive to water stress will allow the correct allocation of water resources throughout the season to avoid a major impact on yield and quality. This study therefore aimed to induce a slight water stress during flowering and fruit set, early fruit growth and fruit maturation and to determine the impact of water stress at each stage on final yield and quality of the avocado trees. A number of physiological studies were also performed in order to understand if and when the trees were experiencing stress. This will assist growers in future to fine tune irrigation scheduling practices in avocado orchards.”

Mr Ruvekh Singh MSc Hydrology (will submit dissertation in first quarter of 2021)
“The Evaluation of Conventional and Earth Observation techniques to measure the water use of Avocado Trees: A Case Study at the Everdon Estate Avocado Orchard” Mr Singh is registered for an MSc degree in hydrology and assessed the feasibility of remote sensing to determine the water use of avocado orchards.

“Water security is a growing concern across the globe and especially in South Africa, due to a growing population and increasing variability in rainfall patterns due to climate change. Agriculture is one of the biggest users of available water in South Africa, so it is imperative that crops are irrigated with minimal wastage as possible. Dwindling water stocks need to be used as efficiently as possible, this requires a greater understanding of the hydrological cycle. Evapotranspiration (ET) is a vital component of the hydrological cycle, however, the measurement of ET is challenging. Conventional methods used to physically measure ET such as the eddy covariance technique or scintillometry are difficult, expensive and time consuming. An alternative to traditional methods is remote sensing, which can estimate ET efficiently and economically on a large scale, however, there is a level of uncertainty in these estimations. Previous studies have shown promising results and support in-situ measurements well, but further investigation was required. This study aimed to evaluate the use of remote sensing to estimate ET using the Penman-Monteith equation corrected with satellite derived normalized difference of vegetation index (NDVI) using a crop factor (K_c) linear regression equation. These estimates were evaluated against measured ET using an eddy covariance system at two avocado orchards at different growth stages (mature and intermediate sized orchards). The satellite derived NDVI was validated using Spectral Reflectance Sensors (SRS) used to measure NDVI and photochemical reflectance index (PRI). Two study sites were selected for the project, both located in the Everdon estate, Howick, KwaZulu-Natal, where two EC systems in different avocado orchards were set up, and measurements are ongoing. The satellite derived NDVI values have correlated well with the SRS measured NDVI. This collectively with the use of Google Earth Engine to process and download the NDVI values from Sentinel-2 images, the satellite derived ET estimations looks promising in comparison to EC measured ET at the two sites.

Ms Letisha Govender BSc (Hons) Hydrology (Graduated 2020)
"The water use a of non-bearing avocado orchard". Ms Govender completed her BSc (Hons) degree in 2020 and focussed on the water use of a non-bearing avocado orchard.

"Avocados are one of the fruits that are in high demand, and farmers are expanding their production. However, there is little to no information on the water use of avocado orchards, especially young avocado trees, making any water resource planning challenging. In these young orchards, the trees are relatively small and much of the interrow is exposed to incoming solar radiation, which can result in high rates of evaporation from the grass cover and soil in between trees. Depending on the irrigation system and vegetation in between the trees, transpiration is often a very small percentage of total evapotranspiration. Differentiating between beneficial (tree transpiration) and non-beneficial (evaporation from the soil and grass cover) water use will provide useful information for growers to maximise water use efficiency of these young orchards and reduce non-beneficial water use."

7.2 NON-DEGREE PURPOSES

7.2.1 ORGANISATION

Capacity building, in terms of both measurement techniques and modelling, was built at the various institutions, as a result of collaboration between the different institutions, which all have a unique set of skills. These skills included the estimation of transpiration through sap flow techniques, estimation of total evapotranspiration using the eddy covariance technique, ecophysiology measurements relating to water relations of the crops and horticultural knowledge of the phenological cycle of the crops. In addition, training of technical personnel within the institutions was performed.

7.2.2 COMMUNITY

The information obtained in this study was disseminated to Technical Advisors in the subtropical fruit industry in order to ensure that producers can take advantage of the improved understanding of water use of both avocado and macadamia orchards. It was therefore possible to improve the capacity of the broader subtropical fruit producing community in terms of irrigation management and scheduling. Results from the project were shared with farmers and irrigation consultants on a number of occasions and a number of popular articles were published.

8. KNOWLEDGE DISSEMINATION AND TECHNOLOGY TRANSFER

Conference proceedings

Mazhawu, E., A. D. Clulow, N. J. Taylor, and M. J. Savage. 2020 Water use of an intermediate and a mature avocado orchard. In *XXX International Horticultural Congress IHC2018: International Symposium on Cultivars, Rootstocks and Management Systems of 1281*, pp. 555-562.

Popular articles

Mazhawu, E., A. D. Clulow, M. J. Savage, N. J. Taylor, 2018 Water use of avocado orchards – Year 1. South African Avocado Growers' Association Yearbook 41: 37-41

Mazhawu, E., A. D. Clulow, M. J. Savage, N. J. Taylor, 2019 Water use of avocado orchards – Year 1. South African Avocado Growers' Association Yearbook 42: 48-51

Mazhawu, E., A. D. Clulow, M. J. Savage, N. J. Taylor, 2020 Water use of avocado orchards – Year 1. South African Avocado Growers' Association Yearbook 43: 11-17

Taylor, NJ; Clulow AD, Roets N. 2019 What is the best way to manage irrigation in avocado orchards. Subtrop Journal 26: 26-29

Presentations at local and international conferences

E. Mazhawu, A.D. Clulow, N.J. Taylor and M.J. Savage. Measurement and comparison of water use in an intermediate and a mature avocado orchard. 30th International Horticultural Congress 2018 in Istanbul, Turkey from 12-16 August 2018

NJR Roets and NJ Taylor. The effects of water stress at different phenological stages on growth, production and postharvest fruit quality of avocado. January 2020 Combined Congress Bloemfontein.

NJ Taylor, NJR Roets, E Mazhawu, A Clulow and MJ Savage Presentation to the SAAGA Letaba Study Group on 11 July 2017, outlining the scope of the project, the measurement plan and the importance of the work.

NJ Taylor, NJR Roets, E Mazhawu, A Clulow and MJ Savage Water use of avocado orchards. SAAGA Research Symposium 15 February 2018

NJ Taylor, NJR Roets, E Mazhawu, A Clulow and MJ Savage How thirsty are avocado orchards? SAAGA Research Symposium 14 February 2019

NJ Taylor, NJR Roets, E Mazhawu, A Clulow and MJ Savage How thirsty are avocado orchards? Presentation to SAAGA Letaba study group on 14 May 2019 in Tzaneen providing more detailed results from the study.

NJ Taylor, NJR Roets, E Mazhawu, A Clulow and MJ Savage How much water do avocado orchards need and what happens if there is not enough water? SAAGA Research Symposium 13 February 2020

NJ Taylor, NJR Roets, E Mazhawu, A Clulow and MJ Savage How much water do avocado orchards need? SAAGA Levubu Virtual Study Group 2 June 2020

NJ Taylor, NJR Roets, E Mazhawu, A Clulow and MJ Savage How much water do avocado orchards need and what happens if there is not enough water? SAAGA Virtual Research Symposium 17 February 2021

9. DATA STORAGE

All data from the study will be stored on Google drive as facilitated by the University of Pretoria and on external hard drives at the University of Pretoria, Hatfield, Pretoria.