Water Use of Macadamia Orchards

Volume 2

Report to the

Water Research Commission

and

Macadamias South Africa NPC

by

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This report forms part of a series of two reports. The other report is *Water Use of Avocado Orchards* (WRC Report No 2552/1/21).

EXECUTIVE SUMMARY

BACKGROUND

Adequate water for irrigation is critical for the sustainability and continued growth of the macadamia industry. As there is unlikely to be an increase in the water allocation to agriculture, industry expansion needs to take place within the existing allocation, obliging growers 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, which results in growers often receiving reduced water allocations during these years. The growing population and increased demand from industry is placing existing scarce water resources in South Africa under even more pressure and agriculture needs to compete with these two sectors for water. 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 macadamia orchards is required. Currently there is a considerable gap in knowledge on water use of macadamia 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 macadamia orchards and to assist in the fair allocation of water resources to growers and the Validation and Verification of Lawful Water Use.

A recent census by SAMAC estimates that close to 44 800 ha are planted to macadamia in South Africa, with just over 5000 ha planted in 2020 (SAMAC, pers. comm. 2020). The most important established growing areas for macadamias are found in Limpopo, Mpumalanga and KwaZulu-Natal, with smaller plantings in the Eastern Cape and Western Cape. The most popular cultivars currently planted are ‘Beaumont’ (695) and ‘A4’, which are often grafted on ‘Beaumont’ rootstocks. South Africa is the largest producer of macadamias in the world, with 98% of the produce exported (https://www.samac.org.za/industry-statistics/). The macadamia industry therefore makes an important contribution to the gross domestic product, with the total value of the industry increasing from R32 million in 1996 to approximately R4.8 billion in 2021 As macadamias are evergreen they require water all year round. In South Africa macadamias are largely grown in the summer rainfall region, and therefore a large portion of the water requirements can be provided by rainfall, but irrigation is crucial during dry periods (e.g. in spring during flowering and nut set) and has become critical in areas suffering from droughts in recent years. Macadamia orchards therefore represent a significant user of freshwater, with optimal irrigation of orchards required for optimal production. Importantly, some evidence suggests that macadamias may be sensitive to too much water.

Accurate information on the water use of macadamia 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 macadamia in relation to yield at orchard scale.

Specific objectives

1. To measure unstressed water use of macadamia according to seasonal growth stages from planting to mature canopy size for selected cultivars and locations;
2. To model unstressed water use of macadamia 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 macadamia on yield and quality for selected cultivars and locations;
4. To quantify water use efficiency and water use productivity of macadamia for selected cultivars and locations

SCOPE OF THE PROJECT

The project encompassed the quantification of transpiration and evapotranspiration of three macadamia orchards varying in canopy size in a single climactic region in South Africa. Weather data were also collected in conjunction with these measurements in order to determine the driving variables for macadamia water use. Detailed ecophysiological measurements were also performed to ensure the determination of unstressed water use and to help explain how the environment and the hydraulic capacity of the tree impact tree transpiration. These data were used to evaluate water use models for use in macadamia 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 one orchard. The second aspect of the project was to determine the impact of water stress at different phenological stages on yield and quality of macadamias. 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 and nut set, nut sizing and premature nut drop, shell hardening and oil accumulation stages. These treatments were compared to a well-watered control, in which irrigation was scheduled by the grower.

METHODOLOGY

The study for the determination of water use of macadamia orchards was conducted in the Schagen Valley, approximately 30 km from the town of Nelspruit in the Mpumalanga Province. The area has a seasonally dry sub-tropical climate ideal for macadamia production, although environmental conditions can vary considerably. On average the area has an annual precipitation of approximately 750-850 mm and has an annual average temperature of 23°C, with January typically being the hottest month (Schulze, 1997).

This study encompassed the measurement and modelling of water use of macadamia orchards from planting to mature canopy size and the impact of water stress at different phenological stages on yield and quality of macadamias. The cultivar in all study orchards was ‘Beaumont’ (695) grafted onto ‘Beaumont’ rootstocks. This is the predominant cultivar planted in South Africa and is a hybrid of *Macadamia integrifolia* and *Macadamia tetraphylla*. It is favoured for its precocity and high yields and is considered to be drought tolerant. For the water use measurements trials were conducted in the 2016/17, 2017/18 and 2018/19 seasons in three orchards varying in canopy size. The mature full-bearing orchard was characterized as an orchard were a complete hedgerow has formed and where canopy cover exceeds 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 are trees that have yet to bear a commercial crop and where canopy cover was lower than 15%. Details of these orchards are provided in Table 1. All the orchards were irrigated using microsprinklers, with a delivery rate of 50 L h^{-1}. Irrigation was typically scheduled once a week with soil water content monitored using DFM capacitance probes in the mature orchard. However, in the two other orchards a fixed weekly irrigation schedule was followed, with approximately 150 L tree^{-1} week^{-1} in the intermediate orchard and approximately 50 L tree^{-1} week^{-1} in the non-bearing orchard. 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).

Table 1: Details of 'Beaumont' macadamia orchards where transpiration measurements were performed

Orchard	Mature bearing		Intermediate bearing		Non-bearing
GPS co-ordinates	25°21'50.36" S, 30°46'46.47" E		25°21'2.01" S, 30°43'44.30" E		25°23'43.47" S, 30°46'59.24" E
Start	10-08-2016		16-08-2017		17-04-2018
End	07-08-2018		04-06-2019		05-04-2019
Duration (days)a	728		720		354
Age (years)	11		5		1
Planting pattern (m)	4 m x 8 m (32 m^2), planted on ridges		4 m x 8 m (32 m^2), planted on ridges		4 m x 8 m (32 m^2), planted on ridges
Planting density (trees ha-1)	312		312		312
Orchard area (ha)	3.8		3.0		5.0
Canopy cover[a]	0.72		0.28		0.08
Height (m)[a]	5.7		4.2		1.6
ET_o (mm)	1196[x]	1189[y]	1189[y]	1195[z]	1195[z]
Rainfall (mm)	1170	760	760	774	774
Irrigation (mm)	164	135	ND[b]		ND
Transpiration (mm)	340	316	195	167	11

[a] at the start of the trial
[b] ND – not determined
[x] 2016-2017
[y] 2017-2018
[z] 2018-2019

Transpiration in these orchards was determined using the heat ratio method, which is a heat-pulse sap flux density method. These measurements occurred for the duration of the trial. Evapotranspiration (ET) was determined for window periods in the mature and non-bearing orchards using an open path eddy covariance system. Additional data collected included leaf area index (LAI), fractional interception of photosynthetically active radiation (PAR), volumetric soil water content, tree water status, gas exchange, stomatal conductance and yield and nut quality. These additional data were used for modelling exercises and to explain the water use patterns of the macadamia trees in response to weather variables. Attempts to model the water use of macadamia 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 transpiration with estimates of canopy conductance using a parameterised Jarvis approach, whilst direct estimates of transpiration were obtained following a modified Jarvis-Steward type model, as proposed by Whitley et al. (2009).

Using the data (transpiration and yield and quality) obtained in the mature orchard, water use efficiency (WUE) was calculated as kg dry nut in shell and kg kernel produced per m^3 of water transpired. In addition, by considering grade and style of the nuts from the trees determined by a processor, water use productivity (WUP) was determined as Rands per m^3 of water transpired.

Measurements for the water stress trial took place in the 2017/18, 2018/19 and 2019/20 seasons in a mature 'Beaumont' macadamia orchard and an intermediate orchard on the same farm in the Schagen Valley. Trees in the mature orchard were irrigated by means of one microsprinkler sprinkler (50 L h^{-1}) per tree, with a wetted diameter of 3 m, according to a cycle determined by readings from a capacitance probe (DFM Software Solutions CC, Stellenbosch, Western Cape, South Africa) installed at a 1.2 m depth between two macadamia trees in the orchard. Stress treatments in the 2017/18 season consisted of a control (farmer's irrigation schedule), ½ irrigation (25 L h^{-1} microsprinklers) and a rainfed treatment and these treatments continued for the duration of the trial. In 2018/19 and 2019/20 water stress at different phenological stages were implemented and included flowering and nut set, nut sizing and premature nut drop, shell hardening and oil accumulation stages. 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 using Chameleon sensors, predawn leaf water potentials and midday stem water potentials, stomatal conductance and gas exchange. Yield and quality of the trees in each treatment was determined at the end of each season. Unfortunately, the yield in the 2019/20 could not be recorded due to the COVID-19 level 5 lockdown.

RESULTS AND DISCUSSION

Macadamia photosynthesis (*A*) was found to be slightly lower than that of other evergreen subtropical crops, which is largely attributed to substantial stomatal and non-stomatal limitations to *A*. Non-stomatal limitations to *A* were linked to an internal light limitation resulting from the sclerophyllous nature of leaves. Stomatal limitations stem from the predominantly isohydric nature of macadamias, where stomatal conductance (g_s) is carefully controlled in order to maintain midday leaf water potential within certain safety margins. Isohydric behaviour suggested an underlying hydraulic limitation, which was found to exist within the stem to leaf interface of macadamias. Responses of g_s to leaf vapour pressure deficit (VPD$_{leaf}$) showed that g_s declined as VPD$_{leaf}$ exceeded 2.5 kPa. The response of g_s to VPD$_{leaf}$, however, varied throughout the season, being significantly higher during fruiting periods compared to non-fruiting periods, implying isohydrodynamic behaviour and emphasizing the influence of phenology on leaf gas exchange.

Besides physiological and phenological variables influencing macadamia E_c, physical attributes (i.e. canopy size) and weather variables remained the key driving variables of E_c. Macadamia E_c increased in a linear fashion when VPD$_{air}$ < 0.8 kPa, solar radiation (R$_s$) <0.3 MJ m^{-2} h^{-1} and reference evapotranspiration (ET$_o$) <0.13 mm h^{-1}, but failed to increase at the same rate when these limits were exceeded. The reduction in the rate of E_c in response to increases in environmental evaporative demand under non-limiting soil water conditions, indicates that E_c in macadamias is a supply-controlled system. Supply-controlled E_c was confirmed upon examination of maximum daily recorded E_c ($E_{c\ max}$) in response to increases in the aforementioned weather variables, with daily $E_{c\ max}$ failing to increase at VPD$_{air}$ >1.5 kPa, R$_s$ > 15 MJ m^{-2} day^{-1} and ET$_o$ > 3.5 mm day^{-1}. The response of E_c and $E_{c\ max}$ to these weather variables did not vary between the two orchards, however, the magnitude of both E_c and $E_{c\ max}$ differed between orchards, being highest in the MB orchard. Higher E_c in the MB orchard was largely attributed to a ~60% larger canopy, with E_c in the MB orchard being ~60% more than E_c in the IB orchard.

Transpiration measured in this study, however, remained site specific, and identification and validation of crop water use models were therefore needed to extrapolate data to a broader range of growing environments. Annual E_c for the mature orchard was on average 328 mm, whilst it was 181 mm for the intermediate orchard. Annual E_c was very low for the non-bearing orchard with 11 mm measured. This is, however, reasonable when considering the canopy size in relation to the two other macadamia orchards in this study. The study showed, that a poor estimation of daily transpiration crop coefficient (K$_t$) and subsequently E_c was obtained using the FAO-56 dual crop coefficient model, which was largely attributed to overestimation of K$_t$ and therefore E_c when daily reference evapotranspiration (ET$_o$) rates exceeded 4.0 mm day^{-1}, and an underestimation of K$_t$ and E_c when ET$_o$ < 2.0 mm day^{-1}. The model, however, provided reasonable estimates of K$_t$ and E_c on a monthly or seasonal basis, with only slight discrepancies observed between measured and simulated K$_t$ and E_c from January to April in each season, which was attributed to physiological upregulation of E_c in the presence of fruit. The mechanistic canopy conductance (g_c) estimations in conjunction with the Penman-Monteith equation, provided more accurate estimates of daily E_c in both the MB and IB orchards, compared to the empirical FAO-56 dual crop coefficient model, but was particularly sensitive to seasonal changes in leaf area index (LAI), with adjustments of maximum canopy conductance ($g_{c\ max}$) required to achieve accurate estimates of E_c. An adjustment for variations in LAI, however, failed to increase the accuracy of E_c estimates during the January to April period, reaffirming the phenological and physiological influence of fruit on g_c and E_c during this period. Estimates of macadamia g_c in this study were rather low (0.3-0.7 mm s^{-1}) in relation to g_a (37-75 mm s^{-1}), confirming that macadamias are well coupled to the atmosphere, with an average decoupling coefficient of 0.08 for both orchards. The high degree of coupling in macadamias implies that changes in g_c lead to direct changes in E_c, which contributed to the success of using a simplified mechanistic E_c model. This model provided reasonable estimates of daily E_c without multiple adjustments for canopy size being needed within each of the orchards. This empirical E_c model, similar to the other models tested, however, failed to provide reasonable estimates of E_c during the January to April period.

Water use efficiency and water use productivity in the mature orchard, based on transpiration data and in shell mass, was very similar for the two seasons. Water use efficiency was 0.72 and 0.69 kg m^{-3} for the 2016/17 and 2017/18 seasons respectively. Water use productivity was the same for both seasons with a value of R118 m^{-3}.

Results from the study on the impact of water stress at different phenological stages on yield and quality of macadamia orchards suggest that macadamias are less sensitive to water stress than most other horticultural crops. This is based on the findings that withholding water during key phenological stages had no impact on yield for one season of measurements relative to the control, where irrigation was scheduled by the grower according to soil water measurements. In addition, irrigating half the volume of the grower scheduled control or relying solely on rainfall had no impact on yield over two seasons. A second season of yield measurements quantifying the impact of stress at different phenological stages was unfortunately lost due to the COVID-19 lockdown and these results could have proven invaluable in reaching a more definite conclusion regarding how water stress impacts yield and quality of macadamia orchards. Importantly, what the study has illustrated is that despite withholding irrigation for fairly long periods of time, key indicators of plant stress, did not suggest that the trees were often stressed, when compared to the well-watered control. In the current study, this was complicated by the fact that there was large variation between replicates, which was probably indicative of variations in spatial water availability, which could have resulted in some trees having access to more water than other trees. Nevertheless, tentative results from this study suggest that both predawn leaf water potential and midday stem water potential can be used as indicators of water stress in macadamia orchards, with predawn <-0.6 MPa probably indicating the onset of stress that could impact yield. Importantly, this trial has also demonstrated that the “traditional” ways of scheduling irrigation with capacitance probes may need to be adjusted for macadamia orchards, as a slight yield penalty was noted in the grower control when compared to the half irrigation and rainfed treatments. This suggests possible overirrigation, which had a negative impact on yield. When using the half irrigation as the “control” and comparing to the yield from when water stress was implemented at different phenological stages, yield from the half irrigation treatment was significantly higher than these treatments. This reiterates the importance of choosing the right control and ensuring that this treatment is irrigated optimally. Mild stress was achieved in some trees during the flowering and fruit set stage, when conditions were fairly dry, due to increasing temperatures in spring but as yet no rainfall. This may be a critical time for irrigation in macadamia orchards. However, the impact of VPD on stomatal conductance needs to be considered at this time and relying solely on ET_o to schedule irrigation may result in over-irrigation.

NEW KNOWLEDGE AND INNOVATION

This study is only the second study attempting to quantify transpiration and evapotranspiration of macadamia orchards. This study built on work from a previous WRC project (Report No. 1770/1/14) by measuring transpiration of orchards with different canopy sizes and performing detailed ecophysiological measurements to explain the trends in measured transpiration. Whilst research on the response of macadamia gas exchange and water relations to changing environmental conditions have been published, these have not included a detailed analysis across seasons and these studies were also performed in a more humid region than most of the growing regions in South Africa. This increased understanding of macadamia water relations has allowed the evaluation of suitable water use models and these were parameterised successfully to provide reasonable daily and fortnightly estimates of water use. For planning purposes, the FAO-56 crop coefficient model of Allen and Pereira (2009) can be used on a seasonal basis to provide good estimates for a range of orchards, using the parameters provided by this study. If estimates are required on a shorter time scale then both the Penman-Monteith and Whitley et al. (2009) models can be used with reasonable confidence, especially within the Nelspruit region.

As seasonal estimates of transpiration were made, it was possible to determine water use efficiency and water productivity of the orchards based on seasonal transpiration values. These values should allow benchmarking of the industry in future and provide an indication of the value of water used in the production of macadamia nuts. This is proving to be an important marketing tool for the industry, as consumers aim to consume products that are produced in an environmentally sound manner. As macadamia is an oil storing crop with low yields, it is important to indicate the value of the product per volume of water transpired or evapotranspired.

Whilst results from the water stress trial were not conclusive, as yield was lost in the third season, it demonstrated that the traditional manner of scheduling irrigation in macadamia orchards solely using soil water content measurements and traditional refill and stop points may not always be appropriate and that macadamias are most likely more tolerant of water stress than many other horticultural crops. As yield of the rainfed treatment was not significantly different to the control, it also indicated that rainfall needs to be considered in irrigation schedules and “room should be left” for rain. The study also suggested that a predawn threshold of -0.6 MPa could be used as an indication of mild water stress in macadamia orchards.

CAPACITY BUILDING

There were three students registered on this project (1 PhD and 2 MSc). One of the PhD students (Mr Theunis Smit) graduated in 2020, with a thesis entitled “Seasonal water use dynamics of Macadamia (F. Muell) orchards”. Funding from this project will be used for the remaining two 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 SAMAC research symposium; a scientific publication in *Scientia Horticulturae*, a publication in a conference proceeding and a number of publications in the SAMAC yearbook and other popular publications.

CONCLUSIONS

This study has provided reliable estimates of E_c for three macadamia orchards which vary in canopy size. Furthermore, it was demonstrated that these E_c volumes were dictated by canopy size and the prevailing weather conditions. Whilst E_c increased with increasing canopy size, in an almost linear fashion, the increase of E_c with increasing ET_o was not constant and a plateau was reached when a threshold ET_o was reached. This also applied to VPD and suggested that water use in macadamias is supply limited rather than demand limited. This was confirmed by ecophysiological studies of stomatal conductance and leaf water potential, which demonstrated that macadamias follow a predominantly isohydric water use strategy. In this regard, a decline in stomatal conductance was observed when VPD_{leaf} passed a certain threshold ($\text{VPD}_{\text{leaf}} > 2.5$ kPa). This quick response of stomata resulted in fairly low photosynthetic rates and would also have contributed to the fairly low E_c rates determined in this study relative to many other horticultural tree crops.

The high degree of coupling in macadamias added to the success of mechanistic modelling approaches used in this study, with the Jarvis-Steward type g_c model accurately estimating macadamia E_c on a daily or weekly basis when used in conjunction with the Penman-Monteith equation, provided that canopy size was taken into account using leaf area index (LAI) measurements. The distinct relationship between g_c and E_c, as a result of the high degree of coupling, created an opportunity to estimate E_c directly using a simplified and less parameter intensive model. The study therefore evaluated a model, similar to that proposed by Whitley et al. (2009), in macadamias. Not only did the model provide good estimates of E_c on both a daily and weekly basis, with comparable accuracy to the g_c model, it only required an adjustment for canopy size between orchards, using easily obtained measures of canopy dimensions including canopy width and breadth used in the calculation of the effective fraction of ground cover ($f_{c\ \text{eff}}$). The crop coefficient approach of Allen and Pereira (2009) was also evaluated in this project as it is a widely accepted model. The model, however, provided reasonable estimates of K_t and E_c on a monthly or seasonal basis, which is most likely due to compensatory errors over the longer period of estimation. The FAO-56 dual crop coefficient model could therefore be used with a great degree of reliability by institutions that depend on crop coefficients to determine water allocations.

Results from the water stress study suggest that macadamias are less sensitive to water stress than most other horticultural crops. This is based on the findings that withholding water during key phenological stages had no impact on yield for one season of measurements relative to the control, where irrigation was scheduled by the grower according to soil water measurements. In addition, irrigating half the volume of the grower scheduled control or relying solely on rainfall had no impact on yield over two seasons. Despite withholding irrigation for fairly long periods of time, key indicators of plant stress, did not suggest that the trees were often stressed, when compared to the well-watered control. Nevertheless, tentative results from this study suggest that both predawn leaf water potential and midday stem water potential can be used as indicators of water stress in macadamia orchards, with predawn <-0.6 MPa probably indicating the onset of stress that could impact yield.

RECOMMENDATIONS FOR FUTURE RESEARCH

Whilst this study provided good estimates of transpiration for macadamia orchards from planting to full maturity, these estimates were only provided for a single cultivar. Although this is the dominant cultivar planted in South Africa, it is not very popular in the rest of the world. There is also the perception in industry that different cultivars have different water use behaviours, with some cultivars being more drought tolerant and others “using” more water. It would therefore be of great interest to researchers to determine possible difference in leaf gas exchange between the various cultivars. Of particular interest would be to examine if differences in the response of A_{max} and g_{s} to increases in $\mathrm{VPD}_{\mathrm{leaf}}$ exists between cultivars, and if these differences could help explain cultivar performance in relation to growing environment.

Furthermore, the daily and seasonal total E_{c} reported in this study were unexpectedly low considering the size of trees used in this study. It would therefore be of great value to the macadamia industry to obtain additional measurements of E_{c} in a range of different orchards, consisting of different cultivars and in different regions, to aid macadamia growers in increasing irrigation and water use efficiency. It is further proposed that additional measurements of E_{c} in macadamias are necessary to validate parameters generated in the models developed in this study outside the region of calibration. Of particular interest would be to determine if differences exist in both $g_{\mathrm{c\,max}}$ and $E_{\mathrm{c\,max}}$ between different cultivars, as these parameters could have a significant impact on model accuracy.

This water stress study has provided a good foundation for future research, but there are still many issues which are unresolved. Due to the limited amount of stress measured in the current trial, it will be very important to continue this work in a location where it is easier to implement stress. For this a more uniform orchard needs to be chosen with a deep, well-drained soil. This should hopefully allow the determination of more accurate predawn and midday stem potential thresholds for stress in macadamia and allow for improvements in irrigation scheduling that ensure optimal utilisation of a scarce and finite resource. It will also allow a more in-depth analysis of which are the most sensitive phenological stages to water stress in terms of yield and quality.

GENERAL

The contract objectives for this project have been met, and in some instances even exceeded. Water use was quantified in three orchards in a single climatic region. These orchards fell within a warm subtropical zone in Nelspruit, Mpumalanga. 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 transpiration of these orchards in relation to canopy size and how evapotranspiration is partitioned into transpiration and evaporation in different sized orchards. It also 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 mature orchard.

Three seasons of different irrigation volumes (half the control and rainfed) and two seasons of water stress at different phenological stages were successfully completed during the course of the study. However, due to the COVID-19 level 5 lockdown, the trial could not be harvested by the researchers in the 2019/2020 season and this information was lost. Information gained from this trial will assist growers with knowing when to avoid water stress in their macadamia orchards and should assist in future with refining irrigation scheduling in macadamia orchards, as it would appear that using traditional soil water content measurements and refill points may lead to overirrigation.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABA	Abscisic Acid
ANOVA	Analysis of Variance
AQE	Apparent Quantum Efficiency
AWS	Automatic Weather Station
D	Willmot index of agreement
DIS	Dry in Shell
EC	Eddy Covariance
ET	Evapotranspiration
FAO	Food and Agriculture Organization of The United Nations
GPS	Global Positioning System
IB	Intermediate Bearing
IRGA	Infrared Gas Analyser
LAI	Leaf Area Index
LCP	Light Compensation Point
LSD	Least Significant Difference
MAPD	Mean absolute percentage difference
MB	Mature Bearing
NIH	Nut In Husk
OPEC	Open Path Eddy Covariance
PAR	Photosynthetically Active Radiation (µmol s^{-1})
PFTE	Polytetrafluoroethylene
PPFD	Photosynthetic Photon Flux Density
R^2	Coefficient of Determination
REML	Restricted Maximum Likelihood Estimation
RH	Relative Humidity
RMSE	Root of the mean square error
RWC	Relative Water Content
SAMAC	South African Macadamia Association
SPAC	Soil-Plant-Atmosphere-Continuum
TDP	Thermal dissipation probe
TDR	Time-Domain Reflectometer
TKR	Total kernel recovered
TPU	Triose Phosphate Use
VEPAC	Variance Estimation, Precision & Comparison

VPD	Vapour Pressure Deficit
WIS	Wet in Shell
WRC	Water Research Commission
$\mathrm{WUE_T}$	Water Use Efficiency based on transpiration volumes (kg m^{-3})
$\mathrm{WUP_T}$	Water Use Productivity based on transpiration volumes (R m^{-3})

Symbol	**Description**
A	net carbon dioxide (CO_2) assimilation rate (µmol m^{-2} s^{-1})
A_max	maximum net carbon dioxide (CO_2) assimilation rate (µmol m^{-2} s^{-1})
c_w	specific heat capacity of the wood matrix (J kg$^{-1\circ}$ C^{-1})
c_s	specific heat capacity of the sap (J kg$^{-1\circ}$ C^{-1})
C_i	internal CO_2 concentration (µmol mol^{-1})
$\mathrm{C_p}$	specific heat capacity of air (J kg^{-1} K^{-1}))
d	zero plane displacement (m)
E_c	canopy transpiration (L or mm)
$E_\mathrm{c\ max}$	maximum canopy transpiration (mm)
E_leaf	leaf transpiration rate (mmol H_2O m^{-2} s^{-1})
$\mathrm{E_s}$	evaporation from the orchard floor (mm)
$\mathrm{ET_c}$	crop evapotranspiration (mm)
$\mathrm{ET_o}$	reference evapotranspiration (mm)
dT	temperature difference (ºC)
f_ceff	effective fraction of ground covered or shaded by vegetation near solar noon
$\mathrm{f_{IPAR}}$	fraction of intercepted photosynthetically active radiation
$\mathrm{F_r}$	adjustment factor relative to stomatal control
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})
$g_\mathrm{c\ max}$	maximum canopy conductance (m s^{-1})
g_m	mesophyll conductance (µmol m^{-2} s^{-1} Pa^{-1})
h	mean maximum plant height during the midseason period or full cover period (m)
J_max	electron transport rate (µmol m^{-2} s^{-1})
J	sap flux (kg m^{-2} s^{-1})
K	dimensionless flux constant

k	Von Karman’s constant
k	hydraulic conductance (mmol m^{-2} s^{-1} MPa^{-1})
k_L	leaf specific hydraulic conductance (mmol m^{-2} s^{-1} MPa^{-1})
$k_{soil\text{-}stem}$	hydraulic conductance within the soil to the stem pathway (mmol m^{-2} s^{-1} MPa^{-1})
$k_{stem\text{-}leaf}$	hydraulic conductance within stem to the leaf pathway (mmol m^{-2} s^{-1} MPa^{-1})
$\mathrm{k_w}$	thermal diffusivity of green (fresh) wood (cm^2 s^{-1})
$\mathrm{K_c}$	crop coefficient
$\mathrm{K_{cb}}$	basal crop coefficient
$\mathrm{K_{cb\ full}}$	basal crop coefficients for fully grown orchard
$\mathrm{K_d}$	canopy density coefficient
$\mathrm{K_e}$	soil water evaporation coefficient
$\mathrm{k_{e1}}$	model parameter for vapour pressure deficit
$\mathrm{k_{e2}}$	model parameter for vapour pressure deficit
$\mathrm{k_{D1}}$	model parameter for vapour pressure deficit
$\mathrm{k_{D2}}$	model parameter for vapour pressure deficit
$\mathrm{k_R}$	model parameter for solar radiation
$\mathrm{k_T}$	model parameter for temperature
$\mathrm{K_t}$	transpiration crop coefficient
l	stomatal limitation (%)
LE	latent energy
$\mathrm{m_c}$	moisture content of sapwood sample (%)
$\mathrm{M_L}$	parameter that simulates the physical limits imposed on water flux through the plant root, stem and leaf systems
N	number of samples
$\mathrm{P_a}$	atmospheric pressure (Pa)
$\mathrm{RH_{min}}$	minimum relative humidity (%)
$\mathrm{r_{leaf}}$	mean leaf resistance (s m^{-1})
$\mathrm{r_s}$	mean surface resistance (s m^{-1})
R_{d}	mitochondrial respiration rate (µmol m^{-2} s^{-1})
$\mathrm{R_m}$	arbitrary radiation constant (fixed at 1000 W m^{-2} in this study)
$\mathrm{R_n}$	net radiation flux density (W m^{-2} or MJ m^{-2} day^{-1})
$\mathrm{R_s}$	daily solar radiation (MJ m^{-2} day^{-1})
$\mathrm{R_{so}}$	theoretically derived solar radiation for clear sky (MJ m^{-2} day^{-1})
$\mathrm{S^2}$	sum of squares

SFD	sap flux density (cm^3 cm^{-2} h^{-1})
S_R	solar radiation (W m^{-2})
T_{air}	mean daily air temperature at 2 m height (°C)
T_{leaf}	leaf surface temperature (°C)
T_L	lower temperature limit to transpiration (°C)
T_{max}	maximum temperature (°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)
$\psi_{sun\ leaf}$	sun exposed leaf water potential (MPa)
ψ_{soil}	soil 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)
x	distance between the heater and the upper and lower thermocouple
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})
z	wind measurement height (m)
z_o	roughness length (m)
γ	psychrometric constant (kPa K^{-1})
λ	the latent heat of vaporization (J kg^{-1})

$\propto$	fraction of sunlit canopy leaf area
θ	soil water content
φ	latitude (radians)
δ	solar declination (radians)

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1 INTRODUCTION

1.1 BACKGROUND

The macadamia nut, which is known to be one of the most expensive tree nuts, is a fruit produced by two *Macadamia* (F. Muell) species consisting of *M. integrifolia* (Maiden & Betche) and *M. tetraphylla* (L.A.S. Johnson) and hybrids thereof. These species originated from coastal Australia, with commercial orchards now occurring in many other parts of the world, with South Africa, Kenya, and China currently producing a large portion of the world macadamia crop. The macadamia industry in South Africa has seen rapid expansion in the past 10 years, with the best current estimate of 44 776 ha planted to macadamias across South Africa (SAMAC pers. comm. 2020). Expansion is mostly driven by the global demand and accompanying high prices, but further expansion in many producing countries is limited to some extent by the availability of suitable land, and more specifically by the availability of freshwater suitable for irrigation.

The largest macadamia producing countries, Australia and South Africa, have faced extreme water shortages in the past few decades and more dry weather extremes are expected in years to come (Baudoin et al., 2017, Deo et al., 2017, Malherbe et al., 2016). Shifts in rainfall patterns have seen supplementary irrigated macadamia orchards becoming fully irrigated, if water is available, and rain-fed macadamia orchards becoming rather unproductive. The value of macadamia nuts has, however, seen growers acquiring increased volumes of water, by either purchasing freshwater at exorbitant prices or applying for increased water licencing allocations. Both of these options, although feasible, create a range of social problems, especially when considering that in times of drought, communities are also faced with water restrictions and human consumption of water takes precedence over commercial agriculture. Furthermore, in the era of food labelling (Asioli et al., 2017), macadamias are not seen as a sustainably produced product given negative perceptions of their water footprints and may in fact result in decreased demand by its affluent consumers.

Further complications are linked to the limited research on macadamia water use and irrigation, creating a great deal of uncertainty regarding the water needs of the crop. Most knowledge used by producers has, as a result, been gathered from either trial and error or from studies conducted in Australia (Stephenson et al., 1989; Lloyd, 1991; Lloyd et al., 1991; Trochoulias and Johns, 1992; Stephenson et al., 2003) and one study in South Africa (Gush and Taylor, 2014). Even though this information has guided producers in the management of irrigation in macadamia orchards, these studies did not provide insight into the dynamic relationship between crop physiology and the environmental variables driving macadamia water use. An in-depth understanding of this dynamic relationship could prove to be fundamental to the sustainable production of this high value crop.

Our current understanding of the water requirements of this recently commercialized crop is limited to a few published studies, which have reported water use (evapotranspiration) figures ranging from 720-1200 mm per season (Stephenson et al., 2003; Gush and Taylor, 2014). Anecdotal evidence has also shown that high yields have been reported in areas, such as Hawaii, were annual rainfall exceeded 2000 mm (Stephenson and Trochoulias, 1994). This wide range of reported values reflects the unique nature of ET measurements, which are dependent on both the local climate, tree size and the manner in which the orchard is managed, e.g. irrigation system and pruning. In order to explain these different values, more information is required on the factors which drive macadamia water use, specifically transpiration, and how these factors subsequently influence dry matter accumulation and yield. For example, in areas where annual rainfall exceeds 2000 mm (Stephenson and Trochoulias, 1994), is the volume of water alone driving production or is the increase in humidity accompanying the well distributed rainfall leading to increased production? Currently available research, although limited, would suggest that humidity and more specifically vapour pressure deficit is one of the key driving variables of stomatal conductance (Lloyd, 1991; Lloyd et al., 1991) and would therefore also be a key driving variable of macadamia water use. There is, however, no research on macadamias that have investigated the manner in which other variables impact water use, such as canopy size, crop phenology, and crop physiology, which are fundamentally important to constructing practical and comprehensive irrigation and water requirement guidelines. There is also only limited information available on how water stress during different phenological stages impacts yield and quality of macadamia orchards, which is important for years in which water allocations are reduced during droughts.

Given the lack of research into water use and water relations of macadamia, in combination with the rapid expansion of the industry in areas outside that of the crop’s natural environment, which are often faced with limited freshwater resources for irrigation, it is absolutely critical that crop water use models, which are not only accurate but are easily parameterized and user friendly, be evaluated. To date, no such models have been used in the macadamia industry, which is most likely due to the lack of information needed to successfully parameterize these models (Carr, 2013). Successful parameterization of a crop water use model specific to macadamias, would not only aid growers in selecting sites which are more suitable for production, but will aid them in managing water in existing orchards with greater care, which would subsequently increase efficiencies and sustainability of the crop (Liu et al., 1998, Nguyen et al., 2017, Thorp et al., 2018).

Although various publications have suggested that macadamias are well adapted to a range of environments and have attributes that make them tolerant to extended periods of water shortages (Searle and Lu, 2002; Stephenson et al., 2003; Carr, 2013; Stephenson and Searle, 2014), the current value of the crop, in combination with increased variability in rainfall, dictates a risk aversion strategy amongst macadamias growers, which increases their reliance on freshwater. It is also highly unlikely that this strategy will change in the foreseeable future, due to the continuous growth in demand, and the lag between research and dissemination of results to growers. The increased reliance on freshwater, and lack of water specific research in the macadamia industry therefore motivates the need for this study, which not only addresses some of the current knowledge gaps in the field of macadamia water research, but will attempt to provide more insight into the driving variables of macadamia water use and the responses to water stress. This would serve as a foundation for future research in the field, whilst being fundamental to water licencing bodies, and most importantly to farmers, to aid in the determination of water requirements of macadamias.

Research questions for this study therefore included

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

1.2 AIMS AND OBJECTIVES

General aim

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

Specific objectives

1. To measure unstressed water use of avocado and macadamia according to seasonal growth stages from planting to mature canopy size for selected cultivars and locations;
2. To model unstressed water use of avocado and macadamia 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 and macadamia on yield and quality for selected cultivars and locations;
4. To quantify water use efficiency and water use productivity of avocado and macadamia for selected cultivars and locations.

1.3 APPROACH AND SCOPE

The project began with a comprehensive literature review, which documented current knowledge on macadamia water use and the impact of water stress on macadamia 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. Following the completion of the literature review orchards for measurements were selected.

The measurement phase of the project encompassed the quantification of transpiration and evapotranspiration of three orchards varying in canopy size using a sap flow technique and an open path eddy covariance system. 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 in the Schagen Valley just outside of Nelspruit in Mpumalanga. Orchards were instrumented in a staggered approach in line with the project budget and the availability of equipment from August 2016 to June 2019. Measurements of transpiration typically lasted 2 years in the mature and intermediate orchard and a single year in the non-bearing orchard. Evapotranspiration measurements were conducted for window periods in the mature orchard and non-bearing orchard. Weather data were collected in conjunction with these measurements in order to determine the driving variables for macadamia water use. Measurements of leaf area index and fractional interception of photosynthetically active radiation were performed on a regular basis to provide a measure of canopy size in all three orchards. Ecophysiological measurements were also performed on a regular basis to ensure the determination of unstressed water use and to understand the water use patterns of macadamia trees. These measurements included photosynthesis, stomatal conductance and leaf water potentials. The water use data were used to evaluate water use models for macadamia orchards and included crop coefficient and canopy conductance approaches. Finally, the water use data together with yield and nut price data was used to derive water use efficiency and water use productivity values for the mature orchard over two seasons.

The second aspect of the project was to determine the impact of water stress at different phenological stages on yield and quality of macadamias. For this purpose, an orchard was selected close to Nelspruit in the Schagen Valley. Stress treatments in the 2017/18 season consisted of a control (farmer's irrigation schedule), ½ irrigation (25 L h^{-1} microsprinklers) and a rainfed treatment and these treatments continued for the duration of the trial. In 2018/19 and 2019/20 water stress at different phenological stages were implemented and included flowering and nut set, nut sizing and premature nut drop, shell hardening and oil accumulation stages. In order to ensure that stress was implemented when irrigation to a treatment was stopped, a number of measurements were made which included soil matric potential, pre-dawn and midday stem water potentials and gas exchange. At the end of each season yield and quality of the nuts from each treatment was determined. In 2020 an additional water stress trial was performed on younger trees on a sandy soil to try and determine thresholds for water stress in macadamias in terms of gas exchange and leaf water potentials.

2 LITERATURE REVIEW

2.1 WATER USE

Water use of recently domesticated subtropical fruit tree crops have been largely understudied, making irrigation water management difficult, especially in semi-arid regions where water is a major limiting factor to crop production (Durán Zuazo et al., 2019, Lu, 2000, Moreno-Ortega et al., 2019, Nhamo et al., 2020, Williamson et al., 2015, Wullschleger et al., 1998). The shortage of information could in part be attributed to the relatively young nature of such species (Fuller, 2018, Jackson et al., 2011), but is also due to the long-term nature and complexity of research required in tree crops (Gasque et al., 2016, Klein et al., 2015, Nicolás et al., 2016, Wullschleger et al., 1998). For *Macadamia* F. Muell and more specifically *M. integrifolia* (Maiden & Betche) and *M. tetraphylla* (L.A.S. Johnson) (Proteaceae*)*, the problem is not limited to that of water use, but extends to other fields of agricultural research, including crop morphology and physiology. It compels researchers to prioritise research according to the needs of the industry as a whole, whilst also trying to obtain a better understanding of the dynamic and interrelated nature of crop morphology, physiology, and the environment.

When examining the overall state of macadamia research, most studies have been conducted in either Australia or Hawaii. Hawaii, being the first country to produce macadamias commercially (Stephenson, 2005), has focused its research efforts on the development of a sound understanding of the botany of the crop (Shigeura and Ooka, 1984). This differs substantially from research conducted in Australia, which has prioritized research linked to canopy management (Huett, 2004, McConchie et al., 1999, Wilkie et al., 2010), and improvements in macadamia yields through cultivar selection (Trochoulias, 1990) and increased pollination and fertilization efficiency (Stephenson et al., 1986, Trueman and Turnbull, 1994, Wilkie et al., 2009).

Both countries have not prioritised water-use and irrigation-related research of macadamia, which is most likely due to the limited number of irrigated orchards (Trochoulias and Johns, 1992). Studies by Trochoulias and Johns (1992), which concluded that macadamias responded poorly to irrigation in high rainfall areas of Australia, might also have contributed to the low priority given to this research. Nevertheless, with the high growth rate of macadamia production in South Africa, where most orchards are irrigated, and Australia which is progressing towards an industry more dependent on irrigation due to irregular rainfall (Hajani and Rahman, 2018), water-related research has become a priority. In order to pursue research that can provide applicable and practical results to the industry it is important to understand the current state of knowledge and to identify the potential shortfalls and gaps in research.

Obtaining a clear understanding of each component in the soil-plant-atmosphere-continuum (SPAC) is fundamental to quantifying and improving crop water use (Katul et al., 2012, Reichardt and Timm, 2020). Within the SPAC, the soil acts as the reservoir for water and nutrients, and as a result dictates the supply of water to both the plant and the atmosphere (Cowan, 1965). The physical and chemical characteristics of soil, which dictates water availability to the plant and the atmosphere can be determined fairly easily using a range of well-defined experimental methods (Doran and Parkin, 1994). In a similar fashion, measurements and determination of atmospheric variables, which often quantifies the demand component of the SPAC, can be obtained with relative ease, albeit at a cost, and typically conform to well-defined and universally accepted methods (Allen et al., 1998, Katerji and Rana, 2014).

The plant component of the SPAC varies considerably and consists of multiple components, each with the potential to impact the supply of water from the soil to the leaf as dictated by atmospheric evaporative demand. The difficulty in quantifying the various plant components arises from the inherent genetic variability between and within species, which is further exacerbated in recently commercialized crops. By determining hydraulic conductances within plants, a better understanding of water movement through plants can be obtained, whilst attempting to identify possible constraints within the plant itself, which will in turn have significant impacts on the entire SPAC (Dubbert and Werner, 2019, Hatfield and Prueger, 2016, Knauer et al., 2018).

Even under conditions where each component of the SPAC is quantified and understood, data is often site-specific and the extrapolation of this data to other orchard environments can be rather challenging due to the large variability in soil type, varietal differences and environmental variation. Fortunately, a range of crop water use models, with varying degrees of complexity, can be utilized to simulate complex soil (Radcliffe and Simunek, 2018), plant (DeJong et al., 2011, Zweifel et al., 2007), and atmospheric (Allen et al., 1998) variability. Most models require crop and site-specific parameters, but model selection, especially for crop water use models, is often dictated by the crop behaviour which would imply that an in-depth understanding of the crop is required before any component can be modelled with confidence (Annandale et al., 1999, Bonan et al., 2014, Boote et al., 1996).

2.1.1 MORPHOLOGY AND PHENOLOGY

2.1.1.1 Macadamia leaf characteristics

Like most members of the family Proteaceae, macadamia canopies consist of xeromorphic evergreen leaves, with characteristic sclerified bundle sheath tissue (Carr, 2013). Notwithstanding the fact that macadamia has its evolutionary origin in the fringes of the subtropical rainforests of Australia, evergreen sclerophyllous leaves are more regularly associated with arid habitats and are rather non-characteristic in plants originating from areas with abundant water (Schlesinger and Chabot, 1977). Despite sclerophylly being well documented (Jordan et al., 2005, Salleo and Nardini, 2000) and universally characterised by hard, stiff and leathery leaves, its adaptive significance has been previously questioned (Read et al., 2006). Oertli et al. (1990) describe sclerophyllous leaves to be an adaptation to periodic water deficits by increasing cell wall thickness and rigidity, thereby reducing the risk of cell collapse due to negative turgor pressures associated with water stress. The hard and stiff nature of the leaves can be attributed to an abundance of mechanical cells, such as fibres and sclereids, that are orientated differently within the leaf mesophyll and depending on location, may have different functions (Salleo and Nardini, 2000). For example, mechanical tissues with large enough lumens may serve as water reservoirs during diurnal water deficits, while mechanical cells surrounding vascular bundles were hypothesized to promote leaf rehydration via capillary action following drought induced cavitation (Salleo et al., 1997). Sclerophyllous trees further tend to have thicker leaves due to the thickening of all leaf tissue and the leaf cuticle which aids plants in limiting water loss from aerial tissue (Parkhurst, 1994).

Not only are evergreen sclerophyllous leaves hypothesized to be advantageous to plants for the survival of periodic drought, sclerophylly may be a nonspecific response to a range of stresses (Read et al., 2006, Salleo and Nardini, 2000). In fact, Read et al. (2006)(referencing others) described evergreen sclerophyllous leaves to be an adaptation to, or a consequence of, low-nutrient conditions. This suggests that evergreen sclerophyllous leaves are more nutrient use efficient, allowing trees to be more adapted to nutrient limited conditions, which commonly occur during occasional soil water deficits (Hu and Schmidhalter, 2005, Vietz, 1972). Sclerophylly is further suggested to provide possible resistance to frost damage (Larcher, 2005) or be a response to, or as a result of, excessive solar radiation (Jordan et al., 2005), which may all interdependently influence tree growth and survival. These leaves are especially beneficial for the conservation of minerals by regulating long-term photosynthetic efficiency and the rate of litter fall, limiting nutrient losses and the carbohydrate expenditure to regenerate a new flush (Baldocchi et al., 2010).

Macadamias solely have stomata on the abaxial side of the leaves at densities of 360-500 mm^{-2} (Carr, 2013), which is similar to what is described for other evergreen horticultural crops, such as citrus and olives (Chartzoulakis et al., 1999, Kriedemann, 1986, Stephenson et al., 1989). Stomatal aperture plays a dynamic role in gas exchange, ensuring adequate CO_2 supply, whilst preventing transpiration rates (E_c) in excess of leaf water supply rate (Drake et al., 2019). Leaf stomatal density (expressed relative to the area of the stomata bearing epidermis) and stomatal conductance, inherently regulate maximum carbon uptake rates and the potential rate of water loss from plant leaves (de Boer et al., 2016). Consequently, hypostomatic leaves (leaves with stomata on only one surface) generally having lower stomatal densities than amphistomatous leaves (stomata on both surfaces), and therefore have an inherent constraint to losing excessive amounts of water over short periods (Drake et al., 2019). Moreover, distribution of stomata over only one surface increases leaf boundary layer resistance, further constraining excessive gas exchange, which is of particular importance during periods of high atmospheric evaporative demand in arid environments (Drake et al., 2019, Drake et al., 2013). Hypostomatous leaves with stomates on the abaxial side typically experience lower radiation and therefore lower evaporative demand, due to the lower leaf temperature when compared to leaves with stomates on the sunlit adaxial side (Schymanski et al., 2013). Hence, by locating the most photosynthetically active cells on the abaxial side of the leaf, hypostomatous macadamia isolate sensitive photosynthetic tissue from large leaf-to-air vapour pressure deficits caused by the outside environment (Buckley, 2017, Drake et al., 2019). In addition, the spatially grouped hydraulic tissue of hypostomatous leaves aids in buffering rapid fluctuations in water potentials during gas exchange (Drake et al., 2019). This hypostomatic leaf characteristic therefore contributes to macadamias evolutionary adaptability to often fluctuating environments, but still allows strict control of tree water status and carbon gain to avoid desiccation.

Plant adaptability to arid environments is primarily determined by a plants ability to regulate water loss from aerial tissue (Baker and Procopiou, 1997). Baker (1974) and Whitecross and Armstrong (1972) have shown that the thickness of the leaf epicuticular wax layer is linearly related to environmental conditions, with an increase in thickness as ambient temperature and radiant flux increases, with a corresponding decline in humidity, which is often the case in arid environments. The authors further found that the wax content of the cuticular layer may be directly related to the plant’s adaptability to drought. A detailed study by Baker and Procopiou (1997) showed that macadamia has an exceptionally thick adaxial leaf cuticular layer, which was similar to that of drought tolerant olive (Gimenez et al., 1996, Sofo et al., 2008). The adaxial leaf cuticular layer of macadamia exceeded 1 mg cm^{-2} and contained large quantities of cuticular waxes in the form of long chain aliphatic constituents absorbed in the cutin matrix.

Despite difficulties in the separation of the cuticular membrane, these authors showed that the abaxial side of macadamia leaves are also protected by a substantial cuticular layer, further highlighting the adaptation of macadamia to environmental stresses. Stephenson et al. (1989) and Trochoulias and Johns (1992) showed that macadamia have no additional wax layer, as well as no pubescence, which are common leaf characteristics on other drought adapted species such as olives. Nonetheless, Baker (1974) revealed that thick, tightly absorbed crystalline waxes in the form of an amorphous crust, such as those found on both the adaxial and abaxial leaf surfaces of macadamia (Baker and Procopiou, 1997), aid pistachio and olive in the upkeep of turgidity of plant cells by dissipating large quantities of incident solar radiation. Baker (1974) indicated that plants tend to change the composition and quantity of these epicuticular waxes in response to stresses, raising concern of the potential counterproductive effects of irrigation on the normal mechanisms of drought tolerance in plants.

2.1.1.2 Macadamia root characteristics

As for macadamia canopy characteristic, a thorough understanding of the morphology, growth dynamics and distribution of a trees root system, together with its adaptations to seasonal water deficits, is required in order to assess the feasibility of different irrigation practices (Fereres and Soriano, 2007, Kirda, 2002, Li et al., 1989). These aforementioned root characteristics tend to differ between different tree species, environmental factors and cropping systems (Fernández et al., 1992). For example, general assumptions are that evergreen trees tend to have relatively large root systems, allowing them to access soil water throughout rainless periods. Similarly, tree crops under rainfed arid conditions are assumed to produce deeper roots, which are critical for survival during prolonged periods of water stress.

These stereotypes, however, may not provide an accurate description of the root system of macadamias since, a very detailed study by Firth et al. (2003) described the macadamia root system to have neither of the typical assumed characteristics of an evergreen or a rainfed tree. Firth et al. (2003) described the macadamia root system as relatively shallow and spreading, with the taproot of an un-grafted seven year old seedling and a 12-year old grafted tree being 1.2 m and 0.6 m in length respectively, while a recent study showed macadamias to have an effective rooting depth of 0.8-1.6 m depending on soil type (Carr, 2013). Even though macadamia seedlings develop a taproot, it is invariably damaged during nursery and transplanting procedures and hence the nature of the root system changes (Stephenson, 2004). The roots of other horticultural crops, such as citrus have been recorded up to depths of 3.6 m, the highest abundance of roots were, however, recorded within the top 0.6 m of the soil surface (Bevington and Castle, 1985), while most tea roots are located in the top 0.3 m of the soil (Fordham, 1972).

Firth et al. (2003) showed that the lateral root framework and associated fibrous roots of macadamia trees occur primarily within the upper 0.4 m of the soil surface, with the presence of dense clusters of proteoid roots at the same depth. Firth et al. (2003) also recorded the highest density of both fibrous and proteoid roots within 1.0 m of the trunk, which is consistent with that of deciduous tree crops, such as apples and pears (Atkinson, 1980). This abundance of fine fibrous and proteoid roots is, however, an integral part of the specialised root system of macadamias, as reviewed by Stephenson (2004).

Macadamias and other members of the Proteaceae family produce dense mats of fine proteoid roots in order to increase water and nutrient acquisition by increasing the root surface area coming into contact with the soil (Figure 2.1) (Dinkelaker et al., 1995). Once water and nutrients are optimally utilized in the rhizosphere, there is no additional advantage to justify carbohydrate allocation to proteoid roots, hence they are generally short lived. Proteoid root abundance is therefore largely related to the availability of nutrients (Watt and Evans, 1999), especially phosphate (P) (Aitken et al., 1992, Dinkelaker et al., 1995, Keerthisinghe et al., 1998), and soil water. Firth et al. (2003) recorded the presence of macadamia proteoid roots at greater depths than what was previously recorded for Proteaceae species and appeared to be functional for over a year under relatively dry conditions. Despite macadamia roots occurring primarily within the upper 0.4 m of the soil surface, Lloyd et al. (1991) previously implied that macadamias may be able to extract and transport water from deep (>60 cm) within the soil profile and at low soil water contents. This in combination with the presence of proteoid roots at greater depths may allow macadamias to maintain their plant water status (avoid stress) during prolonged droughts by extracting soil water at depth (Stephenson and Searle, 2014). In addition, the lateral root framework and associated fibrous roots appeared to retain their function for one and a half years before starting to decay upon the onset of the rain season and wet soil conditions, which are favourable for fungal growth. This raises a concern about the potential counterproductive effects of ineffective irrigation practices to root longevity. Under anaerobic conditions, as experienced under prolonged over-irrigated conditions, root longevity often decreases due to internal and external toxic compounds and the shortage of oxygen (Stephenson, 2004). In addition to a decrease in nutrient uptake, over-irrigation further increases microbial growth, which may result in an increased potential for root diseases, as well as a reduction in root growth due to a decrease in soil temperature.

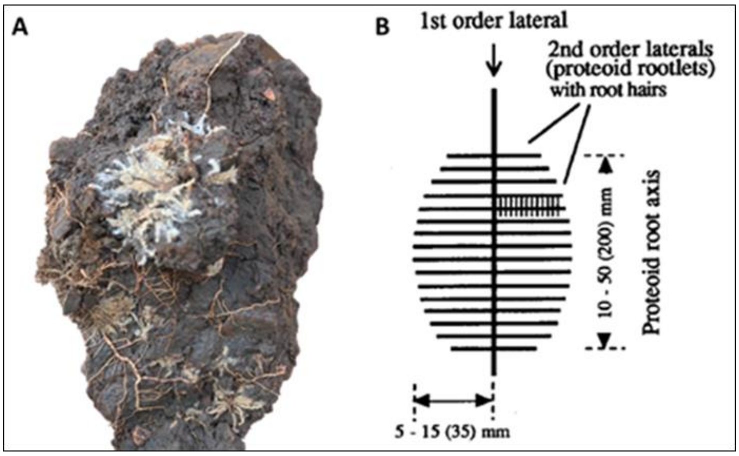


Figure 2.1: Visual (A) and schematic (B) representation of proteoid root characteristics (Dinkelaker, Hengeler and Marschner, 1995)

Root longevity and efficiency in water and nutrient uptake are also related to the suberin levels in root cell walls. Suberin is a fatty acid derived compound which is impermeable to water, hence giving older roots their characteristic brown colour (opposed to the white colour of young root tips) and making them less efficient in water uptake. The suberisation of roots therefore tends to be favourable under dry soil conditions, enabling roots to survive without desiccation. In some plants, roots suberise to the root tip under adverse conditions, but can resume growth upon the onset of favourable conditions, even after prolonged periods of drought. In fact, Firth et al. (2003) noted a similar response in macadamia roots, finding that the fibrous roots of macadamia have the capacity to regenerate new growth from desiccated roots following a drought. The author further observed macadamia fibrous roots to be more hardened and non-fleshy when compared to other subtropical crops, such as avocado, suggesting macadamia roots may be better adapted and less likely to suffer tissue collapse under dry surface soil conditions.

2.1.1.3 Macadamia vegetative growth

Macadamia vegetative growth commonly occurs through periodic flushes (Carr, 2013, Olesen, 2005), followed by budding and stem elongation before a new vegetative flush occurs. Recently emerged macadamia flush leaves expand for approximately 20 days before hardening off (Huett, 2004), which is similar to what was previously noted for avocado (Schaffer et al., 1991). Two major macadamia flushes generally occur during spring (August-September) and end of summer (March-April) under South African conditions.

During autumn and winter months preceding the first spring flush, the tree stores large amounts of carbohydrates in preparation for this event (Cormack and Bate, 1976). Even though the tree is actively photosynthesising during the spring flush period, stored carbohydrate reserves are reported to supplement fruit and shoot growth during peak demand (Huett, 2004). These reserves are therefore at their lowest during periods of peak vegetative and reproductive growth, as illustrated in Figure 2.2 (Stephenson et al., 1989). The spring vegetative flush further coincides with the onset of flowering and the start of nut growth, which further increases the need for readily available energy in the form of carbohydrates (Stephenson et al., 1989). This is exacerbated by the fact that young macadamia flush leaves are initially net sinks of photosynthates, hence they have a negative net assimilation rate (A), before becoming the most productive part of the tree canopy (Huett, 2004).

Vegetative growth, however, is highly influenced by environmental factors including temperature and water availability, as well as various management practices such as pruning and the availability of nitrogen. These factors can influence both the timing and extent of the vegetative flush. Trochoulias and Lahav (1983) showed temperatures between 20°C and 25°C to be optimal for vegetative growth. Although some growth still occurs at 15°C, winter temperatures lower than 10°C may delay the onset of the spring flush, until mean daily temperatures are higher than this lower threshold (Stephenson et al., 1986). Similar inhibitory effects on vegetative growth have been recorded for trees subjected to water stress, with vegetative growth only commencing once favourable soil water content levels are attained (Stephenson et al., 2003).

Analogous to vegetative flushes, macadamias typically have two substantial root flushes within a single production season. These root flushes are believed to commence in the autumn or early winter period, with a second flush in spring, typically alternating with a vegetative flush. Due to competition between roots and shoots for carbohydrate reserves (Stephenson, 2004), smaller root flushes are expected during periods of peak vegetative flush, as observed in Figure 2.2. Similar observations have been made previously for both avocados and other deciduous crops (Bevington and Castle, 1985). In an above-ground rhizotron study in Florida, avocado shoot and root growth flushes appeared to be synchronised and alternated on 30 to 60 day cycles (Ploetz et al., 1993). Although tree carbohydrate dynamics have a distinct influence on the rate and extent of the root flush, factors such as temperature, water, soil chemistry and structure also have a noteworthy effect on root growth.

Trochoulias and Lahav (1983) found that optimal soil temperatures of approximately 15°C may promote root growth, whilst Allan (1972) showed that high soil temperatures (>20°C) can lead to a significant reduction in root growth. The reduction in root growth due to high temperatures can, however, not be explained by a single process, as it is a function of various complex interactions ranging from changes in root respiratory levels to the inhibition of functional enzymes (Pregitzer et al., 2000). High soil temperatures are often linked to higher soil evaporation rates (Monteith, 1981), and inhibition of topsoil root growth could therefore also be due to a reduction in soil water content.

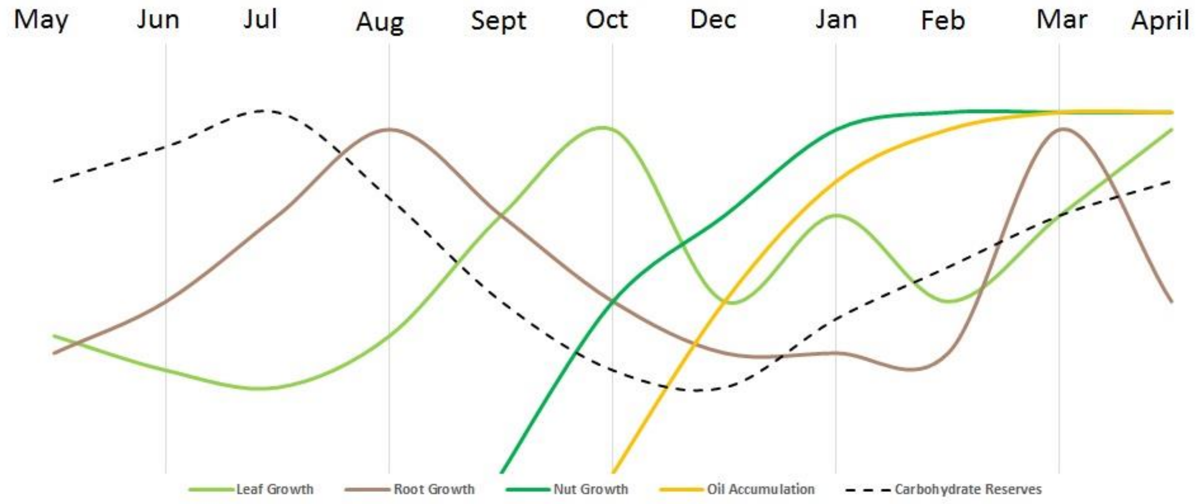


Figure 2.2: Schematic representation of macadamia phenology. Chart derived from Stephenson et al. (1989)

2.1.1.4 Macadamia reproductive development

Macadamia reproductive phenology is influenced by various environmental (Stephenson et al., 1986, Stephenson et al., 2003) and tree specific factors, such as stem length and age (Wilkie et al., 2009). Characteristically, macadamia flower initiation occurs during the shortening days (day length 10 h 40-50 minutes) and decreasing temperatures of early May (late autumn) (Carr, 2013), after which flower buds are dormant for two to three months depending on weather conditions. Macadamia flowering naturally commences with the onset of spring and a rise in temperatures, with flowering concentrated during August and September under South African conditions. Even though Stephenson and Gallagher (1986) have showed that night temperatures may play a major part in the extent and timing of flower development, few studies have described the influence of other environmental variables, especially water availability, on the extent and timing of flower development. A study by Stephenson et al. (2003) has found that the timing of water stress, as well as the severity of water stress had no consistent effect on flowering intensity. Further studies investigating the effect of water stress on flower development is therefore required.

Nonetheless, nut set shortly follows flower anthesis, after which the embryo, ovule and endosperm start growing rapidly after fertilization (McConchie et al., 1996, Walton et al., 2012). Three periods of abscission occur at different stages after anthesis, where after only 0.3% of the initial set fruit set per raceme (6-35%) may reach maturity (Carr, 2013, Nagao, 2011). Pre-mature nut abscission (also known as November drop) occurs around eight weeks after anthesis and can significantly influence final yield. November drop is influenced particularly by high temperatures, low atmospheric humidity (Stephenson and Gallagher, 1986) and water availability, which have been demonstrated to significantly increase pre-mature nut abscission (Stephenson et al., 2003). Pre-mature nut abscission is believed to be a natural crop load adjustment, with studies showing that increased leaf area during this stage decreased nut drop and therefore also increased final nut yield (Stephenson and Gallagher, 1986). Factors influencing the build-up of tree carbohydrate reserves and current photosynthesis during this period can therefore have a significant impact on the severity of abscission.

Following the nut abscission period, the embryo develops in those nuts remaining on the tree and absorbs the entire endosperm (nut fill), until the embryo comes into contact with the inner integumentary membrane of the testa. The testa will harden and become lignified as the embryo matures (McConchie et al., 1996) which is commonly referred to as shell hardening. Macadamia kernel (embryo) takes approximately six months to mature and at this stage the kernel should contain at least 72%, with a specific gravity <1.0 g/cm^3 (Carr, 2013). Nut fill, shell hardening and oil accumulation all require significant carbohydrate expenditure which, if not sufficiently available, may influence final kernel yield and quality. Hence, being a biological process, kernel mass and shell thickness have been found to be particularly influenced by temperature extremes and water limitations during the different phenological stages (Stephenson and Gallagher, 1986, Stephenson et al., 2003).

2.1.2 ECOPHYSIOLOGY AND PLANT WATER RELATIONS

Native to sub-tropical regions of Australia, the evergreen macadamia tree has gained substantial popularity in the global agricultural sector, due to the substantial economic value of its fruit. This popularity has seen macadamia trees planted in environmental conditions which are distinctly different from its native coastal rainforest environment. In environments that are often drier and more marginal than those of its natural habitat, macadamia has shown to be resilient as a commercial crop, sustainably producing economically viable yields (Hardner et al., 2009, Neal et al., 2010). Macadamias therefore have the capability to grow and produce good quality fruits in environments outside of their natural habitat, which is rather significant considering the fact that commercially cultivated macadamias have only recently been domesticated (Hardner et al., 2009, Nock et al., 2019).

The adaptability of macadamias to drier and more marginal environments could potentially stem from a large degree of whole tree and more specifically leaf morphological plasticity and/or as a result of strict control of leaf gas exchange and carbon/water relations in response to environmental variables (Chaves and Oliveira, 2004, Lavorel and Garnier, 2002). The long-lived hypostomatous, sclerophyllous leaves and specialised proteoid roots of macadamia (Dinkelaker et al., 1995, Stephenson, 2005, Syvertsen et al., 1995) could also aid the trees in not only surviving but flourishing in a range of environments. These leaf morphological characteristics are believed to have evolved in response to conditions, where either climate, water or nutrient supply imposed significant constraints on species survival (Gerke, 2015, Miller, 2005, Neumann and Martinoia, 2002, Turner, 1994, Wright and Cannon, 2001). Such suboptimal conditions are, however, rarely present in agricultural systems, and these evolutionary adaptations could potentially place an upper-limit on both crop yield and quality.

In an attempt to better understand leaf gas exchange of macadamia, Lloyd (1991) developed and tested models to study responses of stomatal conductance (g_s) to weather variables. It was established that g_s is largely controlled by leaf to air vapour pressure deficit (VPD_{leaf}) at high irradiances. At low irradiances g_s tended to be more sensitive to leaf temperature (Lloyd, 1991), most likely due to the temperature dependence of metabolic pathways. This distinct response of g_s to VPD_{leaf} is well documented for a range of subtropical tree crops (Flore and Lakso, 1989, Jifon and Syvertsen, 2003, Lloyd and Howie, 1989). There is, however, still considerable uncertainty regarding the mechanisms involved in these responses (Assmann and Shimazaki, 1999, Brodribb and McAdam, 2011, Buckley, 2019, Davies et al., 2002, Lösch and Tenhunen, 1981), as well as the distinct differences observed between and within species (Brodribb et al., 2003, Hetherington and Woodward, 2003, Jarvis, 1976, Schultz, 2003).

The manner in which stomata respond to changes in VPD allows the classification of plant water management strategies (Jones, 1980, Mrad et al., 2019, Smart and Coombe, 1983), and encapsulates the ecophysiological classification of plants by Tardieu and Simonneau (1998) into isohydric or anisohydric plant behaviour. Isohydric plants typically maintain a favourable plant water status by preventing leaf water potential (ψ_{leaf}) from dropping below a minimum value, irrespective of soil water content and atmospheric evaporative demand, and is achieved by means of strict stomatal control. This strategy is in contrast with anisohydric behaviour where a greater diurnal decline in ψ_{leaf} is observed in response to increased atmospheric evaporative demand, compared to isohydric plants, and in general midday ψ_{leaf}

for anisohydric plants will be substantially lower than that of its isohydric counterparts under conditions of higher evaporative demands. It should also be noted that the decline in ψ_{leaf} in anisohydric crops is significantly higher in water stressed plants compared to well-watered plants (Schultz, 2003).

These two distinct water management strategies are based on the role of stomata in maintaining the balance between the plant's ability to supply water to its leaves and the prevailing atmospheric evaporative demand. It is, therefore, intuitive that in the case of isohydric crops, strict stomatal control under rising evaporative demand, especially during increases in VPD_{leaf}, is necessitated by the inability of the crop to maintain the balance between water supply to the leaves and water lost from the leaves, in an attempt to avoid xylem embolism (Sperry et al., 2008). Results from Schultz (2003) suggest that the inability to supply sufficient water to the leaves, stems from inherent hydraulic limitations of the xylem. These limitations can in-part be attributed to the complexity of hydraulic architecture of dicotyledonous species, but is mostly as a result of significant resistance within xylem vessels (Tyree and Zimmermann, 2002). Due to the serial nature of interconnected xylem vessels the term hydraulic conductance is frequently used. If evaporative demand for water exceeds the upper limit of whole tree hydraulic conductance, water potentials decrease significantly (i.e. increased negative pressures) causing an increase in tension between water molecules within xylem vessels, thereby increasing the risk of xylem embolism, which if occurring frequently, could lead to ultimate dysfunction of the hydraulic continuum (Tyree and Sperry, 1988, Tyree and Sperry, 1989, Urli et al., 2013).

In subtropical regions, such as those where macadamias originated from and are currently cultivated, the microclimate is often characterized by high rates of atmospheric evaporative demand which often tends to exceed precipitation, especially during distinctly dry winter periods in summer rainfall regions. The evolutionary fitness of evergreen subtropical species is believed to be linked to the avoidance of runaway embolism mediated by strict stomatal control (Jones and Sutherland, 1991). A risk-avoiding strategy is also evident in the anatomical structure of xylem vessels of these species. Tyree and Zimmermann (2002) reported that these species generally have xylem vessels which are significantly narrower than those of temperate species. The significance of these narrow vessels is that more vessels are present per unit area compared to wider vessels. If, and when embolism does occur, the percentage loss of conducting tissue per unit area will therefore be less in species with narrower vessels, thereby avoiding the risk of complete hydraulic failure (Sperry et al., 2008). It should, however, be emphasized that a decrease in vessel diameter leads to a significant decrease in hydraulic conductance (Tyree and Sperry, 1989, Tyree and Zimmermann, 2002). Combining the risk-avoiding nature of evergreen subtropical species with hydraulic inefficiency, it could be hypothesized that a large portion of these species may be isohydric, including macadamia.

The function of stomata as regulatory valves for the hydraulic continuum is balanced against their other significant function as gateways for carbon uptake and assimilation (Cowan and Farquhar, 1977). Although Buckley (2005) proposed that cavitation avoidance and maximal carbon gain per unit water loss are not competing goals of stomata, it could be said that the upper maximum of carbon gain is a function of cavitation avoidance. This is substantiated by the fact that stomata tend to operate close to the upper limit of plant specific hydraulic capabilities (Brodribb et al., 2003, Tyree and Sperry, 1988). Reduced cavitation risk mediated by stomatal closure will therefore also lead to reduced rates of carbon assimilation (Koch et al., 2004, McDowell, 2011). McDowell (2011) further proposed that in evergreen *Pinus edulis*, known to follow a predominantly isohydric water management strategy, carbon limitation and hydraulic failure were coupled. Studies have also demonstrated that isohydric plants are more prone to cavitation than their anisohydric counterparts (Meinzer et al., 2009, Sperry et al., 2008). There could therefore be an inherent limitation to carbon gain in isohydric evergreen subtropical tree species under hot and dry conditions. Low net carbon dioxide (CO_2) assimilation rates (A) are not uncommon for evergreen trees (Warren and Adams, 2004) and can also be low for a range of subtropical tree crops including macadamias, especially when compared to deciduous fruit tree species (Flore and Lakso, 1989, Huett, 2004, Jifon and Syvertsen, 2003, Medina et al., 2002, Reynoso et al., 2000).

Given the dual function of stomata in facilitating CO_2 assimilation and transpirational water loss, an understanding of the factors influencing both is important. Strict stomatal control presents challenges to leaf level carbon assimilation, which although difficult to scale to canopy level, could lead to the realization of an upper limit of biomass accumulation and more importantly yield. Plant water relations involve the absorption of water, ascent of sap, loss of water by transpiration, and the internal water balance of the tree. Plant water relations are also inherently linked to carbon gain at both leaf and canopy level via the function of the stomata. One of the fundamental stomatal functions is to maintain a favourable trade-off between carbon gain and water loss, described as instantaneous water use efficiency or transpiration efficiency (WUE_t) at leaf level, and as water use efficiency (WUE) at either a canopy or orchard level. At the canopy level, the WUE is often referred to in terms of the harvestable yield per unit of water lost through either E_c or evapotranspiration (ET), and although yield may increase with increased water use, commercial agriculture tends to find more value in expressing water use in terms of income generated per unit of water used, a term often referred to as water use productivity (WUP) (Garcí García, 2012, Kool et al., 2014). Although these terms have been criticized in regards to their transferability between seasons and locations (Binkley et al., 2004, Blum, 2009), they are widely used to estimate how effectively water is used in the production of harvestable crop and income, and provide a benchmark which can be improved upon (Condon et al., 2004, Howell, 2001, Wallace, 2000). Given the mathematical relationship between biomass gain and water loss, increases in WUE can be made by either increasing biomass gain at constant water loss, reducing water loss for a given biomass gain (by means of reduced evaporation and deep percolation of irrigation water), or by a combination of both. However, WUE is generally a conserved trait in plant species, as the above discussion on stomatal regulation would suggest.

The inherently conservative nature of water use amongst isohydric plants could imply that carbon gain is equally conservative. Macadamia nuts have a high oil content (>75%) (Macfarlane and Harris, 1981) and therefore a high carbon and energy demand during the fruiting stages. South African orchards can produce nut in shell yields in excess of 20 kg tree^{-1} (Stephenson et al., 1986), which is considered to be high in the global macadamia industry. It therefore seems unlikely that a conservative carbon gain strategy can support this high demand at certain phenological stages. It is possible that canopy level carbon gain from a high leaf area is more than sufficient to support the substantial demand for carbon, as has been demonstrated in avocado and citrus (Iglesias et al., 2013, Testi et al., 2008, Wolstenholme and Whiley, 1999). Alternatively, macadamia could deviate from its assumed conservative isohydric nature during periods of high carbon demand. Deviation from a pure isohydric strategy to a more dynamic isohydric/anisohydric strategy is not uncommon amongst fruit tree crops (Naor et al., 2013, Sade and Moshelion, 2014, Silber et al., 2013), especially in the presence of a high fruit load.

Relating whole tree carbon demand to tree water use is complicated by the fact that non-environmental effects, such as sink and source relations and carbon metabolism and partitioning, are masked by dominating environmental variables (Lakso, 1989, Nebauer et al., 2013). At a leaf level it is, however, possible to study responses of leaf gas exchange to environmental variables and how these responses vary with phenology. Very few studies have focussed on this aspect of subtropical fruit tree crops, which is rather surprising since phenology plays a significant role in tree water use and irrigation requirements, especially when considering that water stress during certain phenological stages, such as flowering and fruit growth has a greater effect on yield and quality compared to some less sensitive periods, including floral initiation and late fruit maturity stages (Hutton et al., 2007, Li et al., 1989, Martínez-Lüscher et al., 2016, Savé et al., 2012, Silber et al., 2013, Stephenson et al., 2003). Studies on deciduous tree crops, such as peach (Marsal and Girona, 1997), and apple

(Pretorius and Wand, 2003), and subtropical crops such as avocado (Silber et al., 2013), for example, have provided valuable insight into differences in leaf gas exchange and water relations during different phenological stages.

These studies have also highlighted the numerous opportunities to apply an ecophysiological understanding to irrigation and water management. Such opportunities include the use of regulated deficit irrigation, which, could be used to manipulate vegetative growth especially during periods of high assimilate demand (i.e. fruit growth) which could in turn reduce competition between fruit and vegetative flushes for a limited pool of assimilates thereby possibly reducing premature nut drop and subsequently increasing yield in macadamias (Lloyd et al., 1991, Searle and Lu, 2002, Stephenson and Gallagher, 1986, Stephenson and Searle, 2014). Studies by Stephenson et al. (2003) and (Lloyd et al., 1991) suggest that macadamia might be highly suited to the practice of regulated deficit irrigation given the limited effects of mild water stress during certain phenological stages on leaf gas exchange, yield and nut quality. The proposed isohydric nature of macadamia could further motivate the implementation of such strategies. The studies of Stephenson et al. (2003) and (Lloyd et al., 1991), provides us with the best insight with regards to carbon and water relations in macadamia, and can be used to explore possible research shortcomings and opportunities with regards to water relations and the factors affecting these relations.

2.1.2.1 Water relations under conditions of soil water stress

Studies of container-grown macadamias have revealed that complete stomatal closure (g_s =0.00 mol m^{-2} s^{-1}) occurs at ψ_{leaf} of < -2.0 MPa (Stephenson et al., 1989). Although these results cannot be extrapolated to field grown macadamias, given that ψ_{leaf} of < -2.0 MPa have rarely ever been measured in field grown macadamias (Stephenson and Searle, 2014), Lloyd et al. (1991) reported that a significant decrease in g_s was observed at ψ_{leaf} of < -1.2 MPa. This decrease in g_s resulted in a significant decrease in *A*, with Stephenson et al. (2003) reporting values of <2.2 µmol CO$_2$ m^{-2} s^{-1} (average *A* of macadamias under non-stress conditions being 8-10 µmol CO$_2$ m^{-2} s^{-1}) at ψ_{leaf} of between -1.8 to -2.0 MPa. It was surprising that in the study of Stephenson et al. (2003), only slight differences in the diurnal course of g_s were found between water stressed and unstressed trees, and that g_s responded in a similar fashion to VPD$_{air}$, increasing to a maximum when VPD$_{air}$ was favourable, regardless of ψ_{leaf}. These results confirm findings by Lloyd et al. (1991), who stated that stomata respond mainly to VPD$_{air}$ and to a lesser extent to other environmental variables. This study, however, also showed that in field-grown macadamia trees, g_s of water stressed trees was lower than that of well-watered trees exposed to the same set of environmental conditions, but there was little to no difference in minimum ψ_{leaf} for water stressed and well-watered trees. In this sense, it emphasizes the point by Sperry (2000), that stomata act as pressure regulators in plants and that macadamia trees tend to be isohydric..

2.1.2.2 Water relations under conditions of non-limiting soil water

Stomatal responses under water stressed conditions can vary significantly between and within species. These variations are, however, not limited to water stressed conditions and under non-limiting soil water conditions stomata and subsequently ψ_{leaf} tend to differ in their response to environmental variables on a daily basis. The most commonly observed variation in both g_s and ψ_{leaf} under non-stress conditions is found in the hysteresis loop response (Bai et al., 2015, Buckley, 2019, Körner and Cochrane, 1985). The hysteresis loop in g_s and ψ_{leaf} could be explained by means of a three phase process (Körner and Cochrane, 1985, Von Willert et al., 1989) during which g_s increases in in the morning in response to increasing solar radiation, which causes a significant drop in ψ_{leaf} (Phase 1), where after ψ_{leaf} stays fairly constant whilst g_s decreases in response to increasing VPD_{leaf} (Phase 2). The final phase is characterized by a stable recovery of ψ_{leaf} with g_s remaining low, whilst ψ_{leaf} increases.

Based on this response it is evident that the key components driving g_s and ψ_{leaf} in most plants, including macadamias, are solar radiation and VPD_{leaf}. The most significant of these responses was observed in the study by Lloyd et al. (1991), which showed that the highest g_s in macadamias does not correspond to the highest VPD_{leaf} and that under circumstances of non-limiting soil water and saturating levels of solar radiation, g_s can decline rapidly when atmospheric evaporative demand exceeds the maximal rate of water supply out of the leaf. This often results in midday depression of g_s and subsequently A and E_c in plants, and although this has not been extensively reported in macadamias, it has been shown in subtropical fruit trees such as citrus (Hu et al., 2009, Rana and Ferrara, 2019, Veste et al., 2000, Vu and Yelenosky, 1988), olive (Bacelar et al., 2009, Bacelar et al., 2007) and mango (Elsheery et al., 2007, Juntamanee et al., 2013, Jutamanee and Onnom, 2016). Midday depressions were noted in the study by Lloyd et al. (1991), with diurnal macadamia g_s, on a day with high VPD_{leaf} (30 October 1989), having the lowest values of g_s under high levels of irradiance occurring between 12:00 and 13:00. This reduction in g_s could possibly lead to decreased A as reported in both citrus and olive (Jifon and Syvertsen, 2003, Loreto and Sharkey, 1990, Raveh et al., 2003) and offers an opportunity to increase crop growth and yield either through selecting sites which have less diurnal fluctuations in VPD or by means of intermittent overhead sprinklers which will reduce leaf temperature and $VPD_{leaf.}$ The latter approach has been shown to increase macadamia kernel yield (Allan et al., 1994), whilst increased A has been reported for citrus by Hu et al. (2009).

Although both proper site selection and evaporative cooling of the canopy can be used to alleviate conditions where VPD_{leaf} leads to significant reductions in g_s, an in-depth analysis of the response of g_s to VPD_{leaf} is required to establish the optimal VPD_{leaf} range for macadamias. To date, no studies have investigated this aspect of macadamias, but the potential to increase g_s and subsequently A is a promising aspect to potentially increase growth, yield, and quality of macadamias. It should, however, be noted that stomatal behaviour is not solely under the control of VPD_{leaf}, and environmental and physiological variables such as solar radiation, temperature, wind speed and internal CO_2 concentration (C_i) can also have a significant effect on stomatal behaviour (Brodribb et al., 2003, Jarvis, 1976). To further complicate matters leaf phenological aspects, such as leaf age and history, could also have a profound impact on response of stomata to environmental variables (Choat et al., 2006, Huett, 2004, Marias et al., 2017).

Regardless of how both g_s and ψ_{leaf} can vary within or between species, or with phenology, microclimate, and orchard specific conditions, it is established that, in fruit tree crops stomata respond primarily to VPD_{leaf} to maintain a favourable plant water status, with decreases in g_s occurring without substantial changes in ψ_{leaf} (Flore et al., 1985, Klein, 2014, Miner et al., 2017). Transpiration volumes are therefore likely to be controlled by g_s at the leaf level, and g_c when scaled to the canopy level. Although atmospheric evaporative demand would determine the rate of water loss from the leaf or canopy, the rate of water loss would not increase linearly with increased evaporative demand (i.e. supply controlled E_c) due to the strong stomatal influence present in these crops. This is supported by the results of Stephenson et al. (2003) showing no differences in mean daily water use between non-stressed and mildly stressed macadamia trees even though ψ_{leaf} differed between the two treatments, indicating that g_s and factors driving g_s, which according to the current knowledge available is largely VPD_{leaf}, dictates water use in macadamias. It will therefore be critical to select crop water use models that account for physiological control over water use, where E_c is not solely dictated by atmospheric evaporative demand.

2.1.3 ESTIMATES OF WATER USE

Water use, defined as total ET (Allen et al., 1998), serves as the baseline for a crop's irrigation water requirements. For macadamias, it was initially believed that in order to achieve high yields, a well-distributed rainfall exceeding 2000 mm per annum was needed (Liang et al., 1983). Trochoulias and Johns (1992) later reported that additional irrigation reduced yields of macadamias in areas receiving rainfall ranging between 1200-2000 mm per annum. It was therefore believed that a mean minimum annual rainfall of 1200 mm would be sufficient for macadamia production. This estimate of macadamia water requirement was, however, obtained by assessing WUE and not necessarily WUP and/or actual measurements of ET of macadamias.

Nevertheless, with the exception of ET measurements using large through-draining lysimeters conducted by Stephenson et al. (2003), very few studies have been published regarding macadamia ET. The study by Stephenson et al. (2003) found that well-watered mature macadamia trees had an average daily ET ranging between 50-80 L tree^{-1} day^{-1}. Given these values of ET, and assuming a South African industry standard spacing of 8 x 4 m (32 m^2 per tree) the total seasonal ET of macadamias according to Stephenson et al. (2003) should be approximately 570-900 mm. This estimated total ET is considerably lower than the initial estimates of the rainfall requirements (~1200 mm) for macadamia and highlights the lack of water use research in the macadamia industry whilst also emphasizing the need for seasonal measurements of water use in macadamias.

The only other report of macadamia water use was published by Gush and Taylor (2014), who used a combination of sap flow and short-term eddy covariance measurements to determine ET of field grown macadamias in South Africa. Total seasonal ET calculated in this study was approximately 720 mm, which was highly comparable with that reported by Stephenson et al. (2003), given the fact that variations in canopy size and prevailing weather conditions between the two studies were likely. Gush and Taylor (2014) further reported that the 1200 mm of rain and irrigation applied over the 2011/2012 season exceeded ET by approximately 500 mm and exceeded ET$_o$ at the site (1162 mm). It was concluded that the orchard was over-irrigated. The volume of water (1200 mm) applied in this study, however, agreed with the minimum rainfall volume required by macadamias as published by Trochoulias and Johns (1992), which considering the fact that the volume applied in the study by Gush and Taylor (2014), exceeded both total ET and ET$_o$ it seems likely that if guidelines by Trochoulias and Johns (1992) are to be followed indiscriminately as an irrigation guideline, a large portion of orchards could be over-irrigated.

2.2 MODELLING WATER USE OF SUBTROPICAL CROPS

The lack of, but high demand for, irrigation related information specific to macadamia 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 parameterization 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 (K_c) approach (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 macadamia is the lack of suitable K_c values, given the lack of macadamia ET data which is required for the calculation of K_c. Reported K_c values for macadamia were approximately 0.65 (Carr, 2013), which was in the range (0.50-0.78) reported by Gush and Taylor (2014). As transpiration of macadamia trees seem to be supply limited, a demand limited model may not be appropriate for accurate estimates of water use on short time steps, e.g. daily. 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 macadamias, the successful parameterization 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 (E_s) and E_c. 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 2.3), 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 2.3). In mature evergreen crops, such as macadamia and citrus, the canopy size changes significantly less over a season compared to deciduous and 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). Gush and Taylor (2014) showed that K_c of macadamia showed greater changes with values in the first season of 0.50 to 0.78 and decreased in the second season to between 0.60 and 0.78.

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}, to account for the degree of stomatal control over transpiration, but due to the lack of water use data for macadamias, this approach has yet to be tested in this crop. Considering the reported variable responses of g_s to increases in VPD_{leaf} in the presence or absence of a considerable sink (i.e. fruit load), and assuming that g_c responds in a similar fashion to that of g_s (Irmak et al., 2008, Lhomme et al., 1998), it is not unreasonable to attribute some of this variation in K_c to physiological factors and it would be advisable to investigate changes in g_c and subsequently F_r over a season.

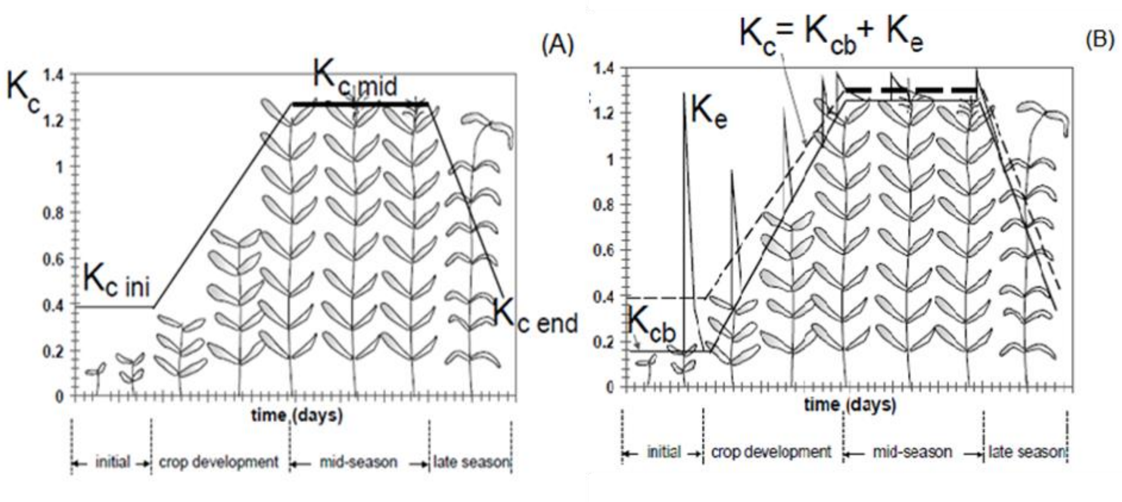


Figure 2.3: (A) General single crop coefficient (K_c) curve and (B) variation in dual crop coefficients including basal crop coefficient (K_{cb}) and soil evaporation coefficient (K_e) throughout the various crop stages as from Allen et al. (1998)

Determining the contribution of physiological factors to the K_c is rather difficult when considering the timeframe of physiological changes (days to weeks) relative to that of reported K_c values (months). In crops that exert significant stomatal control over transpiration, as found in crops following a predominantly isohydric strategy, which likely includes macadamia, the K_c model might provide reasonable estimates of seasonal ET, 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 ET. The K_c 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 the 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}).

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

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 content (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.

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

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

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

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

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

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 Equation [6] and Equation [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 macadamias, 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 estimate 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) has 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 estimate in 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 sclerophyllous macadamias, 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, only Gush and Taylor (2014) have attempted to model macadamia water use. They reported that under conditions of high atmospheric evaporative demand, the FAO-56 crop coefficient model tended to overestimate macadamia water use. It was proposed that a model including the driving variables of canopy conductance and transpiration would be better suited to macadamias. There are, however, no published studies for macadamia that have successfully parameterized canopy conductance models feeding into equations calculating canopy transpiration. From the current assessment of available literature on water use modelling of macadamia, it is concluded that models incorporating g_c should be investigated if reasonable estimates of macadamia ET are to be achieved. Although g_c is rather difficult to measure, models combining the work of Lloyd (1991) with the derivatives of Jarvis-type models (Cohen et al., 1983, Oguntunde et al., 2007, Testi et al., 2006, Villalobos et al., 2000) and Villalobos et al. (2013) could potentially be used to obtain reliable measures of g_c.

2.3 IRRIGATION

Most macadamia orchards are irrigated using microsprinkler systems applying water at various rates as determined by the emitter and irrigation system pressure. Microsprinklers are placed either close to the tree trunk or in the middle of two neighboring trees. The former is less favorable due to increased stem wetness, which has been suggested to increase the probability of *Phytophthora cinnamomi* infection, as seen in other tree species (Tippett and Hill, 1983). Placing the microsprinkler close to the tree trunk also creates an uneven wetting of the soil beneath the tree canopy, as can be seen from Figure 2.4. The more favoured placement position of the micro sprinklers, which is between two trees, provides a more even wetting pattern.

Growers have also installed drip irrigation systems, although these systems are less favored than the more conventional microsprinkler systems. Nonetheless, growers are advised to have a single drip-line during the first year after planting, where after the number of drip-lines are increased to at least three when trees are approximately 5-years old. Newly developed ultra-low flow drippers (<1.0 L h^{-1}), provide growers with a large wetting pattern similar to that delivered by micro sprinklers (Figure 2.4) , but at a higher efficiency (Dasberg and Or, 2013, Wamser et al., 2014). However, only a few of these systems have been installed in South Africa, mainly due to the higher maintenance required by drip irrigation systems. as opposed to microsprinkler systems (Nakayama and Bucks, 1991).

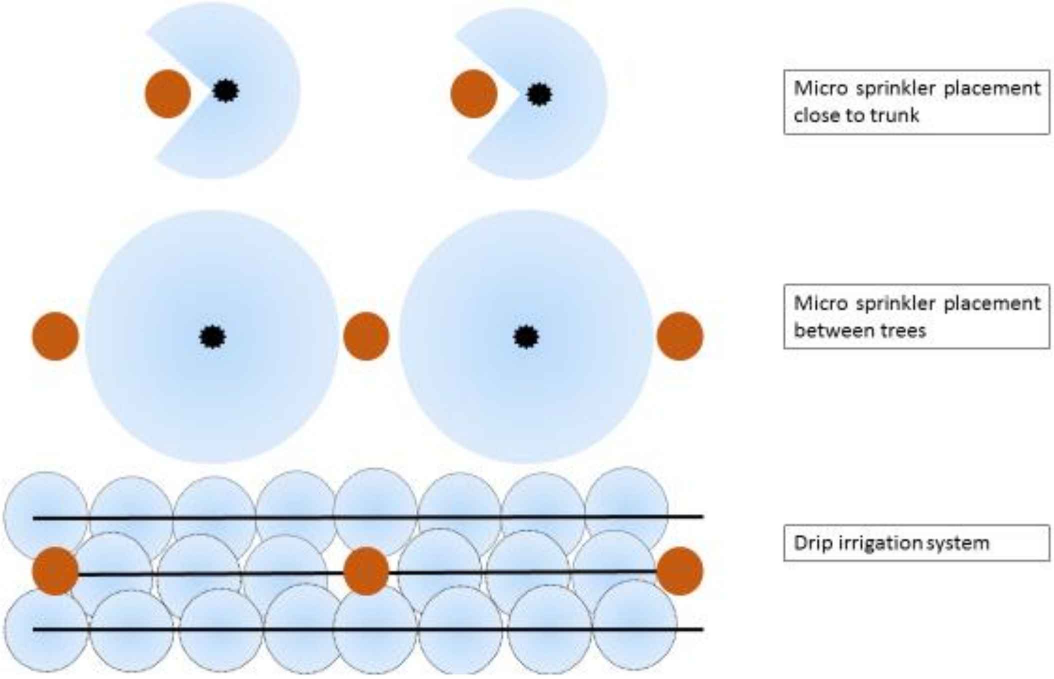


Figure 2.4: Wetting patterns and sprinkler placement of micro sprinklers and drip irrigation systems in macadamia orchards in South Africa

In a review of the Hawaiian macadamia industry by Shigeura and Ooka (1984) it was found that only a single orchard was irrigated at the time. This might have been due to the inconsistent response of macadamias to irrigation observed by Awada et al. (1967) and Cataluna (1973). Results from Awada et al. (1967) demonstrated that macadamia yields did not respond significantly to three different irrigation regimes, whereas Cataluna (1973) found that yields only increased by 10% after 1 year. Even though macadamia nuts are of high economic value a 10% increase in yield might not be sufficient to justify irrigation, especially during the time that the research was done. Nonetheless, Trochoulias and Johns (1992) set out to investigate what the effect of irrigation would be on macadamia on the north coast of New South Wales after observing that other tree crops responded positively to irrigation. Results obtained from this study found that tree size did not differ substantially between irrigated and non-irrigated treatments, with the exception that in wet years irrigated trees showed less growth than non-irrigated trees. This could mainly have been due to the effect of waterlogging and excessive nutrient leaching, which has been shown to decrease growth of other subtropical trees (Schaffer et al., 2006). The study also revealed that irrigation had no effect on the total number of nuts, but irrigation reduced both nut size and kernel quality. The poor response of macadamias to irrigation in this study is most likely due to the fact that irrigation was applied in an area where annual rainfall typically exceeded 1600 mm per year on average. Macadamias may respond positively to irrigation during drier years or in areas with lower annual rainfall. Results from a study in Malawi also suggested that irrigation was not justified for mature in an area with 1200 mm of rainfall and deep soils (Carr, 2013). Even a 4 month long dry period did not seem to impact yields in this study. However, in other areas in Malawi with higher annual temperatures and a longer dry season, water stress led to smaller nuts as a result of premature shell hardening and leaf discolouration in some clones.

According to Stephenson and Trochoulias (1994), approximately 1000 mm of rainfall per year is needed to successfully grow macadamias. With the exception of parts of KwaZulu-Natal, large portions of Mpumalanga only receive an average of 800 mm annually. These areas also receive most of their rainfall in the summer months from October to March. As a result, most trees in Mpumalanga and certain parts of KwaZulu-Natal are irrigated in order to supplement the required water throughout the year. In South Africa it is believed that irrigation significantly improves the yield and quality of macadamias, however, this has not been systematically investigated. These beliefs might, however, be warranted when evaluating the results obtained from Stephenson et al. (2003) which showed that water stress during the reproductive stages of macadamia can significantly reduce yield and quality. The reproductive growth period of macadamias in South Africa typically starts at the end of August, with flowering and nut set taking place in September to October. Rainfall during these months is usually less than what might be required by macadamias during this period. Supplementary irrigation during these critical periods might therefore have a positive effect on both yield and quality of macadamias. Even though studies by Awada et al. (1967) and Trochoulias and Johns (1992) have failed to show that irrigation increases tree size, nut yield or quality, it might have been that trees in these studies were not stressed sufficiently, since results by (Stephenson et al., 2003) proved that water stress significantly impacts macadamia growth and yield.

2.4 WATER USE EFFICIENCY AND WATER PRODUCTIVITY

There is extremely limited published or grey literature available on water use productivity or water use efficiency of macadamias. The cyclical and highly variable nature of macadamia yields makes it very difficult to quantify cause and effect between water application and yield and therefore to quantify the yield response to water (Carr, 2013). As a result, Huett (2004) suggests that at least 5 years are needed to demonstrate a response. These kinds of extended projects are seldom funded. Carr (2013) also states that most irrigation experiments have been poorly planned and as a result most results are inconclusive. There is also no evidence suggesting that irrigation is worthwhile or that increases in yield can be expected as a result of irrigation. However, as most of the irrigation trials were performed in Australia in areas where rainfall closely matched tree water requirements, these results are probably not applicable to South Africa and this needs to be assessed under local conditions. As macadamia is also an oil storing nut crop, water productivity is expected to be low, however, it is a high value crop.

2.5 THE INFLUENCE OF WATER STRESS AT DIFFERENT PHENOLOGICAL STAGES ON YIELD AND QUALITY

Despite macadamias growing in many regions of the world where rainfall is often insufficient or too erratic to ensure the sustainability of high yields, very little research has been conducted to understand the impact of water deficits on yield and quality of macadamia. Trochoulias and Johns (1992) in an 8 year experiment failed to show any consistent impact of varying levels of irrigation from flowering to harvest on yield on Macadamias in northern New South Wales, where annual rainfall varied between 1232 and 2283 mm. Although irrigation reduced the nut in shell weight by 7%, the kernel recovery percentage did not differ between treatments, whilst the proportion of “floaters” in tap water was slightly reduced by irrigation (3% fewer grade 1 nuts). The smaller nuts in irrigated treatments could be explained by the retention of more nuts on these trees.

Following on from the study of Trochoulias and Johns (1992), Stephenson et al. (2003), withheld water at different phenological stages for trees in draining lysimeters in Queensland in order to induce a water stress. Water stress was induced at four phenological stages (months are specific to conditions in Queensland) and included floral initiation (April), floral development (July to August), premature nut drop (November) and nut maturation (December) over a 5 year period. Although there were inconsistent results over the 5 year period, stress during the floral initiation period had little effect on yield, but stress from flowering to nut maturation tended to depress yield. Although stress during flowering reduced nut set by impacting flower quality, stress had no impact on flowering intensity.

November drop was influenced particularly by high temperatures, low atmospheric humidity (Stephenson and Gallagher, 1986) and water availability, which were demonstrated to significantly increase pre-mature nut abscission (Stephenson et al., 2003). Pre-mature nut abscission is believed to be a natural crop load adjustment, with studies showing that increased leaf area during this stage decreased nut drop and therefore also increased final nut yield (Stephenson and Gallagher, 1986). Factors influencing the build-up of tree carbohydrate reserves and current photosynthesis during this period can therefore have a significant impact on the severity of abscission. Stress during premature nut drop and nut maturation (early oil accumulation) severely depressed yields (Stephenson et al., 2003). The reduction in yield was largely a result of a smaller number of nuts, and in the case of stress during the premature nut drop stage the reduced yield could also be attributed to smaller nuts. However, despite smaller nuts from trees stressed during premature nut drop, the kernel recovery percentage was higher, as kernel size tended to be unaffected. This was most probably attributable to a lower crop load on these trees as a result of an early crop load adjustment. These authors concluded that “even 20 days of a mild stress resulted in depressed yield and quality during the critical floral development, premature nut drop, and nut maturation” periods.

In terms of quality, stress during premature nut drop did resulted in thin and underdeveloped shells which tended to split, whilst stress during nut maturation resulted in very low kernel recovery percentages. In this treatment kernels tended to be discoloured and shrivelled. Stress during floral initiation and floral development had no impact on nut quality. Nut fill, shell hardening and oil accumulation all require significant carbohydrate expenditure, which if not sufficiently available, may influence final kernel yield and quality. Hence, being a biological process, kernel mass and shell thickness have been found to be particularly influenced by temperature extremes and water limitations during the different phenological stages (Stephenson and Gallagher, 1986, Stephenson et al., 2003). Stephenson et al. (2003) concluded that in years where water is very limited irrigation should be restricted to the premature nut drop stage (yield is severely depressed) and the nut maturation stage (quality is severely depressed).

3 MATERIALS AND METHODS

3.1 WATER USE OF MACADAMIA ORCHARDS

3.1.1 ORCHARD DESCRIPTIONS

The trial was conducted on a commercial macadamia farm located approximately 35 km west of Nelspruit in the Schagen Valley, Mpumalanga, South Africa (25°21'50.36" S, 30°46'46.47" E, approximately 900 m.a.s.l.). The area has a seasonally dry sub-tropical climate ideal for macadamia production, although environmental conditions can vary considerably. On average the area has an annual precipitation of approximately 750-850 mm and an annual average temperature of 23°C, with January typically being the hottest month (Schulze, 1997). The trial consisted of three orchards, a fully irrigated mature bearing (MB) macadamia orchard, a fully irrigated, intermediate bearing (IB) macadamia orchard and a fully irrigated non-bearing (NB) macadamia orchard (Table 3.1 and Figure 3.1). The 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 yet to bear a commercial crop and where canopy cover was lower than 15%.

Figure 3.1: Location of the three 'Beaumont' macadamia orchards in the Schagen Valley

The MB orchard was planted in 2005 and was approximately 3.8 ha in size, planted at a population of 312 trees ha^{-1} (spacing 8 x 4 m, i.e. 32 m^{2} per tree) (Figure 3.2). Trees were planted in an approximate north-south orientation and were allowed to form a complete hedgerow, with height being controlled below 6.0 m by means of annual hand pruning. Pruning practices included selective limb removal of the tallest vertical branch and a single major side branch. These trees had an average leaf area index (LAI) of 5.25 m^{2} m^{-2} and an estimated canopy cover of 0.72 at the start of the measurement period (10 August 2016). The orchard was irrigated using one 50 L h^{-1} (5.5 mm h^{-1}) microsprinkler per tree, with a wetted diameter of 1.7 m and irrigation was typically scheduled once a week with soil water content monitored using DFM capacitance probes. This was historically a high yielding orchard, with up to 6 t ha^{-1} dry in-shell (DIS) previously recorded in this orchard. Inter-rows consisted of grass cover, interspersed with a variety of weeds. Tree rows were free of weeds as a result of shading under the trees.

Figure 3.2: The location of the mature bearing (MB) 'Beaumont' macadamia orchard and the automatic weather station on Mayo Estate in the Schagen Valley close to Nelspruit.

The IB orchard was located approximately 4 km North-West of the MB orchard and consisted of 5-year old (Planted 2012) macadamia trees, planted at a population of 312 trees ha^{-1} (spacing 8 x 4 m, i.e. 32 m^{2} per tree) (Figure 3.3). The trees were planted in an approximate east-west orientation and were characterized by canopies which had not yet formed a hedgerow (i.e. canopies not touching within the row). Trees within this orchard were lightly pruned by means of selective limb removal to maintain an approximate cone shape and had an average leaf area index (LAI) of 1.44 $m^2\ m^{-2}$ and an estimated canopy cover of 0.28 at the start of the measurement period (16 August 2017). Furthermore, this orchard was irrigated by means of one 50 $L.h^{-1}$ microsprinkler per tree (wetted diameter of 1.4 m), placed in close proximity to tree stems. No irrigation scheduling equipment (i.e. capacitance probes) was present at the intermediate orchard site and a fixed irrigation regime of approximately 150 L $tree^{-1}$ $week^{-1}$ (0.70 mm $week^{-1}$) was maintained. Given that these orchards had just started producing, historic yields were low (between 1 and 2 t ha^{-1}) but were within industry norms. Tree rows were kept clean by means of regular herbicide applications, with shortly mown inter-rows consisting of a mixture of weeds and grasses.

Figure 3.3: The intermediate bearing (IB) macadamia orchard with short, mown inter-rows consisting of grasses and a variety of weeds.

Non-bearing orchards were located on a commercial macadamia farm approximately 5 km south-east of the MB orchard within the Schagen valley. Trees were planted in September 2017 and were approximately eight months old at the commencement of measurements. These trees were planted on ridges in a north-south orientation at a population of 312 trees ha^{-1} (spacing 8 x 4 m, i.e. 32 m^2 per tree). Each tree was fitted with a cone shaped microsprinkler with an emitter rate of 50 L h^{-1} and a wetted diameter of 1.0 m. Similar to the IB orchard, no pre-installed irrigation scheduling equipment was present at the site and a fixed irrigation regime of approximately 50 L $tree^{-1}$ $week^{-1}$ (0.22 mm $week^{-1}$) was maintained. Tree rows were not kept clean from weeds, with the exception of an area approximately 1.0 m in radius around the base of the tree being kept clean of any weeds by means of mowing and application of organic mulch. Inter-rows consisted of a shortly mown mixture of weeds and grasses (Figure 3.4). Water stress in this orchard was not assessed by means of pre-dawn leaf water potentials due to the destructive nature of the measurements and the limited canopy size of trees within the orchard. Transpiration measurements in the non-bearing orchard began on 17 April 2018 using the thermal dissipation (TD) method (Granier, 1985, Granier, 1987) (TDP10, Dynamax Inc., Houston, USA).

Figure 3.4: Position of the 2-year old non-bearing 'Beaumont' macadamia orchard with mown inter-rows consisting of grasses and a variety of weeds.

Table 3.1 Details of the 'Beaumont' macadamia orchards where water use is being estimated

Orchard Reference	Mature Bearing (MB)	Intermediate Bearing (IB)	Non Bearing (NB)
Cultivar	‘Beaumont’ Macadamia	‘Beaumont’ Macadamia	‘Beaumont’ Macadamia
Rootstock	‘Beaumont’	‘Beaumont’	‘Beaumont’
Planting date	2005	2012	2017
Orchard block area	3.8 ha	3.0 ha	5.0 ha
GPS co-ordinates	25°21'50.36" S, 30°46'46.47" E	25°21'2.01"S, 30°43'44.30"E	25°23'43.47"S, 30°46'59.24"E
Tree spacing	4 m x 8 m (32 m^2), planted on ridges	4 m x 8 m (32 m^2)	4 m x 8 m (32 m^2), planted on ridges
Row orientation	North-South	East-West	North-South
Irrigation - Type - Delivery rate - Wetted diameter	 Microsprinkler 50 L h^{-1} 1.7 m	 Microsprinkler 50 L h^{-1} 1.4 m	 Microsprinkler 50 L h^{-1} 1.0 m
Canopy dimension	Height – 5.7 m Width – 5.8 m Breadth – 4 m – Hedgerow	Height – 4.2 m Width – 3.0 m Breadth – 3.0 m	Height – 1.6 m Width – 1.7 m Breadth – 1.6 m
Canopy cover	0.72	0.28	0.08
Leaf area index – orchard ($\bar{x}$ = 4 measurements) – individual trees	 5.25 m^2 m^{-2} 1 – 5.49 m^2 m^{-2} 2 – 5.25 m^2 m^{-2} 3 – 4.95 m^2 m^{-2} 4 – 5.33 m^2 m^{-2}	 1.44 m^2 m^{-2} 1 – 0.88 m^2 m^{-2} 2 – 1.64 m^2 m^{-2} 3 – 1.75 m^2 m^{-2} 4 – 1.49 m^2 m^{-2}	Not determined
No of experimental trees	4	4	4
Tree circumferences at the start of measurements	1 – 46.2 cm 2 – 45.6 cm 3 – 44.6 cm 4 – 50.9 cm	1 – 35.2 cm 2 – 37.8 cm 3 – 37.2 cm 4 – 36.5 cm	1 – 8.7 cm 2 – 8.1 cm 3 – 9.8 cm 4 – 11.0 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 the locally manufactured equipment. 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 in trees of the MB and IB orchards. 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 (2.5 mm). 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 2.5×10^{-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:

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

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

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

The wound width was assessed through visual inspection and subsequent measurement of the outer diameter of the wound. These measurements were made at the end of the measurement campaign in both the MB and IB orchards, with measurements of wounding in both orchards being minimal and were on average 0.30 cm, which included the total width of probes and wound (Table 3.2). In order to assess the accuracy of the determined wounding factor, measurements of evapotranspiration made alongside measurements of transpiration during periods with no rainfall and/or irrigation (20-31 July 2018, i.e. little to no soil evaporation) were used. This assessment revealed that estimates of transpiration obtained from sap flow data and evapotranspiration measurements made using the eddy covariance technique were fairly similar when using the measured wounding width (0.30 cm). If a wounding width greater than 0.30 cm was used in the calculation, measurements of transpiration during this period, exceeded measurements of total evapotranspiration (Figure 3.5). Although, measurements of transpiration, using a wounding width of 0.30 cm, was on average 0.15 mm day^{-1} lower than that of total evapotranspiration, it is unreasonable to assume that no evaporation or transpiration from the plant cover between the rows (both weeds and grass) would have occurred.

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. As there was no change in colour of the wood from the outside (youngest wood) to the centre of the core (oldest wood) in any of the samples taken in each orchard, it was assumed that no heartwood (non-conducting xylem) was present. This was confirmed by the uniformity of the safranin stain across the wood sampled. Other wood characteristics, including sapwood moisture content (m_c) and density (ρ_b) were determined from additional core samples taken during the measurement period (Table 3.2).

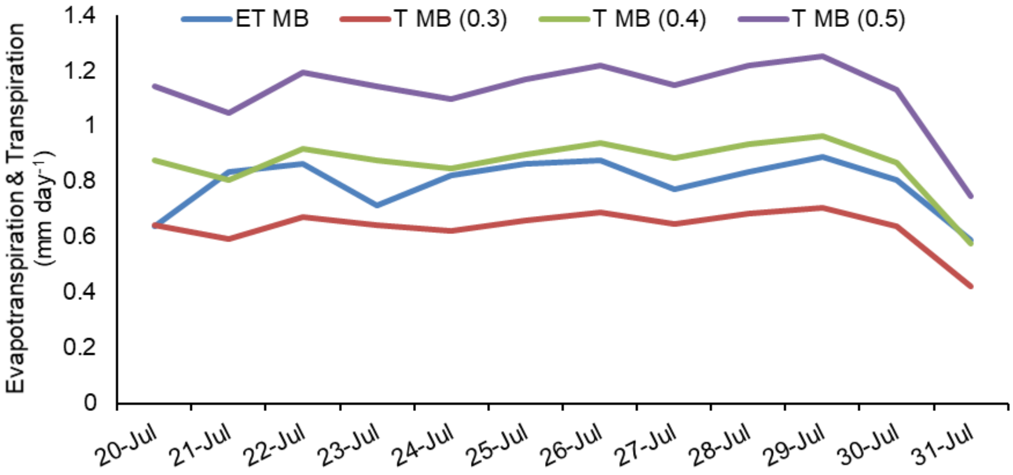


Figure 3.5: Measurements of evapotranspiration (ET) and transpiration (T) using three different wounding widths (0.30, 0.40, and 0.50 cm) in the mature bearing (MB) orchard from 20 July 2018-31 July 2018.

Table 3.2: Parameters used for transpiration estimates obtained from destructive measurements in the mature bearing (MB) orchard

Parameter	Value used
Wood density (ρ_b)	0.69 g cm^{-3}
Wood moisture content (m_c)	62.0%
Wound width*	0.30 cm

*Wound width was taken as an average of measurements made from the four experimental trees, in both the MB and IB orchard, and was assumed that wound width was radially constant. Wound width was measured as the total width of the probe and additional wounding that occurred as part of the installation process.

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):

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

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.

In the non-bearing orchard the trees were still relatively small and as a result a TDP system was used to determine transpiration. Thermal Dissipation Probes were installed by drilling two holes, 40 mm apart, into the bark to insert the needles directly into the sapwood of the tree because this is the only part that conducts water. A waterproof seal was used around the stem to protect the probes. A reflection shield was wrapped around the sensor and secured with cable ties (Figure 3.6) to prevent water from damaging sensors and to shield the sensors from thermal radiation to avoid inaccurate measurements (TDP Thermal Dissipation Probe User Manual, 1997).

The thermocouples measure the difference in temperature between the upper and lower needles (Figure 3.6). The lower needle is referred to as the reference needle because only the upper needle is continuously heated, this allows for determination of the ambient temperature of the wood. The upper needle consists of a heating element and copper-constantan thermojunction (TDP Thermal Dissipation Probe User Manual, 1997).

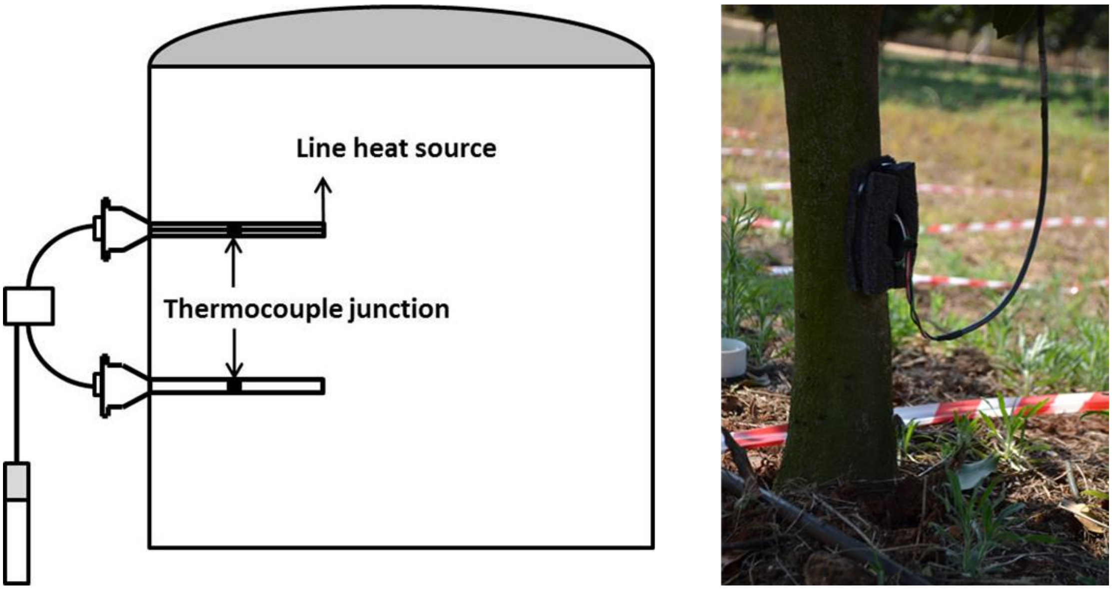


Figure 3.6: Left diagram of TDP and right insertion of TDP probe into a macadamia stem

The temperature difference (ΔT) is influenced by the sapwood heat dissipation of sap flow near the sensors. Sap flow cools down the heated upper needle, reducing its temperature therefore when dT is minimal sap flow is higher stems (TDP Thermal Dissipation Probe User Manual, 1997). The ΔT was recorded on a CR1000 Campbell Scientific data logger, and power was provided by a solar panel. TDP10 sensors (Dynamax Inc., Houston, TX, USA) were installed on all four trees. 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. Data was logged every 15 min.

According to Granier (1985) SFD can be calculated 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 (K), 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. The outer bark diameter was measured to determine the sapwood area. These parameters were used to determine the sap flow rate and to upscale sap flow to tree transpiration.

3.1.2.2 Evapotranspiration

Fluxes of latent (LE) and sensible heat (H) were measured with an extended open path eddy covariance (OPEC) system, comprising an IRGASON open-path analyser and sonic anemometer (Campbell Scientific Inc., Logan, Utah, USA), which was mounted on a lattice mast 7.5 m above the soil surface (1.5 m above the canopy) in the mature orchard and at 5 m above the soil surface in the non-bearing orchard (2.5 m above the canopy) (Figure 3.7). Upwind and downward fetch of the prevailing northerly westerly and south easterly winds was 150 m. Air temperature and humidity were measured using a HygroClip2 HC2-S(3) thermohygrometer probe (Rotronic Instruments, Bassersdorf, Switzerland). Net radiation (R_n) was measured using an NR-Lite net radiometer (Model 240-110 NR-Lite, Kipp & Zonen, Delft, Netherlands) 7.5 m above ground for the mature orchard and 5 m above the ground for the non-bearing orchard. Four soil heat flux plates (model HFT-S, REBS, Seattle, Washington, USA) were used to measure soil heat flux (G) at a depth of 80 mm under the trees and between the rows, and four TCAV-L soil temperature averaging probes (Campbell Scientific Inc., Logan, Utah, USA) at depths of 20 and 60 mm were used to calculate the heat stored above the plates. Volumetric soil water content in the first 60 mm of the soil surface was measured using two time domain reflectometer (CS616, Campbell Scientific Inc., Logan, Utah, USA) placed near the heat flux plates. Measurements were sampled at a frequency of 10 Hz and logged on a CR3000 data logger (Campbell Scientific Inc., Logan, Utah, USA) using the Easyflux-DL software from Campbell Scientific. The program applies the most common open-path EC corrections to fluxes.

Measurements in the mature orchard took place during two measurement campaigns. The first campaign was from 29 July to 16 August 2017 and the second campaign was from 12 May to 7 August 2018. In the non-bearing orchard measurements took place from 4 October 2018 to 12 March 2019.

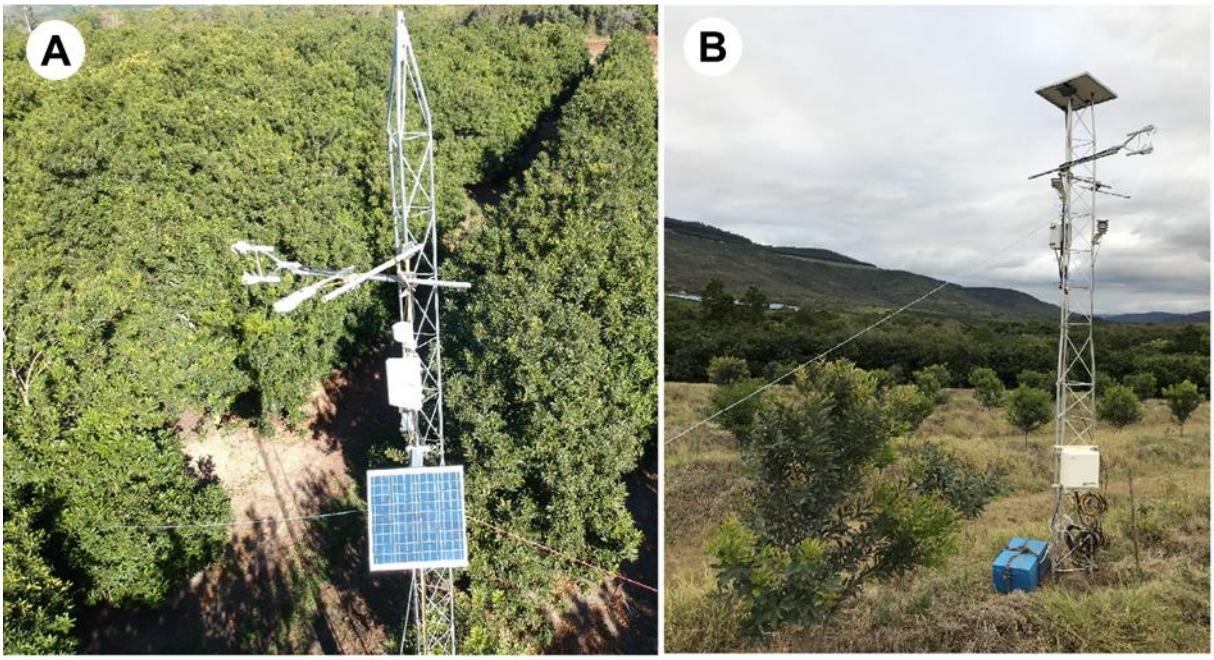


Figure 3.7: Eddy covariance system installed in the A) full-bearing 'Beaumont' macadamia orchard and B) the non-bearing 'Beaumont' macadamia orchard

3.1.2.3 Irrigation volumes and soil water content monitoring

Irrigation volumes were measured with a water meter plumbed into the irrigation line at the start of the tree row (Figure 3.8), with readings taken every 7 days. The frequency of irrigation was monitored with a Decagon PS-1 Irrigation Pressure switch attached to an EM50 Logger (Decagon Device Inc, Pullman, WA, USA) in the mature bearing orchard (Figure 3.8).

Figure 3.8: Water meter (left) plumbed into the start of the irrigation line to which the Decagon PS-1 Irrigation Pressure switch (right) was attached

Volumetric soil water content (θ) was measured using a TDR100 system (Campbell Scientific Inc., Logan, Utah, USA) and logged at hourly intervals on a CR10X data logger in the mature orchard. The system was installed at the beginning of August 2016 in the row next to the trees monitored with sap flow systems to avoid disturbance to the root system of the measurement trees (Figure 3.9). The 28 CS610 TDR probes were installed in five profiles around a tree to account for the variation in wetting from irrigation and rainfall and shading by the tree (Figure 3.10). Profile 1 was on the east side of the tree, 1.1 m from the middle of the tree row and still within the root zone of the tree (installation depths 0.1, 0.2, 0.3, 0.5 and 0.8 m from the soil surface). Profile 2 was in the centre of the tree row, 1.3 m to the south of the tree trunk (installation depths 0.1, 0.2, 0.3, 0.4, 0.6 and 0.8 m from the soil surface). Profile 3 was on the west side of the tree, 1.4 m from the middle of the tree row and still within the root zone of the tree (installation depths 0.1, 0.2, 0.3, 0.4, 0.6 and 0.8 m from the soil surface). Profile 4 was on the west of the tree and halfway down the ridge, 2 m from the tree trunk and close to the edge of the root zone of the tree (installation depths 0.1, 0.2, 0.3, 0.4, 0.6 and 0.8 m from the soil surface). Profile 5 was in the middle of the work row, 3.6 m from tree trunk and at the edge of the root zone of the tree (installation depths 0.1, 0.2, 0.3, 0.5 and 0.8 m from the soil surface).

Figure 3.9: Installation of TDR100 system in the full-bearing 'Beaumont' macadamia orchard

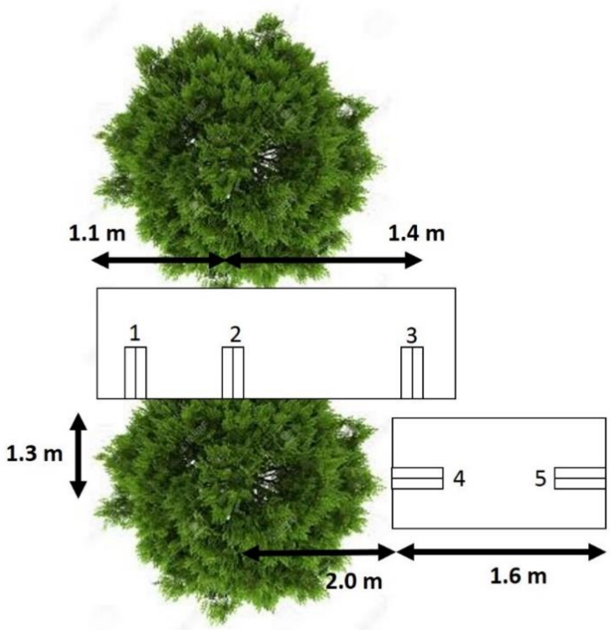


Figure 3.10: Placement of the TDR100 system in the full-bearing 'Beaumont' macadamia orchard

Measurements of soil water potential (ψ_{soil}) using MPS-6 calibrated water potential sensors (Decagon Devices Inc, Pullman, WA, USA) were made in the IB orchard (Figure 3.11). These sensors were installed within the wetting diameter of the microsprinkler (i.e. 1.5 m from the trunk) at depths of 0.2, 0.4 and 0.6 m from the soil surface. Sensors were connected to a CR1000 data logger (Campbell Scientific Ltd, Logan, Utah, USA) and measurements were logged at hourly intervals.

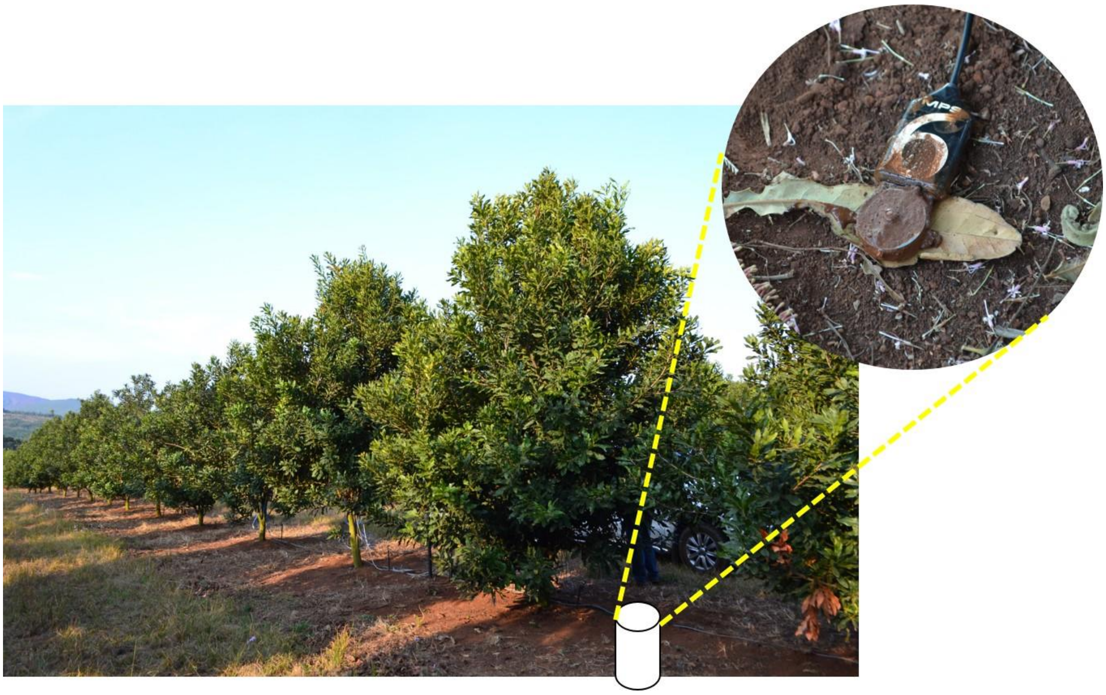


Figure 3.11: Placement of MPS-6 soil water potential sensors in the 5 year old 'Beaumont' macadamia orchard

3.1.3 WEATHER DATA

A WS-GP1 Delta-T (Delta-T Devices Ltd, Cambridge, United Kingdom) weather station was installed close to the MB orchard (Figure 3.2). The station collected weather data including solar radiation (R_s), windspeed (u_2) and direction, air temperature (T_{air}), air relative humidity (RH) and rainfall at 20-minute intervals for approximately 3 years (10 August 2016-5 August 2019). Air vapour pressure deficit (VPD_{air}) was calculated from T_{air} and RH. Reference evapotranspiration (ET_o) was calculated using the FAO Penman-Monteith equation for a short grass reference surface, as described by Allen et al. (1998) and Pereira et al. (2015). The weather station was installed over a dry short grass surface and was within 50 m of irrigated MB orchard. There was natural vegetation to the north and east of the weather station, which consisted mostly of short grass. Thus, depending on wind direction, the ET_o was either well estimated or slightly overestimated. When wind blew over the natural vegetation towards the AWS the air was likely to be fairly dry air, resulting in an overestimation of ET_o, as opposed to the well-watered reference surface. Quality assessment and quality control of the data was performed according to the procedures described by Allen (2008). Throughout the entire data set, only corrections to R_s were required, with a multiplication factor of 1.27 applied to measured values. This value was used based on assessments of R_s on clear days, which fell significantly below the computed R_s under clear sky conditions (R_{so}).

3.1.4 TREE CHARACTERISTICS

Canopy dimensions (height, width, and breadth) were measured throughout the trial in all orchards. Additional measurements of canopy dimension were made using drone imagery and processing software developed and maintained by Aerobotics (Cape Town, Western Cape, South Africa). Drone technology has been shown to provide reasonable estimates of tree height and canopy dimension measurements (Dempewolf et al., 2017, Panagiotidis et al., 2017), and was as a result deemed as acceptable for this study. Canopy volume was calculated by assuming that macadamia canopies have an ellipsoid shape. Measurements of leaf area index (LAI) and fractional interception of photosynthetically active radiation (PAR) were performed randomly throughout the duration of the trial using a Decagon AccuPAR LP-80 ceptometer (Decagon Devices, Pullman, WA, USA). Sampling of PAR below the canopy was conducted across and within the row (covering the total area allocated to one tree) at pre-determined 1 m intervals (Figure 3.12), whilst full sun measurements were taken in an open area next to each orchard. All measurements were taken between 12:00 and 14:00, under clear sky conditions.

Figure 3.12: Grid system for fractional interception of PAR measurements in the mature bearing (MB) macadamia orchard

3.1.5 ECOPHYSIOLOGY MEASUREMENTS

Ecophysiological measurements were restricted to only the MB orchard, where clear phenological changes and the large canopy of trees within in the MB orchard were ideal for the measurements. Leaf gas exchange spot measurements were made on the four sample trees during eleven data collection campaigns from August 2016 to May 2018. Measurements were made on randomly selected mature, hardened-off leaves, which were fully exposed to the sun prior to measurement and typically situated on the outside of the canopy, within 2 m of the ground surface. Measurements were made between 09:00 and 16:00, during which either the western or eastern face of the canopy was exposed to direct sunlight.

The gas exchange parameters measured included net light-saturated CO_2 assimilation rate (A_{max}), stomatal conductance (g_s), and intercellular CO_2 concentration (C_i), obtained using a photosynthesis system (Model: LI-6400 XT, LI-COR, Lincoln, NE, USA). Sensors inside the cuvette monitored photosynthetically active radiation (PAR) and leaf temperature (T_{leaf}). Chamber CO_2 concentration was maintained at 400 µmol mol^{-1}, the flow rate was 400 µmol s^{-1}, PAR inside the chamber was maintained between 1500-2000 µmol m^{-2} s^{-1} (LI-6400 XT LED light source), and RH was maintained at more than 50% (to prevent stomatal oscillations). Leaf-to-air vapour pressure deficit (VPD_{leaf}) was calculated by the LI-COR software. Measurements were typically recorded as soon as A stabilized, usually within two minutes of leaf insertion.

The auto program function of the LI-6400 XT was used to obtain photosynthetic light and CO_2 response (A/C_i) curves using mature sun-exposed leaves on the four sample trees in the orchard. Light and A/C_i curves were performed by altering the PAR (2000, 1500, 1000, 600, 400, 200, 100, 50, 0 µmol m^{-2} s^{-1}) and CO_2 concentration (400, 300, 200, 150, 100, 50, 0, 400, 600, 700, 1000, 2000 µmol mol^{-1}) within the chamber. For light response curves the CO_2 concentration was controlled at 400 µmol mol^{-1}, whilst PAR was set at 1500 µmol m^{-2} s^{-1} for A/C_i curves. T_{leaf} was controlled within 5°C of ambient by Peltier coolers, and RH within the chamber was maintained at more than 50%. Data points were logged within one to two minutes, and all measurements were made based on a stability factor where A had a standard deviation of less than 0.5 µmol m^{-2} s^{-1} and a rate of change per minute less than 0.1 µmol m^{-2} s^{-1}. Curve fitting and analysis was done using the monomolecular function for light response curves as described by Causton and MP (1990) and by fitting the model described by Sharkey et al. (2007) for CO_2 response curves. CO_2 response curves were also used to calculate stomatal limitation (l) as described by Long and Bernacchi (2003). Light saturation point for macadamia was calculated from light response curves as the light level where A was approximately 90% of $A_{\max}$ as determined using the model of Causton and MP (1990).

Supplementary measurements of stomatal conductance (g_s) were also measured using an AP4 porometer (Delta-T Devices Ltd, Cambridge, United Kingdom) and/or an SC-1 leaf porometer (Decagon Device Inc, Pullman, WA, USA). Stomatal conductance was sampled at 30-minute intervals throughout the day. These measurements were assumed to be a representative sample of leaves on the tree and should approximate canopy conductance.

Measurements of pre-dawn leaf water potential (ψ_{pd}) were made in both the MB and IB orchard using a Scholander pressure chamber (Model 600, PMS Instrument Company, Albany, OR, USA). These measurements were made on the same four trees used for sap flow measurements in order to assess the water status of trees in an attempt to eliminate water stress as a confounding factor in any of the results presented. A total of 180 ψ_{pd} measurements were made in the MB orchard and 63 ψ_{pd} measurements in the IB orchard throughout the duration of the trial. Water stress is suggested to occur at ψ_{pd} less than -0.5 MPa based on research from Stephenson et al. (2003). Pre-dawn leaf water potential (ψ_{pd}) was measured on a weekly basis from October 2016.

Additional leaf (ψ_{leaf}) and stem (ψ_{stem}) water potential were measured on the four sample trees using a Scholander pressure chamber from before sunrise to sunset on selected days. For each tree, measurements were taken hourly for three randomly selected mature sun-exposed leaves (ψ_{leaf}), three shade leaves on the inside of the canopy (ψ_{leaf}) and three shade leaves (enclosed) on the inside of the canopy (ψ_{stem}) (36 measurements per cycle). The latter were enclosed in aluminium covered bags (PMS Instrument Company, Albany, OR, USA) for at least 30 min prior to measurement.

Hydraulic conductance (k) was estimated according to Moreshet et al. (1990) where k was separated into the pathway from the soil to the stem ($k_{soil\text{-}stem}$) and from the stem to the leaves ($k_{stem\text{-}leaf}$). Daily values of k were calculated as a mean of daytime hourly values. The root-stem interface was calculated using Equation [18], where J is sap flux and ψ_{soil} was assumed to be equal to pre-dawn leaf water potential. The hydraulic conductance between the stem and leaf interface was calculated based on Equation [19], with the fraction of sunlit canopy leaf area ($\propto$) estimated using visual inspections of the tree canopy in a similar fashion to that described by Moreshet et al. (1990). Whole tree hydraulic conductance ($k_{soil\text{-}leaf}$) was calculated using Equation [20], with whole plant leaf specific hydraulic conductance (k_L) calculated using

Equation [21], as outlined by Hubbard et al. (2001). It should be noted that estimates of k_L were obtained by using measurements of g_s (measured using the LI-6400 XT) and ψ_{leaf} obtained from the same leaf and VPD_{air} obtained from the weather station, with the assumption that macadamias are well-coupled to the atmosphere being a tall, rough surface.

$$k_{soil\text{-}stem} = J/(\psi_{soil} - \psi_{stem}) \qquad [18]$$

$$k_{stem\text{-}leaf} = J/(\psi_{stem} - (\propto\psi_{sun\ leaf} + (1\text{-}\propto)\psi_{shade\ leaf})) \qquad [19]$$

$$k_{soil\text{-}leaf} = J/(\psi_{soil} - (\propto\psi_{sun\ leaf} + (1\text{-}\propto)\psi_{shade\ leaf})) \qquad [20]$$

$$k_L = g_s/((\psi_{soil} - \psi_{sun\ leaf})/VPD_{air}) \qquad [21]$$

3.1.6 DETERMINATION OF YIELD AND QUALITY

Yield was measured on an individual tree basis by means of hand harvesting trial trees in both the MB and IB orchard. Yields including nut in husk (NIH), wet in shell (WIS) and dry in shell (DIS) masses were recorded separately. Harvested nuts were de-husked using a single de-husking plant to ensure that similar WIS recovery rates were obtained from each tree. Following the de-husking process, WIS nuts were dried at a temperature of 34°C for approximately 14 days, where after the DIS weight was measured. Quality assessments were conducted by the processing facility staff by means of hand sorting kernel according to industry developed standards.

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 was as follows:

Water use efficiency

$$WUE = \frac{yield}{ET} \qquad [22]$$

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 will therefore be kg m^{-3}.

Water use productivity

$$WUP = \frac{Output}{ET} \qquad [23]$$

Where Output is defined as the value of the produce and will consider the quality of the macadamia nuts and the fact that quality influences the price of the product. As a result, the different grades of product harvested from the study orchard needs to be 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}.

3.1.8 STATISTICAL ANALYSIS

To analyse the influence of T_{leaf} and VPD_{leaf} on A_{max} and g_s, data from all measurement dates were grouped into five T_{leaf} categories spanning 5°C, and eight categories of VPD_{leaf} spanning 0.5 kPa. Using repeated measures ANOVA with Restricted Maximum Likelihood estimation (REML) in the Variance Estimation, Precision & Comparison methodology (VEPAC) of Statistica (TIBCO Software Inc. Version 13.3), a test for A_{max} and g_s was conducted. The individual tree replicate was a random variable so that N=4. Using LSD multiple comparisons, the treatment means were regarded as different if $p \leq 0.05$.

Statistical assessment of the seasonal changes in A_{max}, g_s and VPD_{leaf} (from leaf gas exchange measurements) and corresponding VPD_{air} and T_{air} (from the automatic weather station) were also analysed using repeated measures ANOVA with REML in VEPAC (Statistica, TIBCO Software Inc. Version 13.3). Five of the measurement dates had data for all four trees (i.e. containing full data sets) and could be used for this analysis. Using LSD multiple comparisons, the treatment means were regarded as different if $p \leq 0.05$.

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

3.2.1 ORCHARD DESCRIPTION

Two trial sites were used during the course of this study. Water stress at different phenological stages was implemented in a mature orchard over three seasons, whilst a shorter trial to assess the physiological response of young macadamia trees (intermediate orchard) was conducted over a period of a month. Both orchards were located on the same farm, situated approximately 25 km west of Nelspruit town in the Schagen Valley, Mpumalanga. An additional trial to understand the response of macadamias to water stress was deemed necessary due to the loss of harvest data in April 2020 as a result of the Level 5 COVID-19 lockdown.

The mature orchard consisted of 14-year-old macadamia trees and was approximately 2.9 ha (896 trees) in size (GPS-Coordinates: 25°23'43.3"S 30°46'47.1"E, Figure 3.13). The orchard consisted of 18 rows of full bearing, microsprinkler irrigated macadamia trees (cv. HAES 695, ‘Beaumont’, *M. tetraphylla x M. integrifolia*, grafted on ‘Beaumont’ rootstock) planted on an 8 x 4 m spacing, totalling 312 trees per hectare (Figure 3.14). Trees were planted in a North-South orientation with an average measured tree height at the start of the trial of 5.5 m and canopy width of 4.8 m, forming a complete hedgerow. Trees were pruned on an annual basis in order maximise light interception and orchard ventilation, removing no more than 30% of the tree canopy. The orchard consisted of predominantly 30% Westleigh, 30% Kroonstad, 17% Hutton, 16% Swartland, and 8% Shortlands soil types (See Appendix). The orchard was not ridged and trees were mulched, using pruned material, directly after harvest. Trees were irrigated by means of one microsprinkler (50 L h^{-1}) per tree, with a wetted diameter of 3 m, according to a cycle determined by readings from a capacitance probe (DFM Software Solutions CC, Stellenbosch, Western Cape, South Africa) installed at a 1.2 m depth between two macadamia trees in the orchard. Orchard details are provided in Table 3.3.

Table 3.3: Overview of the ‘Beaumont’ (6 95) orchard at Du Mak Farm in Schagen Valley, Nelspruit

Cultivar	‘Beaumont’
Rootstock	‘Beaumont’
Age	13 years old (planted 2003)
Orchard block area	2.94 ha
Tree spacing	8 m x 4 m (312 trees ha^{-1}), no ridges
Row orientation	North-South
Irrigation	Micro-sprinklers, with a delivery rate of 50 L h^{-1} Wetted diameter = 3 m
Canopy dimension ($\bar{x}$ = 10 measurements)	Height 5.5 m, Width 4.8 m, Complete hedgerow
Canopy cover	0.71
Number of experimental trees	Three experimental blocks with seven treatments per block, each treatment consisting of three trees = 63 trees

Figure 3.13: Positioning of the mature and intermediate 'Beaumont' macadamia orchards on the Du Mak farm

Figure 3.14: The mature ‘Beaumont’ macadamia orchard on Du Mak farm where a water stress was imposed at different phenological stages

The intermediate orchard trial site was situated on the same farm, Du Mak farm, in the Schagen Valley, Mpumalanga (GPS-Coordinates: 25°23'43.47"S, 30°46'59.24"E, Figure 3.13) on a 4-year-old macadamia orchard (planted in 2016). Trees (cv. HAES 695, ‘Beaumont’, *M. tetraphylla x M. integrifolia*, grafted on ‘Beaumont’ rootstock) were planted on an 8 x 4 m spacing, totalling 312 trees per hectare (Figure 3.15). Trees were planted in a North-South orientation with an average measured tree height of 2.8 m and canopy width of 2.5 m. Trees had not yet formed a complete hedgerow. Trees were pruned prior to the installation of equipment and treatment implementation, not removing more than 10% of the canopy volume. The orchard was ridged and consisted of predominantly sandy, well-drained soils. Trees were irrigated by means of one microsprinkler (25 L h^{-1}) per tree, with a wetted diameter of 1.5 m. Micro-jet sprinklers were placed close to the tree trunk, wetting only the immediate root zone within a 1 m radius of the tree base. Orchard details are provided in Table 3.4.

Figure 3.15: The intermediate 'Beaumont' macadamia orchard on the du Mak farm used for the additional physiological measurements

Table 3.4: Overview of the 'Beaumont' (695) intermediate orchard at Du Mak Farm in the Schagen Valley, Nelspruit

Cultivar	'Beaumont'
Rootstock	'Beaumont'
Age	4 years old (planted 2016)
Orchard block area	10 ha
Tree spacing	8 m x 4 m (312 trees ha^{-1}), Ridged
Row orientation	North-South
Irrigation	Microsprinklers, with a delivery rate of 25 L h^{-1} Wetted diameter = 1.5 m
Canopy dimension ($\bar{x}$ = 10 measurements)	Height 2.8 m, Width 2.5 m, not forming a complete hedgerow
Canopy cover	Approximately 20%
Number of experimental trees	Five experimental treatments with three trees per treatments = 15 trees

In order to correlate measured tree variables with microclimatic conditions, weather data was obtained using a WS-GP1 Delta-T (Delta-T Devices Ltd, Cambridge, United Kingdom) automatic weather station, which was installed within 7 km of the site. Weather data included solar radiation, wind speed and direction, temperature, relative humidity and rainfall data at 20-minute intervals. Daily reference evapotranspiration (ET_o) and vapour pressure deficit (VPD) were calculated using the procedure as described in FAO-56 (Allen et al., 1998) from weather data recorded by the automatic weather station.

3.2.2 THE IMPLEMENTATION OF WATER STRESS TREATMENTS

The response of macadamia to mild water stress was measured on the basis of final nut set, nut drop, yield and quality. These measurements were made in conjunction with measurements of the physiological response of the trees to water stress, which included leaf water potential and leaf gas exchange.

The experiment spanned over a period of three seasons from August 2017 to April 2020, where seven water stress treatments were imposed on 63 randomly selected trees and respective yield, quality and physiological characteristics were evaluated. Yield and quality evaluations for 2019/20 season were affected by the Covid-19 pandemic, as a result of harvest needing to occur during lockdown Level 5. The 2017/18 trial consisted of three replicate blocks consisting of three treatments (3 trees per treatment) (n = 9) at different water application rates namely: T1 = no-irrigation/rainfed; T2 = half irrigation; T3 = normal irrigation. Treatment T3 served as the experimental control. In addition to the aforementioned treatments, four water stress treatments at different phenological stages (3 trees per treatment) namely: T4 = flowering and nut set; T5 = nut sizing and premature nut drop; T6 = shell hardening and T7 = oil accumulation, were applied to each replicate block during the 2018/19 and 2019/20 seasons. Treatments were assigned randomly to a completely randomized block design, of which each treatment replicate occurred in every second row, separated by approximately 16 m to avoid any border effect interference (Figure 3.16). Treatments were applied to three consecutive trees within a row and each treatment was separated by approximately two trees or 8 m.

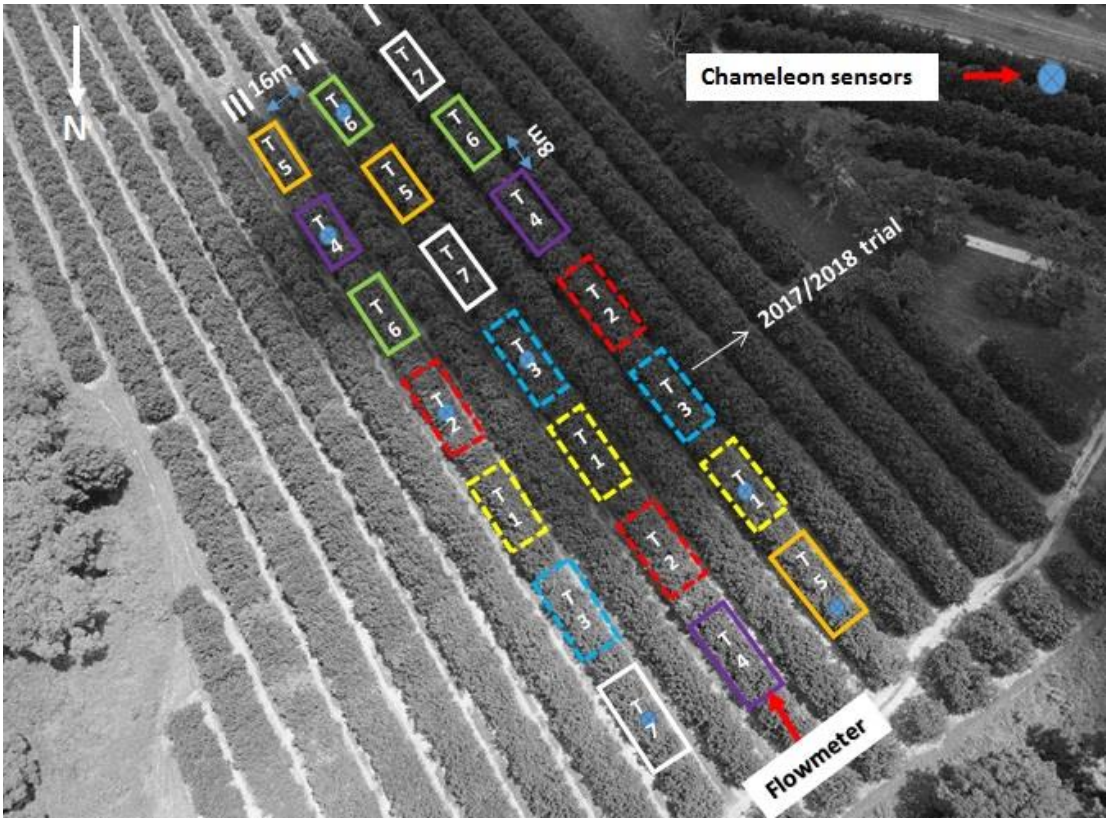


Figure 3.16: Orchard layout and completely randomized block design consisting of three replicated blocks used over a three season period. Dashed (--) blocks representing initial 2017/2018 trial blocks. T1 – no-irrigation; T2 – half irrigation; T3 – normal irrigation (control); and solid blocks representing treatments from the 2018/2019 season T4 – flowering and nut set; T5 – nut sizing and pre-mature drop; T6 – shell hardening; T7 – oil accumulation.

Measurements of soil water matric potential and irrigation volumes were collected throughout the duration of both the 2017/18 and 2018/19 seasons. Soil matric potential readings were performed over both 2017/18 and 2018/19 seasons for control, rainfed and half irrigation trees while matric potentials were only recorded over the 2018/19 seasons for trees stressed at different phenological stages. Soil water matric potential measurements were collected using seven Chameleon probes (VIA 2019), each containing three sensors which were placed at three different depths (20 cm, 40 cm and 60 cm) in one of each of the seven different treatment replicates (Figure 3.16 and Figure 3.17). Sensors were positioned strategically within the canopy drip line and placed within a 1 m radius of the tree stem. Chameleon probes measure soil matric potential and a colour is assigned to each matric potential range. These ranges included, Blue (0 to -20 kPa); Green (-20 to -50 kPa); Red (>-50 kPa); Grey (Unreadable). Measurements within the blue colour range represent conditions of sufficient water for plants, but leaching is likely occurring. Measurements within the green colour range represent conditions of sufficient water but no leaching, while measurements within the red colour range represent dry soil conditions where stress is likely occurring. Grey colours presented in measurement figures are indicators of soil water depletion, with matric potential readings far exceeding -50 kPa, surpassing the measurement accuracy of the Chameleon sensors (VIA 2019). Grey colours could also represent faulty instrumentation.

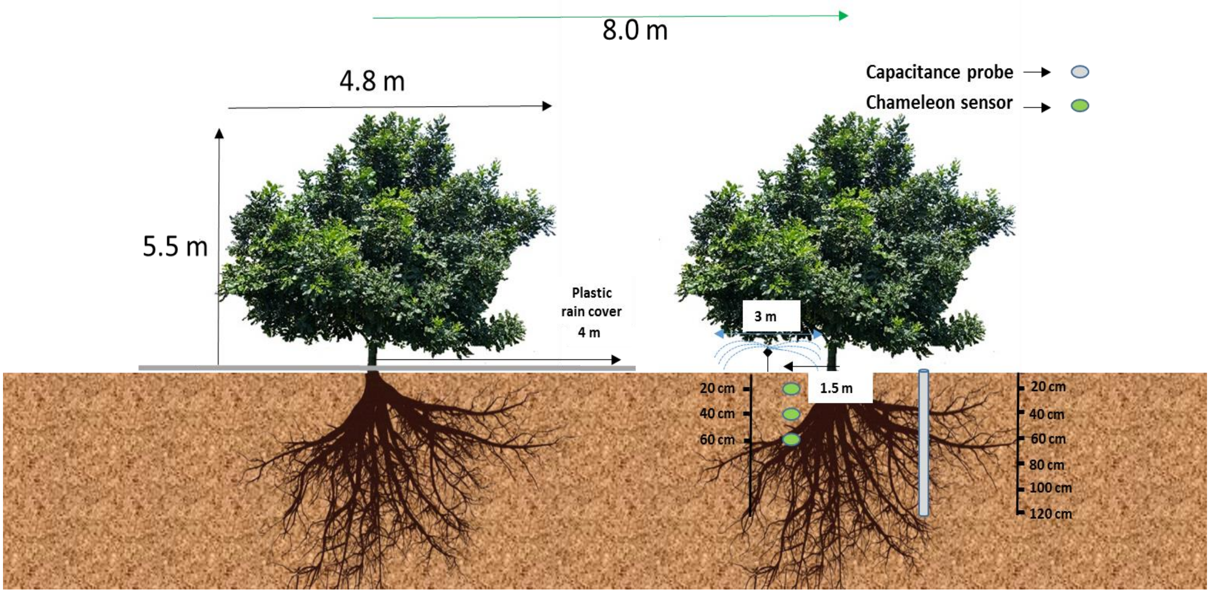


Figure 3.17: Placement of a capacitance probe and chameleon water sensor probes in the mature macadamia orchard at Du Mak Farm in Schagen Valley, Nelspruit.

In order to determine the effect of water stress at different phenological stages, similar to those proposed by Stephenson et al. (2003). 200 µm clear plastic rain-covers were installed on each treatment replicate prior to the onset of a phenological stages (Figure 3.18). Plastic rain-covers were placed up to the tree stem and extended past the 32 m^2 soil surface allocated to each tree, eliminating unintentional water replenishment through the exclusion of rainfall. Valves were fitted to the micro-irrigation tube of each treatment tree in order to “turn-off” the micropsrinkler and eliminate irrigation water during the respective phenological stages. The implementation of a no-irrigation/rainfed (T1) treatment was performed in a similar fashion, as irrigation water was eliminated with the use of valves fitted to the microsprinkler tube of each tree. However, no plastic was placed under these trees. The half irrigation treatment was implemented by replacing 50 L h^{-1} sprinkler heads with 25 L h^{-1} sprinkler heads on each of the T2 treatment trees.

Figure 3.18: Implementation and placement of 200 µm clear plastic rain-covers beyond the 32 m^2 allocated to each treatment tree in order to implement water stress during different phenological stages by eliminating unwanted soil water replenishment

A preliminary water stress trial to determine the level of water stress required to induce a mild macadamia water stress, as well as the rate of decline in pre-dawn stem water potential was performed on one no-irrigation/rainfed (T1) treatment. The preliminary trial commenced after the 2017/18 season harvest on 4 March 2018, where plastic rain-covers were installed on one of the three T1 treatment replicates. The preliminary trial was further used for the implementation of a mild water stress during macadamia flower initiation. Based on the findings by Stephenson et al. (1989), April-May is the best estimate of macadamia flower initiation and was therefore used to determine the effect of water stress during the flower initiation period on flowering intensity, flower panicle size and nut set. Stephenson et al. (1986) further state that potential yield is determined at floral initiation, therefore understanding the impact of the environment on this important process was desirable. The preliminary trial was terminated on 7 May 2018, prior to the onset of flowering.

Stress implementation during flowering and nut set (T4) commenced on 13 July 2018 and 25 July 2019, where nine macadamia trees (3 trees per treatment replicate) were exposed to a mild water stress during flowering and initial fruit set. Pre-dawn leaf water potential measurements were used as an indication of the degree of water stress experienced during the respective phenological stage. Soil water content was replenished at a pre-dawn stem water potential equal to -1.5 MPa (Stephenson et al., 2003, Stephenson and Gallagher, 1987, Stephenson et al., 1989). Replenishment of soil water occured through the opening of valves on the mircosprinkler tubing, allowing for a 2 hour irrigation interval at the normal (50 L hr^{-1}) water application rate. Soil water content was replenished in order to re-establish a pre-dawn stem water potential of -0.7 MPa, maintaining a water stress without causing irreversible physiological damage. Plastic rain-covers were ultimately removed from T4 treatment trees after initial fruit set (2 October 2018 and 5 October 2019), where after trees were irrigated according to the control for the remainder of the season.

The implementation of a slight water stress at nut sizing and premature nut drop (T5), shell hardening (T6) and oil accumulation (T7) during the 2018/2019 season commenced on 1 October 2018, 3 December 2018 and 30 January 2019 respectively. Details of the implementation of the various treatments for the 2018/2019 and 2019/2020 seasons are presented in Table 3.5. Pre-dawn leaf water potential measurements and soil water replenishment occurred in a similar fashion for each of the stress treatments, as described for the T4 treatment. Similarly, plastic rain-covers were removed from treatment trees upon the change of one phenological stage to another, where after trees were watered similar to the control for the remainder of the season.

Table 3.5: The implementation of stress treatments in the mature orchard at Du Mak Farm in the Schagen Valley, Nelspruit. Percentage (%) values represent the quantity of irrigation applied in relation to that of the treatment control, during a specific phenological stage

Treatment	***Season***	***Fruit developmental Stage***				
		Flower initiation	**Flowering and nut set**	**Nut sizing and pre-mature nut drop**	**Shell hardening**	**Oil accumulation**
	2018/19	**4 Mar-7 May**	**13 Jul-2 Oct**	**1 Oct-12 Nov**	**3 Dec-30 Jan**	**30 Jan-21 Apr**
	2019/20		**25 Jul-5 Oct**	**5 Oct-12 Dec**	**12 Dec-7 Feb**	**7 Feb-17 Apr**
T1		0%	0%	0%	0%	0%
T2		50%	50%	50%	50%	50%
T3		100%	100%	100%	100%	100%
T4		100%	0%	100%	100%	100%
T5		100%	100%	0%	100%	100%
T6		100%	100%	100%	0%	100%
T7		100%	100%	100%	100%	0%

The physiological response of macadamia trees to different levels of water stress was determined by measuring leaf water potential, leaf gas exchange, chlorophyll fluorescence and sap flow. The experiment spanned over a two month period from 25 May 2020 to 27 July 2020 where the aim was to implement different soil water deficit levels on 15 selected trees by withholding irrigation for different periods of time. The trial was made up of five treatments consisting of three replicates per treatment (3 trees per treatment) (n = 3). Five different levels of water deficits were implemented on a 4-year-old macadamia orchard namely: I1 = 30 day deficit; I2 = 25 day deficit; I3 = 20 day deficit; I4 = 15 day deficit and I5 = 0 day deficit. Treatment I5 served as the experimental control. Treatments were assigned to three consecutive trees within a row with each treatment separated by one non-treatment tree or approximately 4 m (Figure 3.19). Due to micro-jet sprinklers being placed close to the tree trunk, a 4 m buffer zone between treatments was sufficient and any border effect interference was avoided.

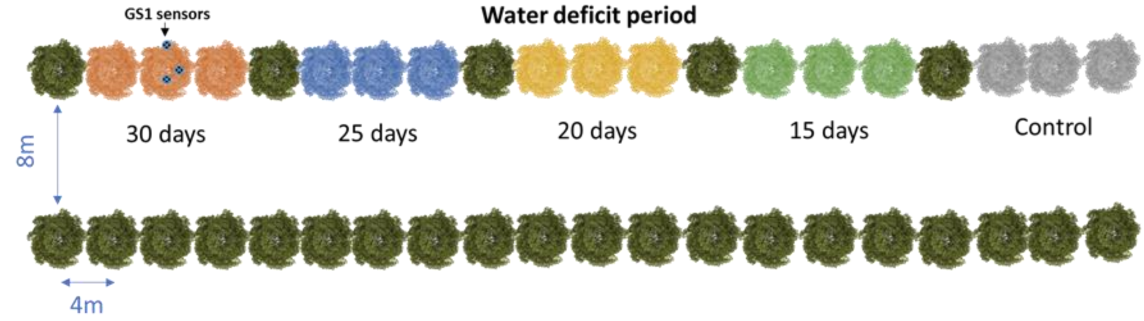


Figure 3.19: Trial design for the implementation of water stress in the intermediate 'Beaumont' macadamia orchard

In order to determine the physiological response of macadamia trees to different levels of water stress, 200 µm clear plastic rain-covers were installed on each treatment replicate on the day of stress implementation (Figure 3.15). Plastic rain-covers were placed up to the tree stem and extended to the edge of the ridged profile, covering the entire soil surface allocated to each tree. Valves were fitted to the microsprinkler tube of each treatment tree in order to "turn-off" the microsprinkler and eliminate irrigation water during the respective treatment stages. A water stress treatment was induced every 5 days, with the 30 day water deficit treatment starting on 25 May 2020. The 25, 20 and 15 day water deficit treatments commenced on 30 May, 4 June and 9 June 2020 respectively. Physiological measurements over all 5 treatments commenced 15 days later on 22 June 2020. The measurement period spanned a 3 day period from 22 June 2020 to 24 June 2020, after which all treatments (I2,3 and 4) other than the 30 day water deficit treatment (I1) and the treatment control (I5) were terminated. The I1 treatment was exposed to another 18 days without water replenishment (48 days cumulative water deficit) before the final physiological measurements were conducted on 9 July 2020. The I1 stress treatment was terminated on 15 July 2020, where after sap flow was monitored until 27 July 2020. A summary of the implementation and termination of treatments in the intermediate orchard is presented in Table 3.6.

Table 3.6: Intermediate orchard treatment implementation and measurement overview at Du Mak Farm in Schagen Valley, Nelspruit. * Indicates the treatment measurement dates, measuring leaf gas exchange

Measurement date	Year	Treatment: Water deficit period				
	2020	**48 days (I1)** **25 May-** **24 June**	**25 days (I2)** **30 May-** **24 June**	**20 days (I3)** **4 June-** **24 June**	**15 days (I4)** **9 June-** **24 June**	**0 days (i5)** **24 June**
22 June		*	*	*	*	*
23 June		*	*	*	*	*
24 June		*	*	*	*	*
9 July		*				*
27 July		*				

3.2.3 ECOPHYSIOLOGICAL MEASUREMENTS

3.2.3.1 Leaf Gas Exchange

Measurements of leaf gas exchange, including net photosynthetic assimilation rate (*A*), stomatal conductance (g_s), leaf temperature (T_{leaf}), leaf transpiration rate (T) and internal CO_2 concentration (C_i), were obtained by using an infrared gas analyser (IRGA) (Model: LI-6400 XT, LI-COR, Lincoln, Nebraska, USA or Model: LI-6800, LI-COR, Lincoln, Nebraska, USA). Leaf gas exchange measurements were performed on mature, hardened-off leaves (the fourth leaf from the terminal end of the flush), chosen from the outer Eastern and Western side of the tree canopy, which were exposed to the maximum photon flux density prevailing at the time. Three leaves per tree per treatment replicate (n = 9) were measured on an hourly basis in the mature orchard. Alternating between stress and control treatment replicates, diurnal leaf gas exchange measurements were performed on the day of termination of three of the stress treatments. Leaf gas exchange was measured over a two-day period on both the control and ongoing phenological stress treatment.

Spot measurements were performed over three measurement campaigns during 2018/19 flower initiation, flower and nut set and shell hardening phenological stages in the mature orchard (Table 3.7). Chamber CO_2 concentration was maintained at 400 $\mu mol\ mol^{-1}$, the flow rate was 400 $\mu mol\ s^{-1}$, PAR inside the chamber was maintained between 1200-1500 $\mu mol\ m^{-2}\ s^{-1}$ and relative humidity (RH) was maintained at more than 50%, as described by Smit et al. (2020).

Table 3.7: Date and measurement frequency (*N*) of leaf gas exchange measurements in the mature orchard at Du Mak Farm in the Schagen Valley, Nelspruit.

Measurements	**Season**	**Fruit developmental Stage**		
	2018/19	**Flower initiation 1 Jun-2 Jun**	**Flowering and nut set 1 Oct-2 Oct**	**Shell hardening 30 Jan-31 Jan**
N		120	232	163

Similarly, leaf gas exchange measurements in the intermediate orchard were performed on mature, hardened-off leaves, chosen from the outer Eastern and Western side of the tree canopy, which were exposed to the maximum photon flux density prevailing at the time. Two leaves per tree per treatment replicate (n = 6) were measured on an hourly basis. Alternating between different treatment replicates, diurnal leaf gas exchange measurements were performed over a 3 day measurement period from 22 June 2020 to 24 June 2020. Additional leaf gas exchange measurements were performed on trees exposed to a 48 day water deficit on 9 July 2020 (Table 3.8).

Table 3.8: Date and frequency (*N*) of leaf gas exchange measurements in the intermediate orchard at Du Mak Farm in Schagen Valley, Nelspruit

Measurements	**Season**	**Date**			
	2019/20	**22 June**	**23 June**	**24 June**	**9 July**
N		264	256	219	100

3.2.3.2 Water potential

Pre-dawn (Ψ_{pd}) and midday stem (Ψ_{stem}) water potentials were measured using a PMS system Scholander Pump Up pressure chamber (PMS Instrument Company, Albany, USA) and a Scholander pressure chamber (Model 600, PMS Instrument Company, Albany, OR, USA) on selective days. Pre-dawn leaf water potential measurements were made upon the implementation of a stress treatment and throughout the duration of the experiment on all stressed and non-stressed experimental trees in the mature orchard. Pre-dawn measurements in the intermediate orchard were only performed on the 4 measurement days, 22-24 June 2020 and 9 July 2020. Mature, fully expanded leaves from the outside of the tree canopy were selected for pre-dawn measurement purposes. Pre-dawn measurement frequencies in the mature orchard depended on the level of water stress, with an increased frequency of measurements at higher water stress levels (<-0.5 MPa), as initial observations showed a rapid decline in Ψ_{pd} once a certain level of stress was reached. All Ψ_{pd} measurements were performed before 6:00.

Midday stem water potentials were measured by selecting fully expanded, mature leaves from within the tree canopy. Selected leaves were enclosed within aluminium foil covered plastic bags for a minimum of 30 min prior to measurement, in order to minimize the effect of external factors on measurements, stopping transpiration and enabling the leaf to come into equilibrium with the water potential of the stem (Begg and Turner, 1970). Midday stem water potential measurements took place between 11:30 and 13:00 on selected measurement days. In order to perform all Ψ_{stem} measurements between 11:30 and 13:00 in the mature orchard, Ψ_{stem} measurements were only performed on control and ongoing stress treatment trees (e.g. Control & T4) for selected days.

3.2.4 THE DETERMINATION OF YIELD AND QUALITY

3.2.4.1 Nut drop

Immediately after nut set, the quantity of racemes and initial nut set were assessed on one branch of each of the 67 treatment trees, totalling 67 replicate measurements. Due to the variable and vigorous macadamia growth habit, branches were selected on the eastern side of all treatment trees based on the number of racemes per branch and the number of nuts set per raceme. Measurements to determine final nut set (January 2018/19 and 2019/20) were performed 4 months after initial nut set counts (October 2018/19 and 2019/20). Subsequent nut counts were expressed as a percentage of initial set per raceme per treatment replicate to overcome variability.

3.2.4.2 Nut yield and quality

Mature orchard trees were harvested by hand upon nut maturation and nut in husk (NIH) yield was determined separately for each treatment replicate. A representative 5 kg NIH sample was taken from the middle replicate tree of each treatment, dehusked and husk- to wet nut in shell (WIS) mass was determined. A representative 2 kg WIS sample was taken and dried to a 1.5% nut in shell (NIS) moisture content. Representative samples were cracked at 1.5% NIS moisture content in order to ultimately determine the percentage total kernel recovery and nut quality parameters for each of the respective treatments. Nut quality parameters include, the percentage total kernel recovery (TKR), percentage sound kernel recovery (SKR), percentage unsound kernel recovery (USK), percentage sinkers, percentage first grade kernel, percentage immature kernel and the percentage discolouration/onion ring of the kernel. The estimated Rand value of the kernel was further determined. Yield and quality data were not determined for the 2019/2020 season due to the Covid-19 national lockdown form 27 March 2020 to 1 May 2020 interfering with the harvesting process.

3.2.5 STATISTICAL ANALYSIS

In the main trial in the mature orchard a randomized complete block design with seven treatments and three replicate blocks consisting of three trees per treatment was used. Statistical analysis was carried out on yield and quality data from the 2017 and 2018 harvests. Yield and quality data were statistically compared between all seven treatments for the 2018 harvest. Yield and quality data for the 2017 and 2018 seasons were, however, only compared for T1, T2 and T3 treatments, treatments T4 to T7 were only implemented from 2018. Analysis of variance (ANOVA) in the Variance Estimation, Precision & Comparison methodology (VEPAC) of Statistica (TIBCO Software Inc. Version 13.3) was used to assess the effect of treatments on yield and quality parameters for each year of harvest. Treatment means were compared using the least significance difference (LSD) procedure with a significance level $p = 0.05$. A two-way ANOVA was used for comparisons between different yield and quality parameters between the 2017 and 2018 harvests, whilst a one-way ANOVA was used to statistically compare yield and quality parameters between different treatments for the 2018 season. A one-way ANOVA was similarly used to detect significant differences ($p \leq 0.05$) between Ψ_L measurements of well-watered and water stress treatments.

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:

$$K_t = \frac{E_c}{ET_o} \qquad [24]$$

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:

$$K_t = K_{t\ full} \times K_d \qquad [25]$$

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

$$K_d = \min\left(1, M_L f_{c\ eff}, f_{c\ eff}^{\left(\frac{1}{1+h}\right)}\right) \qquad [26]$$

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 1.5 recommended for citrus (Allen and Pereira, 2009) and subsequently selected for both macadamia orchards in this study and h is tree height.

The effective fraction of ground covered ($f_{c\ eff}$) was calculated as the ratio of tree canopy width to inter-row spacing or the ratio of ground shaded area by the crop at solar noon to the total area available to the tree, following Allen et al. (1998) in the MB macadamia orchard with a north-south orientation. In the IB orchard, which is orientated in an approximate east west direction, $f_{c\ eff}$ was calculated according to Allen et al. (1998) as follows:

$$f_{c\ eff} = \frac{f_c}{\sin(\beta)} \leq 1 \qquad [27]$$

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

$$\beta = \arcsin\left[\sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\right] \qquad [28]$$

where φ is latitude and δ is solar declination in radians. The average $f_{c\ \mathrm{eff}}$ values determined during the measurement period were 0.73 for the MB orchard and 0.48 for the IB orchard (Table 3.9).

Furthermore, in accordance with Allen and Pereira (2009), $K_{t\ \mathrm{full}}$ can be approximated, for large stand size (greater than about 500 m^2), as a function of mean plant height (h, m) (Table 3.9) 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:

$$K_{t\ \mathrm{full}} = F_r\left(\min(1.0+0.1h,\ 1.20)+[0.04(u_2-2)-0.004(RH_{min}-45)]\left(\frac{h}{3}\right)^{0.3}\right) \qquad [29]$$

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

$$F_r \approx \frac{\Delta+\gamma(1+0.34u_2)}{\Delta+\gamma\left(1+0.34u_2\frac{r_{leaf}}{100}\right)} \qquad [30]$$

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). No published studies have suggested any r_{leaf} values for macadamias and therefore average values of r_{leaf} for macadamias in the MB were calculated during multiple periods (Table 3.10) of the growing season. Given that the average LAI for the IB orchard was less than 3.0 $m^2\ m^{-2}$ the term $r_{leaf}/100$ in Equation [30] 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 [30], after solving for F_r by inverting Equation [29], using known daily values of $K_{t\ \mathrm{full}}$. $K_{t\ \mathrm{full}}$ values were calculated using measured daily K_t and K_d estimated from measured data. The same r_{leaf} and r_s values, which can be found in (Table 3.10), were subsequently used to estimate F_r for independent seasons of measurements using Equation [30] in order to estimate K_t and E_c values for model validation purposes.

Table 3.9: Measured and calculated canopy parameters for the mature bearing (MB) and intermediate bearing (IB) macadamia orchards used as input parameters in the FAO-56 dual crop coefficient model.

Orchard	Mature Bearing	Intermediate Bearing
Between Row Width (m)	8.0	8.0
Canopy Width (m)[a]	5.9	4.0
Canopy Height (m)[a]	6.0	4.7
$f_{c\ \mathrm{eff}}$	0.73	0.48

[a] Mean seasonal measurements

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. Given the lack of information regarding r_{leaf} and r_s in macadamias, it was decided to determine if the accuracy of the FAO-56 dual crop coefficient model would be increased by using monthly r_{leaf} values as opposed to four (quarterly averaged values), two (initial to midseason and end of the season values) or a single (seasonally averaged value) estimate. Both r_{leaf} and r_s values used in this evaluation can be found in Table 3.10.

3.3.1.1 Model parameterization and validation

The FAO-56 dual crop coefficient model was parameterized in the MB orchard by using daily measured K_t and E_c from 2016/08/10 to 2017/07/31 and validated using data from 2017/08/01 to 2018/07/05. The FAO-56 dual crop coefficient model was parameterized for the IB orchard using data from 2017/08/10 to 2018/07/31 and model validation was done from 2018/08/01 to 2019/07/23.

Table 3.10: Average calculated leaf resistance using Equations [29] and [30] (r_{leaf}) for the mature bearing (MB) macadamias orchard and canopy resistance (r_s) for the intermediate bearing (IB) macadamia orchard during different time periods within the parameterization phase of the FAO-56 dual crop coefficient model.. *N* is number of days used for the estimation.

	MB			IB		
	Date Range	*N*	r_{leaf} (s m^{-1})	Date Range	*N*	r_s (s m^{-1})
Single	2016/08/10-2017/07/31	394	2332	2017/08/16-2018/07/31	334	1995
Two	2016/08/10-2017/01/31	174	2301	2017/08/16-2018/01/31	158	1995
	2017/02/01-2017/07/31	175	2369	2018/02/01-2018/07/31	176	1994
Quarterly	2016/08/10-2016/10/31	82	2348	2017/08/16-2017/10/31	76	1977
	2016/11/01-2017/01/31	92	2255	2017/11/01-2018/01/31	82	2014
	2017/02/01-2017/04/30	84	2566	2018/02/01-2018/04/30	85	1833
	2017/05/01-2017/07/31	91	2219	2018/05/01-2018/07/31	91	2155
Monthly	2016/08/10-2016/08/31	22	2448	2017/08/16-2017/08/31	16	1797
	2016/09/01-2016/09/30	30	2093	2017/09/01-2017/09/30	30	1903
	2016/10/01-2016/10/31	30	2503	2017/10/01-2017/10/31	30	2231
	2016/11/01-2016/11/30	30	2093	2017/11/01-2017/11/30	29	2140
	2016/12/01-2016/12/31	31	2278	2017/12/01-2017/12/31	29	1939
	2017/01/01-2017/01/31	31	2393	2018/01/01-2018/01/31	24	1964
	2017/02/01-2017/02/28	24	3035	2018/02/01-2018/02/28	27	1749
	2017/03/01-2017/03/31	31	2168	2018/03/01-2018/03/31	30	1872
	2017/04/01-2017/04/30	29	1994	2018/04/01-2018/04/30	28	1880
	2017/05/01-2017/05/31	30	2495	2018/05/01-2018/05/31	30	2043
	2017/06/01-2017/06/30	30	2062	2018/06/01-2018/06/30	30	2057
	2017/07/01-2017/07/31	31	2600	2018/07/01-2018/07/31	31	2366

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

3.3.2.1 Calculation of canopy conductance

Canopy conductance (g_c) was calculated using hourly transpiration measurements obtained from the MB orchard from 2016/09/15-2017/01/15, by inverting the Penman-Monteith equation (Monteith and Unsworth, 1990) as follows:

$$g_c = \frac{\lambda E_c \gamma g_a}{\Delta(R_n\text{-}G) + \rho_a C_p g_a VPD - \lambda E_c(\Delta\text{-}\gamma)} \qquad [31]$$

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 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}). R_n was estimated from shortwave radiation measured at the automatic weather station according to Allen et al. (1998) using measurements of macadamia albedo (0.13) obtained from the four-component net radiometer on the eddy covariance system.

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

$$g_a = \frac{k^2 u_z}{\ln((z-d)/z_0)\ln((z-d)/(h-d))} \qquad [32]$$

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 = $0.67h_c$, z_o is the roughness length taken as $0.1h_c$ and h is the mean orchard height. Windspeed above the canopy (6 m) was calculated using Equation [33], by calculating the attenuation coefficient (*a*) for macadamias, which was obtained by inverting Equation [33], by using measured values of wind speed from the automatic weather station at 2 m above the ground and above canopy windspeed (measured during a window period in the MB orchard) at a height of 6 m above the ground. The equation was used in accordance to that described by Campbell and Norman (2012) as:

$$u_h = u_z \exp\left[a\left(\frac{z}{h}-1\right)\right] \qquad [33]$$

where u_z is the wind speed (m s^{-1}) at the z wind measurement height (m) and u_h is the wind speed (m s^{-1}) at the top of the canopy (h) height (m), which in this study was 6 m for the MB orchard and 4.7 m for the IB orchard (Table 3.1). The attenuation coefficient (*a*) calculated for macadamias in this study was 0.68.

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:

$$g_{c,j}=g_{c\,max}f(S_R)f(VPD_{air})f(T_{air}) \qquad [34]$$

where $g_{c,j}$ is the canopy conductance predicted by the Jarvis model, $g_{c\,max}$ is the maximum canopy conductance (m s^{-1}), $f(S_R)$ 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. Whitley et al., 2008), 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:

$$f(S_R)=\frac{S_R}{R_m}\left(\frac{R_m+k_R}{S_R+k_R}\right) \qquad [35]$$

$$f(T_{air})=\frac{(T_{air}-T_L)(T_H-T_{air})^t}{(k_T-T_L)(T_H-k_T)} \qquad [36]$$

$$t=\frac{T_H-k_T}{k_T-T_L} \qquad [37]$$

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:

$$f(VPD_{air})=\frac{1+k_{D1}VPD}{1-k_{D2}VPD} \qquad [38]$$

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

3.3.2.3 Model parameterization

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:

$$S^2(k)=\sum_{i=1}^{n}\left(g_{c,i}-g_{c,j}(k,x_i)\right) \quad [39]$$

where $g_{c,i}$ is the i^{th} value of canopy conductance calculated using Equation [31] 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.

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 MB and IB orchard. Model validation in the MB orchard stretched from 2017/08/16-2018/08/06, whilst the model was validated over two consecutive seasons in the IB orchard, with the first validation phase stretching from 2017/09/30-2018/07/31 and the second validation stretching from 2018/08/10-2019/04/30.

3.3.3 MODELLING TRANSPIRATION USING A MODIFIED JARVIS STEWARD TYPE MODEL

The E_c model proposed by Whitley et al. (2009) was modified for this study, by excluding the volumetric soil water content (θ) function from the equation given that both orchards were irrigated throughout the duration of the trial and soil water content was unlikely to have placed a limitation on $E_{c\ max}$ in this study. Measurements of pre-dawn leaf water potential throughout the course of the trial emphasized the absence of water stress in measurement trees. This study did, however, include air temperature (T_{air}) as a modulating factor for $E_{c\ max}$, and the model took the following form:

$$E_c = E_{c\ max} f(S_R) f(VPD_{air}) f(T_{air}) \quad [40]$$

Both the S_R and T_{air} response functions took the same form as that presented in Equation [35] to Equation [37], 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):

$$f(VPD) = k_{e1} VPD_{air} \exp(-k_{e2} VPD_{air}) \quad [41]$$

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 parameterization phase.

Similar to the parameterization 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 [39]). Parameters for Equation [40] were obtained using daily measured E_c obtained from sap flow measurements in the MB orchard from 2016/09/15-2017/02/15

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 MB and IB orchard. Model validation in the MB orchard stretched from 2017/08/16-2018/08/06, whilst the model was validated over two consecutive seasons in the IB orchard, with the first validation phase stretching from 2017/09/30-2018/07/31 and the second validation stretching from 2018/08/10-2019/04/30.

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 differently sized macadamia orchards located in close proximity of one another, and as a result, adjustments for variations in canopy size needed to be made given that the larger of the two orchards was used to parameterize both the g_c and E_c models. It was decided that the g_c model (Equation [34]) would need scaling on the $g_{c\ max}$ term, and was subsequently scaled using measurements of LAI. Scaling was done by dividing

$g_{\mathrm{c\ max}}$ obtained during the model parameterization phase by the average LAI of the MB orchard during the same period. By dividing $g_{\mathrm{c\ max}}$ with LAI, a leaf area specific $g_{\mathrm{c\ max\ LAI}}$ (mm m^2 s^{-1} m^{-2}) could be obtained and substituted back into Equation [34] so that canopy adjusted g_c was obtained as:

$$g_{\mathrm{c\ mod}} = \mathrm{LAI}\ g_{\mathrm{c\ max\ adj}} f(\mathrm{S_R}) f(\mathrm{VPD_{air}}) f(\mathrm{T_{air}}) \qquad [42]$$

Similarly, adjustments for canopy size needed to be made for the $E_{\mathrm{c\ max}}$ term of Equation [40]. 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 $f_{\mathrm{c\ eff}}$ as proposed by Allen and Pereira (2009). The $E_{\mathrm{c\ max}}$ obtained during the model parameterization phase of the MB orchard was divided by the $f_{\mathrm{c\ eff}}$ value of the orchard to obtain $E_{\mathrm{c\ max}\ f\mathrm{c\ eff}}$ (mm h^{-1}). This term was substituted into Equation [40] so that $E_{\mathrm{c\ mod}}$ was obtained as:

$$E_{\mathrm{c\ mod}} = f_{\mathrm{c\ eff}}\ E_{\mathrm{c\ max\ adj}}\ f(\mathrm{S_R}) f(\mathrm{VPD_{air}}) f(\mathrm{T_{air}}) \qquad [43]$$

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< 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 MACADAMIA WATER USE

4.1.1 SEASONAL WEATHER AND TREE PHENOLOGY

Average temperature was fairly similar over the three production seasons with the mean temperature being 18.4, 18.0 and 19.1°C during the 2016/17, 2017/18 and 2018/19 seasons respectively. During all three seasons of measurement, the highest average temperatures were recorded from December to March and were approximately 3.0-4.0°C higher than the respective mean annual temperature (Figure 4.1 and Figure 4.2). Mean daily solar radiation was slightly higher during the 2018/19 season (17.1 MJ m^{-2} day^{-1}) compared to the 2017/18 (16.6 MJ m^{-2} day^{-1}) and 2016/17 (16.1 MJ m^{-2} day^{-1}) seasons. 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 also significantly higher during the 2016/17 season (1170 mm), compared to the 2017/18 (760 mm) and 2018/19 (774 mm) seasons. Mean annual rainfall during both the 2017/18 and 2018/19 seasons were slightly lower than the long term mean annual rainfall for the Nelspruit region of 854 mm (Schulze, 1997).

Average air vapour pressure deficit (VPD_{air}) was similar during both the 2017/18 and 2018/19 (1.0 kPa) seasons, compared to the 2016/17 season (1.1 kPa) (Figure 4.3). Highest monthly VPD values were observed from August to October in all three seasons. Total reference evapotranspiration (ET_o) was negligibly higher during the 2016/17 season (1196 mm), compared to both the 2017/18 (1189 mm) and 2018/19 (1195 mm) seasons, with average daily ET_o being higher during the 2016/17 season (3.32 mm day^{-1}), compared to the 2017/18 (3.25 mm day^{-1}) and 2018/19 (3.30 mm day^{-1}) seasons. The highest average daily ET_o was observed during the September and October periods of all three seasons, with average daily ET_o during this period being 3.9 mm day^{-1} (Figure 4.3). Reference evapotranspiration greater than 6.0 mm day^{-1} was recorded on selected occasions in both September and October of each season. These weather conditions were most likely optimal for macadamia production, with mean annual temperature falling within the optimal 20-25°C range and annual precipitation and irrigation exceeding 1000 mm, as prescribed by Stephenson and Trochoulias (1994).

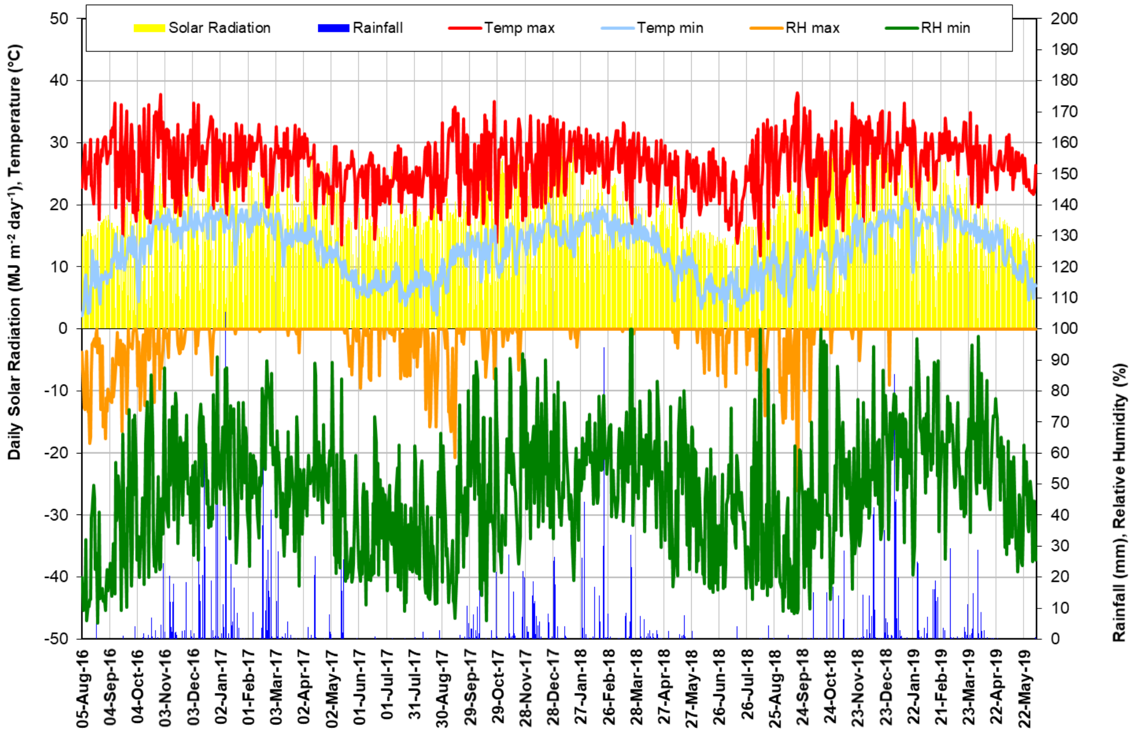


Figure 4.1: Maximum and minimum daily air temperature, maximum and minimum relative humidity, total daily rainfall and solar radiation obtained from the automated weather station located close to the mature bearing macadamia orchard throughout three seasons (5 August 2016 to 5 June 2019)

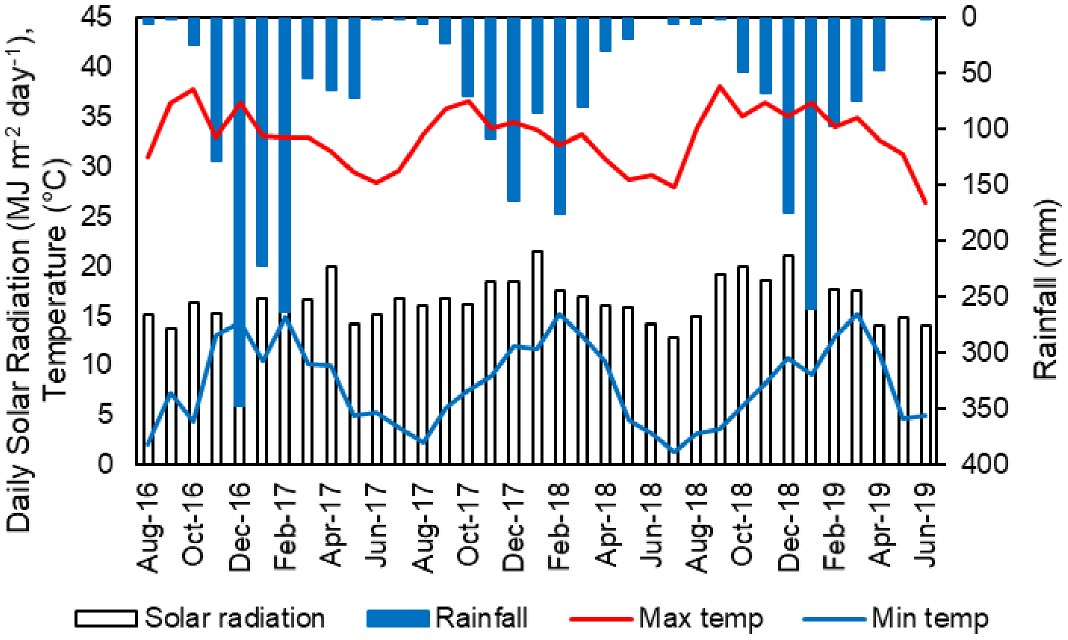


Figure 4.2: Monthly average daily solar radiation and maximum and minimum temperatures, together with total monthly rainfall for the Schagen Valley where water use measurements in 'Beaumont' macadamia orchards were performed.

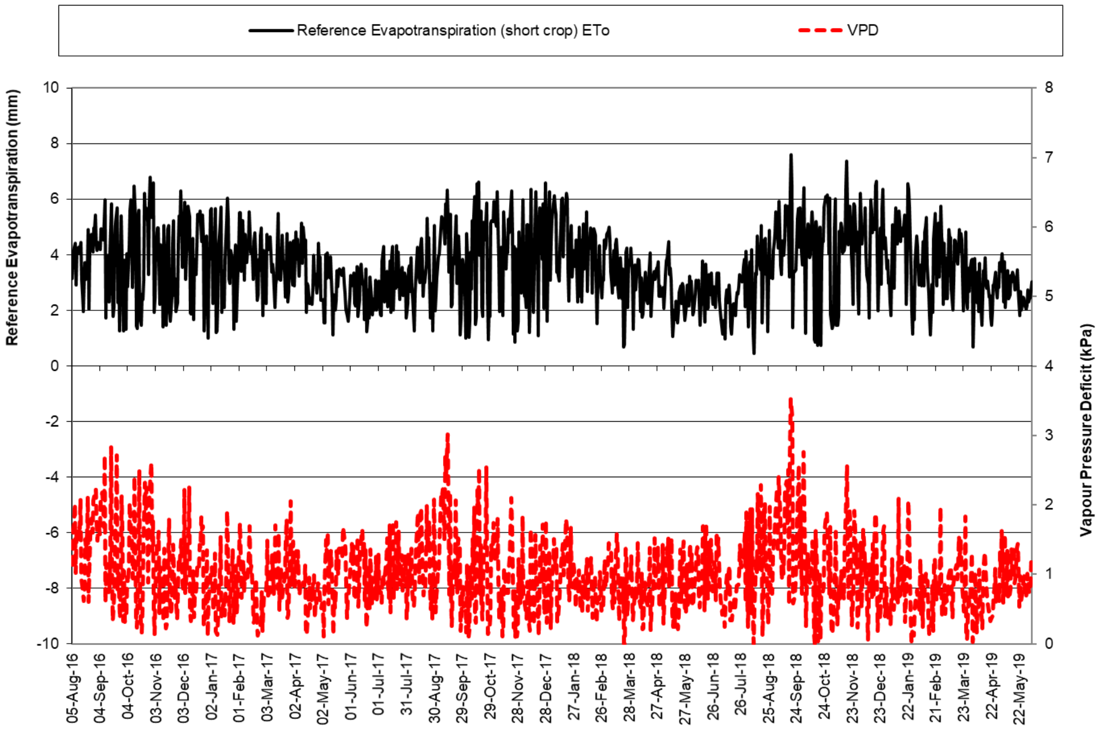


Figure 4.3: Reference evapotranspiration (ET$_o$) and vapour pressure deficit determined from variables measured by the automatic weather station located close to the mature bearing macadamia orchard throughout three seasons (5 August 2016 to 5 June 2019)

Tree phenology, including vegetative flushing patterns and fruit development, followed a similar pattern to that outlined by Stephenson et al. (1986) and Wilkie et al. (2009). These events are illustrated in Figure 4.4 for the mature orchard, with dates provided for both the mature orchard and intermediate bearing orchard in Table 4.1. With the exception of the early summer vegetative flushes, most phenological events occurred at similar periods in each year of the trial. The onset of flowering typically occurred in early August and was followed by nut set in September to October. Following nut set, premature nut drop occurred during late October and was followed by a vegetative flush in middle November. Increases in relative assimilate demand and oil accumulation were included in Figure 4.4 according to phenological stages, using the results of Stephenson et al. (1989). Relative assimilate demand was assumed to increase as vegetative growth and oil accumulation increased, as outlined by Stephenson et al. (1989). Oil accumulation was assumed to commence after shell hardening (end December) and continue until harvest (mid-April). Peak relative assimilate demand (February to April) also coincided with a major vegetative flush at the end of January/beginning February.

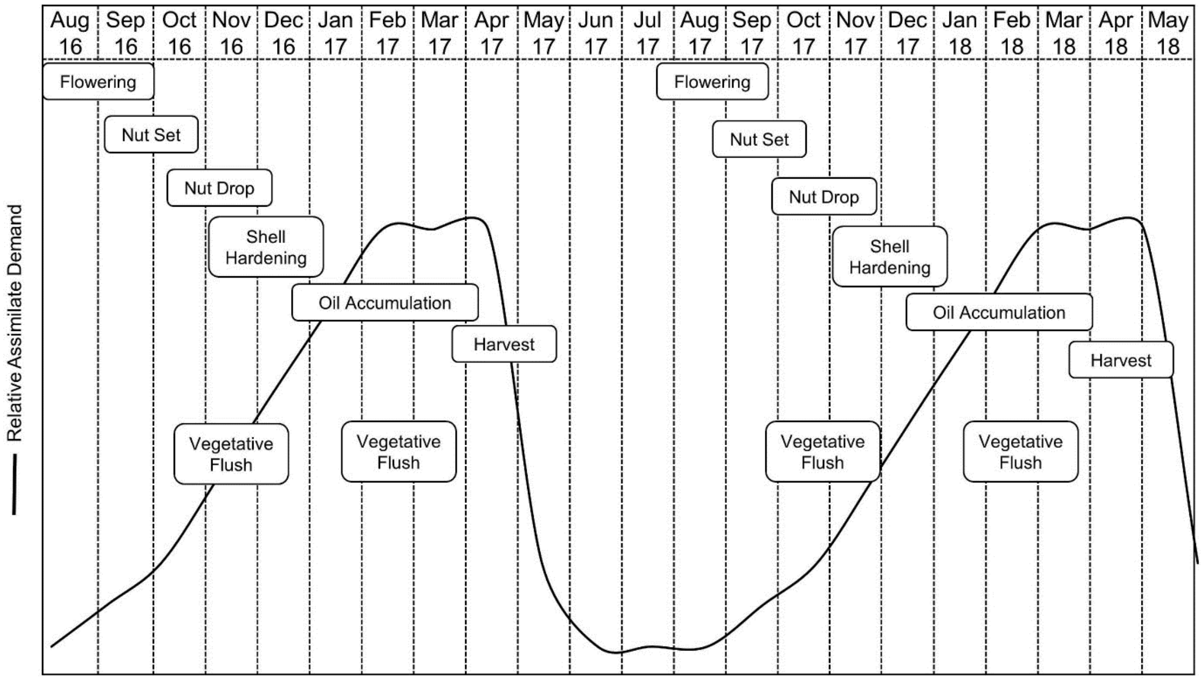


Figure 4.4: Major phenological events and harvest time of the mature macadamia trees from August 2016 to May 2018 based on visual observations. Increases and decreases in relative assimilate demand throughout this period were estimated based on results by Stephenson et al. (1989) and approximately coincide with the presence or absence of fruit and especially the oil accumulation period.

Table 4.1: Phenology and important management practices recorded in the mature bearing (MB) and intermediate bearing (IB) macadamia orchards across three consecutive cropping seasons. The duration of each phenological period was an approximation based on visual inspection.

	Season								
	2016/17			2017/18			2018/19		
Phenological Stage	**Start Date**	**End Date**	**Duration (days)**	**Start Date**	**End Date**	**Duration (days)**	**Start Date**	**End Date**	**Duration (days)**
Pre-flowering	2016/08/10	2016/08/30	20	2017/07/16	2017/08/23	38	2018/07/16	2018/08/14	29
Flowering	2016/08/31	2016/09/20	20	2017/08/24	2017/09/14	21	2018/08/15	2018/09/12	28
Nut Set	2016/09/21	2016/10/15	24	2017/09/15	2017/10/07	22	2018/09/13	2018/10/20	37
Spring Flush	2016/10/16	2016/11/05	20	2017/10/08	2017/10/30	22	2018/10/21	2018/11/09	19
Premature Nut Drop	2016/11/06	2016/11/30	24	2017/10/31	2017/11/26	26	2018/11/10	2018/11/30	20
Nut Growth	2016/12/01	2017/01/15	45	2017/11/27	2018/01/20	54	2018/12/01	2019/01/23	53
Summer Flush	2017/01/16	2017/02/15	30	2018/01/21	2018/02/18	28	2019/01/24	2019/02/12	19
Oil Accumulation	2017/02/16	2017/04/19	62	2018/02/19	2018/04/25	65	2019/02/13	2019/04/20	66
Harvest	2017/04/20	2017/05/15	25	2018/04/26	2018/05/19	23	2019/04/21	2019/05/10	19
Flower Initiation	2017/05/16	2017/06/15	30	2018/05/20	2018/06/15	26	2019/05/11	2019/06/04	24
Pruning & Winter Rest	2017/06/16	2017/07/15	29	2018/06/16	2018/07/15	29	2019/06/05	2019/07/14	39

4.1.2 CANOPY MEASUREMENTS

Trees in the MB orchard had a slightly lower volume of 71 m^3 in the 2016/17 season compared to 77 m^3 in the 2017/18 season, whilst average seasonal canopy volume in the IB remained relatively constant (39 m^3) throughout the 2017/18 and 2018/19 seasons (Figure 4.5).

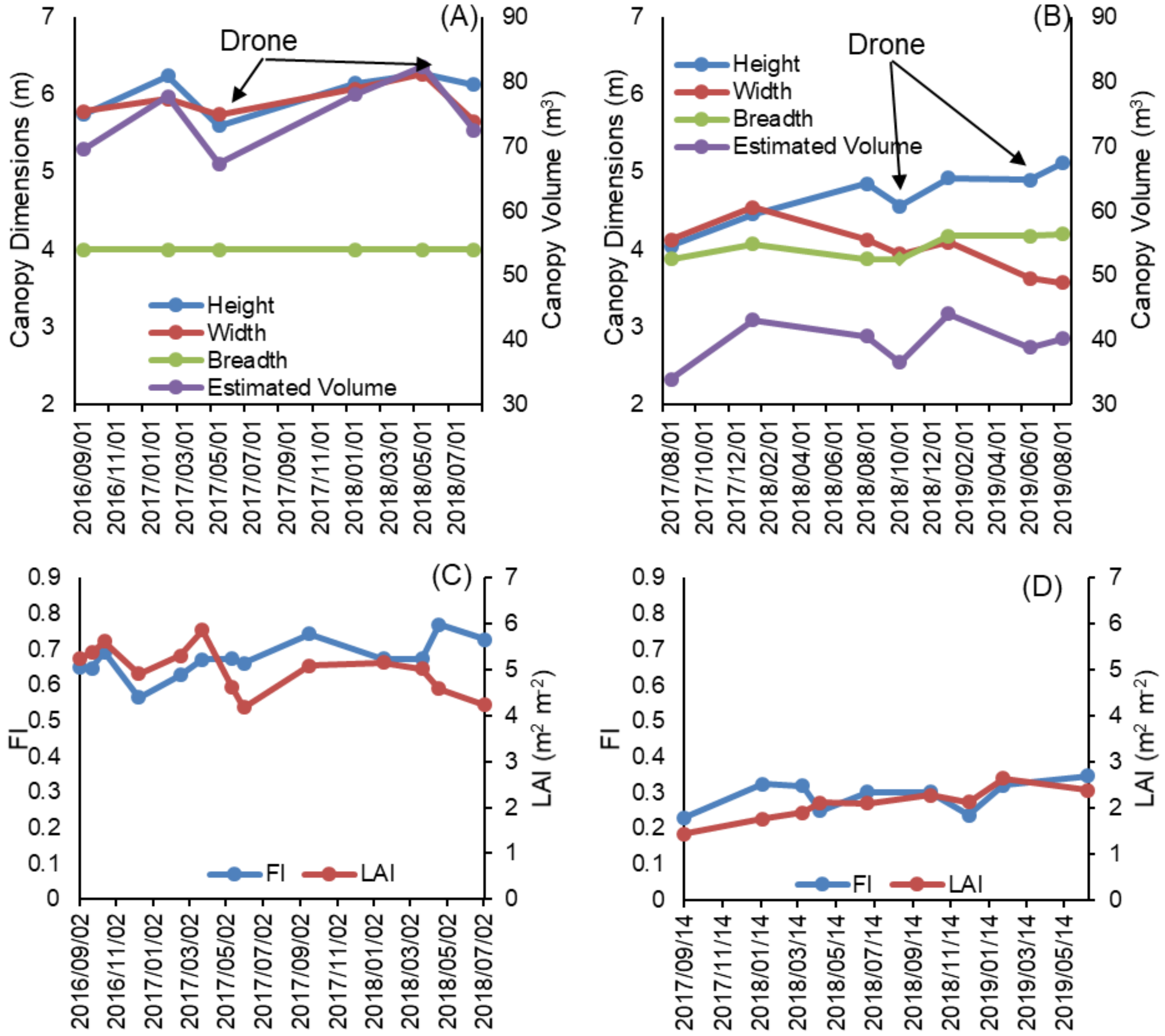


Figure 4.5: Average seasonal variation in canopy dimensions of the same four trees used in transpiration measurements in the (A) mature bearing and (B) intermediate bearing macadamia orchards. Seasonal average measurements of fractional interception of PAR (FI) and leaf area index (LAI) of the same four trees used in transpiration measurements in the (C) mature bearing and (D) intermediate bearing macadamia orchards. Measurements of canopy dimensions made using drone technology is indicated on both graphs by arrows.

Estimated volume of the trees in the non-bearing orchard was approximately 3 m^3 (height, width and breadth of approximately 1.5 m). Trees in the IB orchards were on average approximately half the volume of trees in the MB orchard. In both orchards, trees reached a maximum volume during the late summer period and typically decreased in autumn/winter periods following pruning, as outlined in Table 4.1.

Average LAI in the MB orchard was slightly higher during the 2016/17 season (5.1 m^2 m^{-2}) compared to the 2017/18 season (4.8 m^2 m^{-2}), and was most likely due to the substantial reduction in leaf area brought about by pruning, which removed two large limbs out of each experimental tree, in an attempt to reduce tree height and increase radiation interception. Trees in the IB orchard showed an increase in LAI from 1.8 m^2 m^{-2} during the 2017/18 season to 2.3 m^2 m^{-2} during the 2018/19 season. The increase in LAI in the IB orchard was due to the limited amount of pruning of these orchards during the 2017/18 season, with only vertical, non-branching shoots being removed, which was in accordance with industry practice. A reduction in LAI is, however, seen following a heavier pruning regime in the 2018/19 season (Figure 4.5 D). On an average LAI basis, LAI of the trees in the IB orchard were approximately 60% of those in the MB orchard during the 2017/18 season, during which measurements of transpiration were made in both orchards. Even though seasonal variation of FI was observed in both orchards, FI remained between 0.55 and 0.80 for the MB orchard and between 0.20 and 0.35 for the IB orchard. A reduction in canopy volume and LAI following pruning in the IB orchard during the 2018/19 season, resulted in a slight, but negligible decrease in FI, which was attributed to the dense nature of macadamia canopies.

4.1.3 TRANSPIRATION, EVAPORATION AND EVAPOTRANSPIRATION RATES

Measurements of transpiration (E_c) of macadamia orchards began in a mature, full-bearing orchard (MB) in August 2016 and continued for two years. During this time two window periods of ET measurements were conducted in this orchard, 29 July to 16 August 2017 and 12 May to 7 August 2018. Measurements in an intermediate bearing orchard began in August 2017 and also continued for two years. The final set of measurements was conducted in a non-bearing orchard from April 2018 for a single year. Evapotranspiration measurements in the non-bearing orchard measurements took place from 4 October 2018 to 12 March 2019. The complete set of water use data collected in macadamia orchards during this study is illustrated in Figure 4.6.

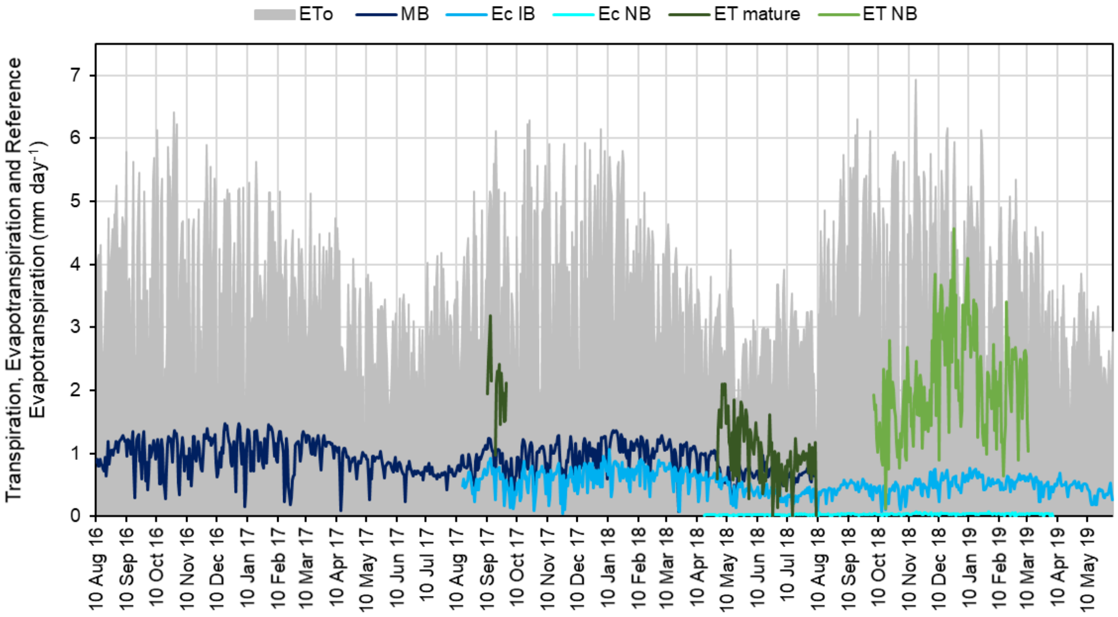


Figure 4.6: Transpiration (E_c), evapotranspiration (ET) and reference evapotranspiration (ET_o) for the entire duration of measurements in the three macadamia orchards in the Schagen Valley outside of Nelspruit. Mature bearing orchard (MB), intermediate bearing orchard (IB), non-bearing orchard (NB).

Transpiration measurements for the MB macadamia orchard commenced on 2016/08/10 and were concluded on 2018/08/08. During the measurement campaign total transpiration ranged from 316-340 mm per annum, being higher during the 2016/17 season compared to the 2017/18 season (Table 4.2). The lower transpiration rates during the 2017/18 season were most likely attributed to slightly lower ET_o and smaller canopy size of the MB orchard during the same period compared to the 2016/17 season. The lowest and highest daily average transpiration rates in the MB orchard were recorded in June (0.7 mm day^{-1}) and January (1.1 mm day^{-1}) of each season, with daily maximum and minimum values of 1.4 mm day^{-1} and 0.2 mm day^{-1} being recorded over the two seasons of measurement (Figure 4.7 A). Irrigation volumes totalled 299 mm in the 2016/17 season and 160 mm in the 2017/18 season. Although these values are lower than transpiration, the good rainfall during both years would have adequately supplemented the applied irrigation.

Measurements of E_c in the IB macadamia orchard commenced on 2017/08/16 and were concluded on 2019/08/05. Total E_c during the 2017/18 season (195 mm) was higher than that measured during the 2018/19 season (167 mm) (Table 4.2). The lowest and highest daily average transpiration rates for the IB orchards were recorded in July (0.3 mm day^{-1}) and January (0.7 mm day^{-1}) of each season. Daily maximum and minimum values of 0.95 mm day^{-1} and 0.06 mm day^{-1} were recorded over the two seasons of measurement (Figure 4.7 A).

When considering the fixed irrigation schedule in this orchard of 150 L tree^{-1} week^{-1}, it is likely that 244 mm of irrigation was applied in a season, if rainfall was not considered which is unlikely. This is higher than seasonal transpiration in this orchard, but as tree growth and yields for this young orchard was within industry norms, it is unlikely that these volumes would have resulted in stress from overirrigation.

Table 4.2: Average daily transpiration rates (mm day^{-1}) across multiple seasons in the mature bearing (MB), intermediate bearing (IB) and non-bearing (NB) macadamia orchards.

Orchard	Season	2016/17	2017/18	2018/19
MB	Spring	1.0	0.9	
	Summer	1.2	1.1	
	Autmn	1.1	0.8	
	Winter	0.9	0.7	
	Average	**1.1**	**0.9**	
	TOTAL (mm)	**340**	**316**	
IB	Spring		0.6	0.4
	Summer		0.7	0.5
	Autmn		0.5	0.4
	Winter		0.4	0.3
	Average		**0.5**	**0.4**
	TOTAL (mm)		**195**	**167**
NB	Spring			0.036
	Summer			0.037
	Autmn		0.02	0.029
	Winter		0.02	
	Average			**0.03***
	TOTAL (mm)			**11.05***

*Total and average reflect measurements from April 2018 to April 2019

Given that the major difference between the MB and IB orchards is the size of the canopies, it is not surprising that trees in the MB orchard with an estimated canopy volume of 71 m^3, approximately double that of trees in the IB orchard, transpired 121 mm (~60%) more during the 2017/18 season than the IB orchard. Comparisons of E_c measurements between the two differently sized orchards, during the same measurement period, revealed that a strong linear relationship (R^2= 0.82) existed between total daily E_c of the two orchards (Figure 4.7 B).

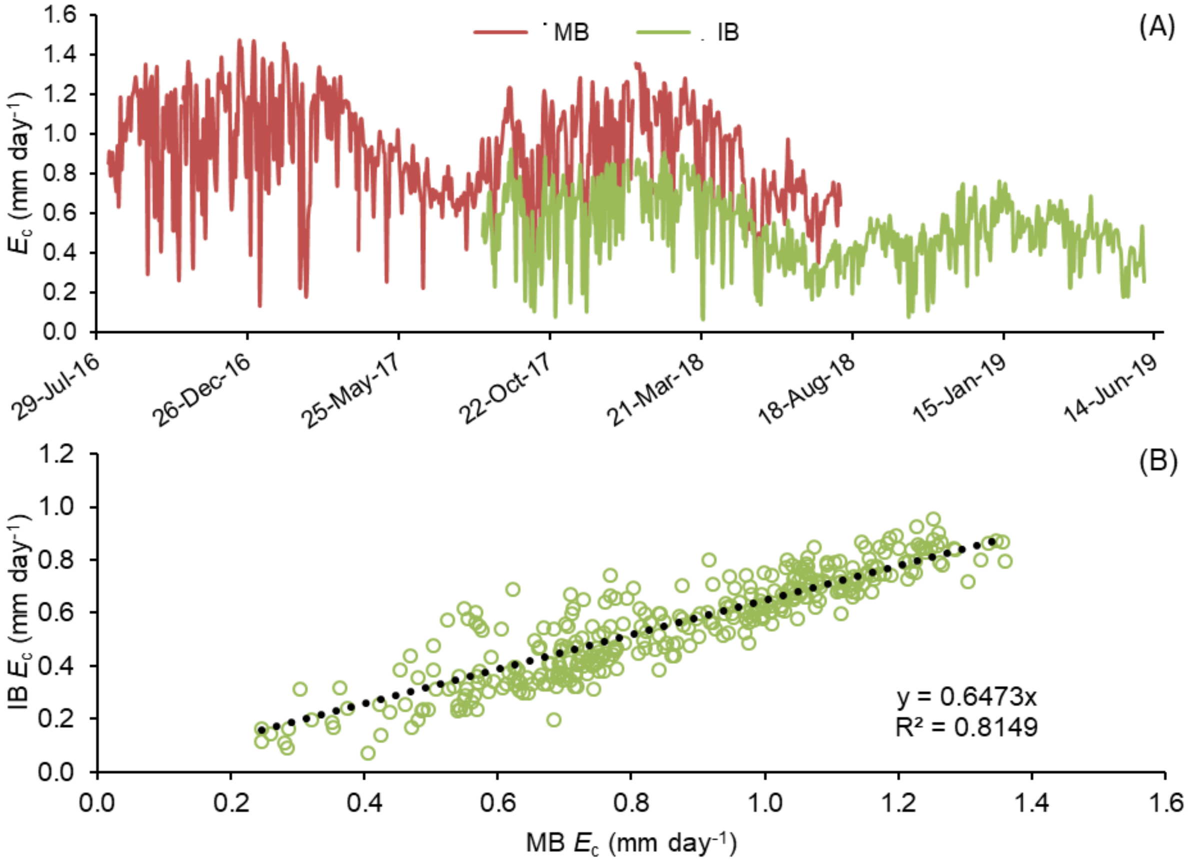


Figure 4.7: Daily transpiration (E_c) for (A) mature bearing (MB) and intermediate bearing (IB) macadamia orchards across three seasons. (B) Linear relationship between daily transpiration of MB and IB orchards from 16 August 2017 to 6 August 2018.

Measurements of E_c in the NB macadamia orchard commenced on 2018/04/17 and were concluded on 2019/04/05. During this year total E_c was 11.05 mm. Transpiration varied from 0.006 mm day^{-1} to 0.081 mm day^{-1}, which equated to 0.02-2.60 L day^{-1}. This was considerably lower than the other two orchards, but when considering the difference in canopy size, these low values are not unreasonable. The trees in the NB orchard were approximately 13 times smaller than the trees in the MB orchard and E_c was approximately 13 times smaller in the NB orchard as compared to the IB orchard.

This study has shown that canopy size is a major determinant of E_c in macadamias, 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). Trees within the MB orchard, which had a LAI 60% higher than trees in the IB orchard, transpired approximately 60% more than the IB macadamia orchard under the same set of environmental conditions. Although variations in canopy size would have a profound impact on E_c, the average daily E_c rates for macadamias in this study was fairly low compared to previously published macadamia studies, with Gush and Taylor (2014) reporting average seasonal E_c rates of 1.2 mm day^{-1} in MB macadamia trees with a seasonal average LAI of ~ 5.0 m^2 m^{-2}. Average daily E_c rates obtained from this study showed that the MB orchard (average LAI of ~ 5.0 m^2 m^{-2}) transpired approximately 0.9 mm day^{-1}, whilst the smaller IB orchard transpired 0.5 mm day^{-1} (average LAI of ~ 2.0 m^2 m^{-2}). The transpiration rates for macadamias measured in this study, were also significantly lower than those measured in mature citrus trees (~4.0 mm day^{-1}) by Rana et al. (2005) using similar sap flow measurements. This is rather surprising considering that the average LAI in the study by Rana et al. (2005) was 2.1 m^2 m^{-2} which was less than half of that reported for the MB orchard in this study, yet E_c in citrus was more than four times greater than that of macadamia. Similarly, Ramos and Santos (2009) reported that E_c for olive with a LAI of 1.1 m^2 m^{-2}, which was almost five times lower than that of MB macadamia trees in this study, was approximately 2.5 mm day^{-1} which is significantly higher than that reported for macadamias in this study. These values of E_c reported for both citrus and olive, are also substantially higher than that reported by Gush and Taylor (2014), which in combination with the results in this study could suggest that macadamias are rather conservative water users, a trait which could stem from strict stomatal control in this predominantly isohydric crop.

Comparisons between E_c measured in the MB and IB orchards, exposed to the same set of environmental conditions, have shown that E_c can be scaled linearly with canopy size. The strong linear relationship ($R^2 > 0.8$) between E_c measured in the MB and IB orchard would suggest that the slope of the relationship can be used to estimate E_c of orchards, with varying canopy size, that are exposed to the same set of environmental conditions. The slope, which is a unitless factor of 0.65, clearly indicates that E_c of trees in the IB orchard, which are half (on a canopy volume basis) that of the MB trees, would transpire 60% the volume of MB trees. Although the robustness of scaling E_c based only on canopy size is questionable, it is believed that given the similar response of E_c to environmental factors between the MB and IB orchards, this approach could prove to be fairly robust. This approach could therefore be used by growers who wish to extrapolate measurements of E_c, under the same set of environmental conditions, from one orchard to other orchards of varying canopy size.

The simultaneous measurement of ET and E_c allowed the estimation of evaporation (E_s) during key window periods in the MB orchard and the NB orchard (Figure 4.6), by calculating E_s as a residual of ET and E_c. Importantly this E_s includes evaporation from the soil and transpiration from understorey vegetation in the orchard. During the first short period of ET measurements in the mature orchard in September and October 2017, average E_s was 1.21 mm day^{-1}, which constituted 58% of ET (Table 4.3). The next period of measurements took place in the autumn and winter months and as a result of low rainfall during this time and reduced growth of the understory vegetation, E_s constituted 40% ET, which was slightly less than in the spring measurements. During this period average E_s was 0.51 mm day^{-1} and average ET was 1.04 mm day^{-1}. In the NB orchard E_s constituted a far greater percentage of ET than in the mature orchard, as a result of the significantly smaller tree canopy and the greater grass and weed cover in the orchard. There was also a significant amount of rainfall during the measurement period which would have maintained a fairly wet soil throughout the orchard for fairly significant periods of time. Soil evaporation and ET were slightly lower in spring (October and November) than in summer (December to March), due to the slightly cooler conditions and lower rainfall. This clearly illustrates that in younger orchards evaporation makes up a considerably greater proportion of ET, which is considered non-productive or non-beneficial 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 the canopy grows and the area under the canopy increases, E_s become a smaller component of consumptive water use (Fereres and Evans, 2006), however, E_s was still 50% of ET at times in the mature macadamia orchard. As a result, even in mature orchards there are opportunities to conserve water through the reduction of evaporation.

Table 4.3: Details of evapotranspiration (ET) and evaporation (E_s) estimates, together with rainfall received and irrigation applied for the mature and non-bearing macadamia orchards. (N= number of measurement days)

Orchard	Dates	N	Average E_s (mm day^{-1})	Average ET (mm day^{-1})	%E_s of ET	Rain (mm)	Irrigation (mm)
Mature	10 Sept- 5 Oct 2017	23	1.21	2.09	58	37	14
	1 May- 7 Aug 2018	83	0.51	1.04	40	23	38
Non-bearing	1 Oct- 30 Nov	88	1.56	1.60	97	109	13$^{\#}$
	1 Dec- 11 March	70	2.32	2.36	98	440	16$^{\#}$

$^{\#}$Estimated based on a fixed weekly irrigation schedule of approximately 50 L week^{-1}

Changes in evaporation rates throughout the measurement periods were influenced by the prevailing weather conditions, influencing the availability of energy to evaporate water, and as a result of the availability of water through irrigation and rainfall (Figure 4.8). In many instances, higher evaporation rates were linked to irrigation or rainfall events in the orchards, with higher evaporation rates observed in the hotter summer months.

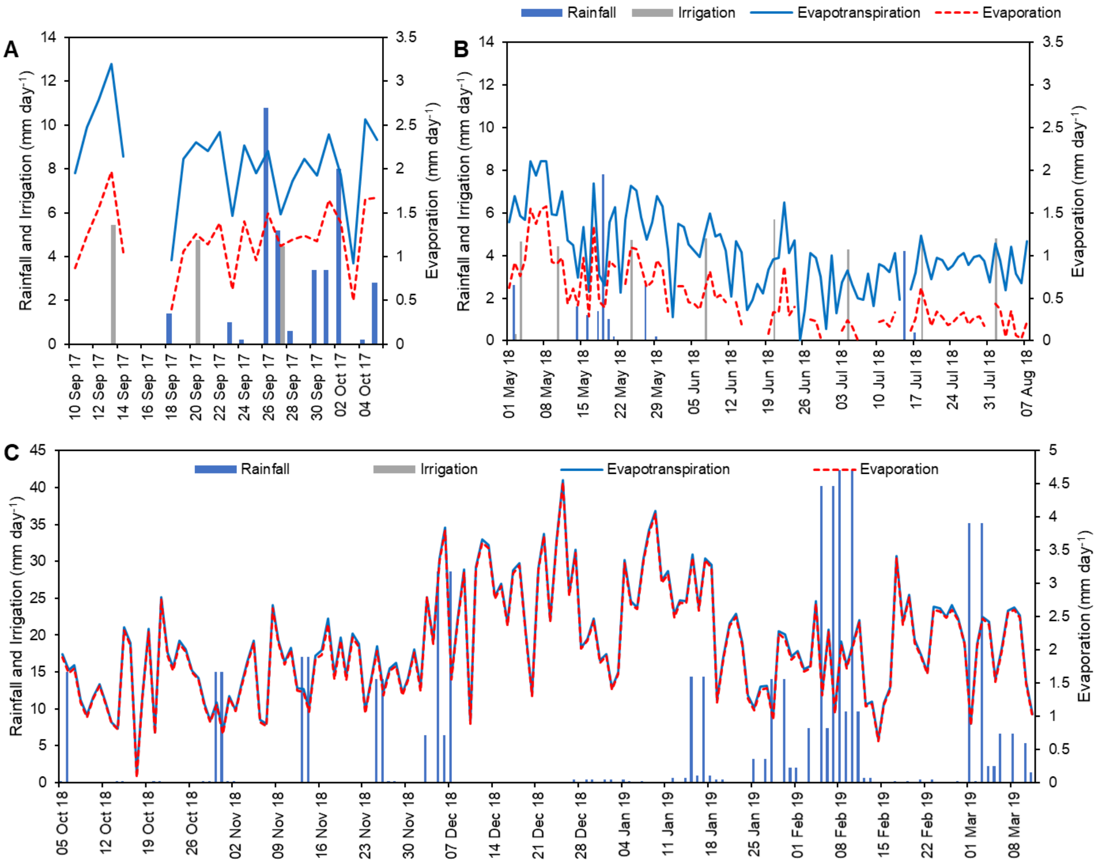


Figure 4.8: Evapotranspiration, evaporation, rainfall and irrigation in the A) mature macadamia orchard from 10 September to 5 October 2017, B) from 1 May to 7 August 2018 and in the C) non-bearing macadamia orchard from 5 October 2018 to 11 March 2019.

4.1.4 TRANSPIRATION RESPONSE TO ENVIRONMENTAL VARIABLES AND ECOPHYSIOLOGY

Transpiration is the most important beneficial component to water loss from crops, and increasing E_c should invariably lead to increased dry matter production. Gaining a clear understanding of the variables driving E_c is therefore critical, not only to the field of water use and irrigation research, but also for new orchard developments where site selection is critical. There have, however, been very few published studies examining driving variables of macadamia E_c, and as a result much uncertainty pertaining to the effective water management of the crop exists. It is also unclear if current water management strategies, derived from anecdotal evidence by macadamia growers, is justified.

4.1.4.1 The response of transpiration to environmental variables

Results from this study show that hourly macadamia E_c increased in a linear manner with weather variables, including VPD_{air}, ET_o, R_s and T_{air}, at low levels of these variables (Figure 4.9). However, after a threshold value was reached the response plateaued and there was very little further increase in the transpiration rate with increasing weather variables. Given that soil water content was unlikely to be limiting in this study based on pre-dawn (Ψ_{pd}), the reduction in the rate of E_c in response to increases in these weather variables is possibly an indication of a supply-controlled system, and is evident in both the MB and IB orchards. A supply-controlled system implies that transpiration is limited by the ability of the plant to supply water to the leaves at a rate that matches the vapour pressure gradient out of the leaf. As a result of this mismatch between demand and supply stomata start to close to limit the rate of water loss from the leaf in order to prevent a drop in leaf water potential that could result in catastrophic embolism (Sperry et al., 2002). This strict leaf level stomatal control at high VPD_{air}, therefore leads to reduced canopy conductance in response to increases in VPD_{air}. This is not unusual for subtropical fruit tree crops and has been previously reported in citrus (Taylor et al., 2015, Vahrmeijer and Taylor, 2018). It would seem as if the rate of increase of transpiration decreases as VPD_{air} increases above 0.7-0.8 kPa in both orchards. The transpiration rate in both orchards also failed to increase at the same rate when R_s exceeded 0.3 MJ m^{-2} h^{-1} (Figure 4.9 B). The response of E_c to ET_o, was similar to the solar radiation response, with E_c in both orchards failing to increase at the same rate above 0.13 mm h^{-1} in the MB orchard and 0.07 mm h^{-1} in the IB orchard when ET_o increased above 0.05 mm h^{--1} (Figure 4.9 A).

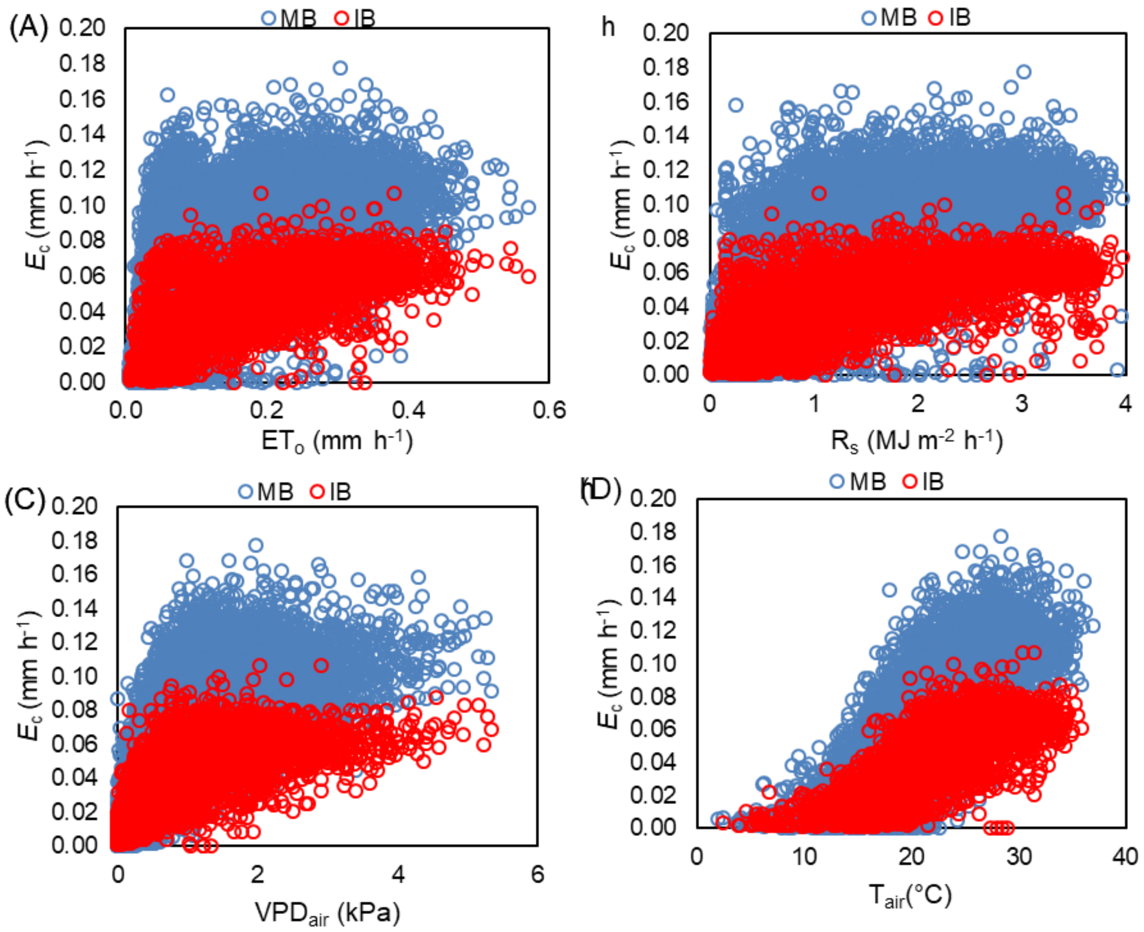


Figure 4.9: Relationship between average daytime hourly transpiration (*E_c*) and (A) reference evapotranspiration (ET_o), (B) solar radiation (R_s), (C) air vapour pressure deficit (VPD_{air}) and (D) air temperature (T_{air}) for mature bearing (MB) and intermediate bearing (IB) macadamia trees.

Diurnal trends in transpiration for both orchards on days with contrasting environmental variables, show that there seems to be an upper limit to E_c, with VPD_{air} and T_{air} appearing to be the major controlling variables of macadamia E_c (Figure 4.10). Average diurnal R_s on 2017/09/11 was fairly similar to that measured on 2018/03/01, whilst both T_{air} and VPD_{air} were higher during the former as compared to the latter day, yet there were no marked differences between the trends in diurnal E_c rates on these two days. The higher VPD_{air} on 2017/09/11 was largely attributed to higher T_{air} and lower relative humidity compared to measurements made on 2018/03/01. When comparing both these days to conditions on 2017/10/01, where VPD_{air} was approximately half of that measured on 2018/03/01, E_c in both the intermediate and mature bearing orchards, was considerably lower than that of the days with higher VPD_{air}.

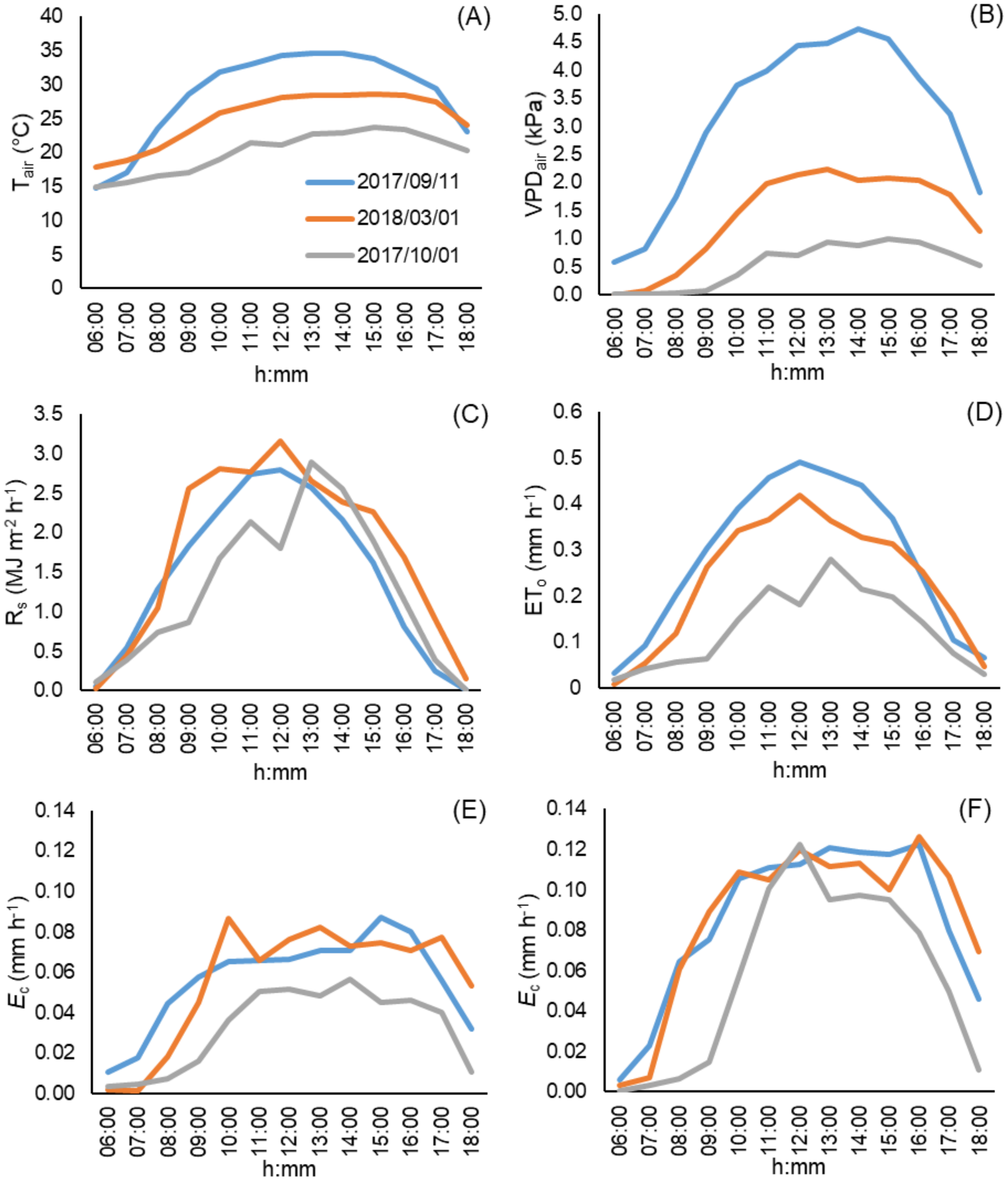


Figure 4.10: Diurnal measurements of (A) air temperature (T_{air}), (B) vapour pressure deficit (VPD_{air}), (C) solar radiation (R_s), (D) reference evapotranspiration (ET_o), (E) intermediate bearing macadamia transpiration (E_c) and (F) mature bearing macadamia transpiration (E_c) on three climatically distinct days 11 September 2017, 1 October 2017, and 1 March 2018.

A maximum rate of E_c was once again evident when examining the trends in diurnal E_c of macadamias during days with moderate and high VPD_{air} and ET_o (Figure 4.10). Measurements of E_c made on 2017/09/11 and 2018/03/01, days with distinctly different VPDs, revealed that E_c increased linearly as VPD increased until approximately 10:00, where after E_c remained fairly constant regardless of increases in VPD until late afternoon (15:00-16:00). E_c then tended to decline in the late afternoon as VPD decreased, but this decrease in E_c was most likely due to the decrease in incident solar radiation. The decrease in E_c of the IB orchard typically occurred later in the afternoon compared to the MB orchard, due to the fact that trees in the IB orchard had not formed a complete hedgerow and distribution of R_s throughout the canopy in these orchards was superior to that of the MB orchard, which had formed a complete hedgerow.

Furthermore, E_c responses to VPD_{air}, ET_o, $R_{s,}$ and T_{air} demonstrated that maximum E_c ($E_{c\ max}$) in both MB and IB orchards increased and decreased at varying rates in response to increases in the respective environmental parameters (Figure 4.11 & Figure 4.12). In both orchards, $E_{c\ max}$ was highest within the 1.0-1.5 kPa VPD_{air} range, reaching transpiration rates of 1.5 mm day^{-1} and 0.9 mm day^{-1} in the MB (Figure 4.11) and IB orchard (Figure 4.12) respectively. VPD_{air} levels greater than 1.5 kPa resulted in a slightly decreased $E_{c\ max}$ in both orchards. The response of $E_{c\ max}$ to increases in R_s was also fairly similar between the two orchards, with the highest rates of $E_{c\ max}$ being observed once R_s exceeded 15 MJ m^{-2} day^{-1}. $E_{c\ max}$ of MB orchards declined slightly as R_s exceeded 25 MJ m^{-2} day^{-1}, which is most likely due to the associated increases in T_{air}, decreases in relative humidity and subsequent increases in VPD_{air}. This is substantiated by the decrease of $E_{c\ max}$ at T_{air} exceeding 25°C (Figure 4.11 & Figure 4.12). $E_{c\ max}$ of the IB orchard, however, showed no decrease in response to R_s exceeding 25 MJ m^{-2} day^{-1}, but the response of $E_{c\ max}$ to T_{air} exceeding 25°C was similar between the two orchards.

Another striking similarity between the two differently sized orchards is the response of $E_{c\ max}$ to increases in ET_o. The $E_{c\ max}$ achieved under ET_o rates exceeding 3.5 mm day^{-1} was substantially different between the MB and IB orchard, with the MB orchard reaching average $E_{c\ max}$ rates of 1.4 mm day^{-1} compared to the IB orchard which reached average $E_{c\ max}$ rates of 0.9 mm day^{-1} at these ET_o rates. Maximum transpiration rates under conditions where ET_o rates exceeded 3.5 mm day^{-1} were therefore approximately 60% higher in the MB orchard, which were ~60% larger, on a LAI basis, than trees in the IB orchard.

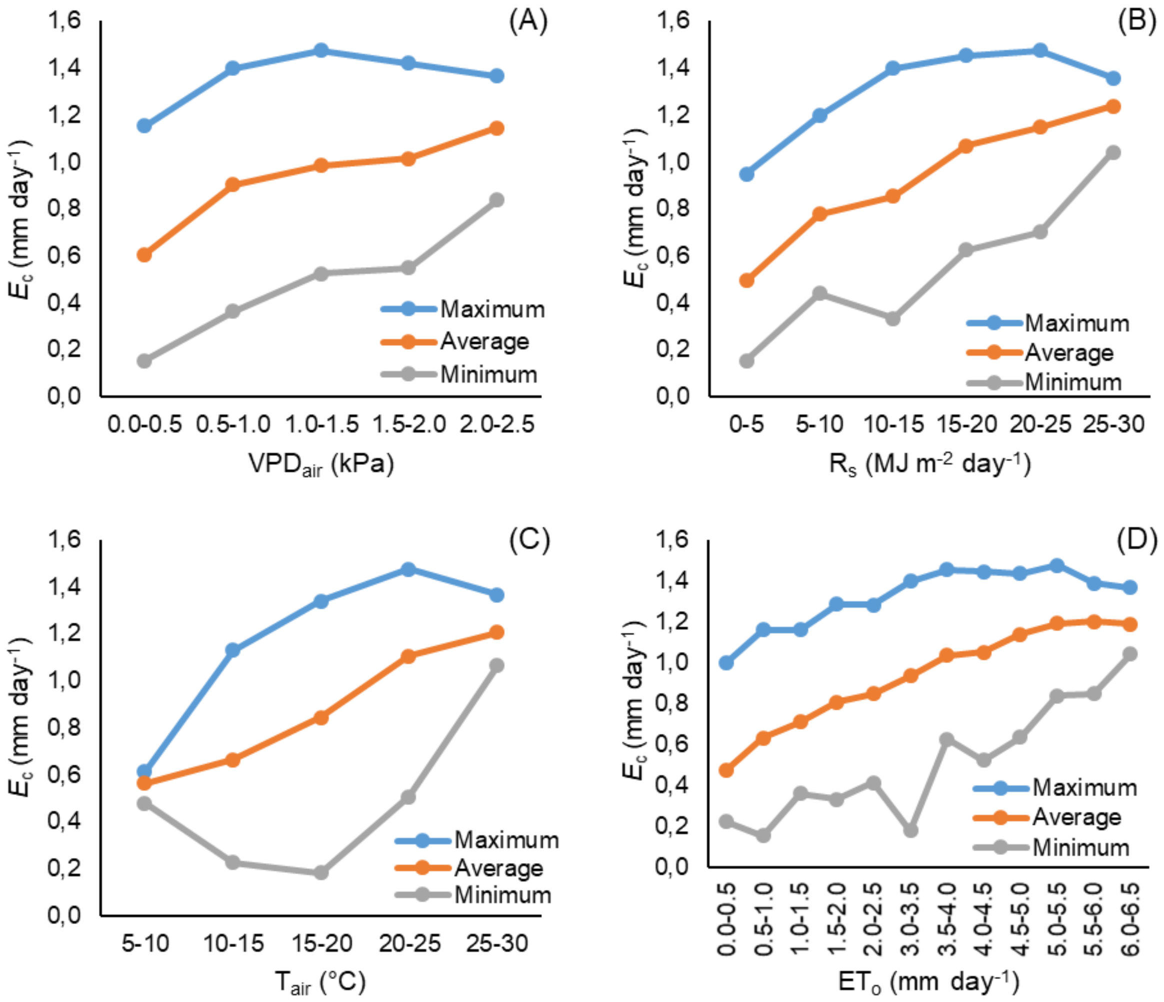


Figure 4.11: Average, maximum and minimum transpiration (E_c) of mature bearing macadamias in response to (A) vapour pressure deficit (VPD$_{air}$), (B) solar radiation (R$_s$), (C) air temperature (T$_{air}$), and (D) reference evapotranspiration (ET$_o$) across two cropping seasons stretching from 10 August 2016 to 6 August 2018.

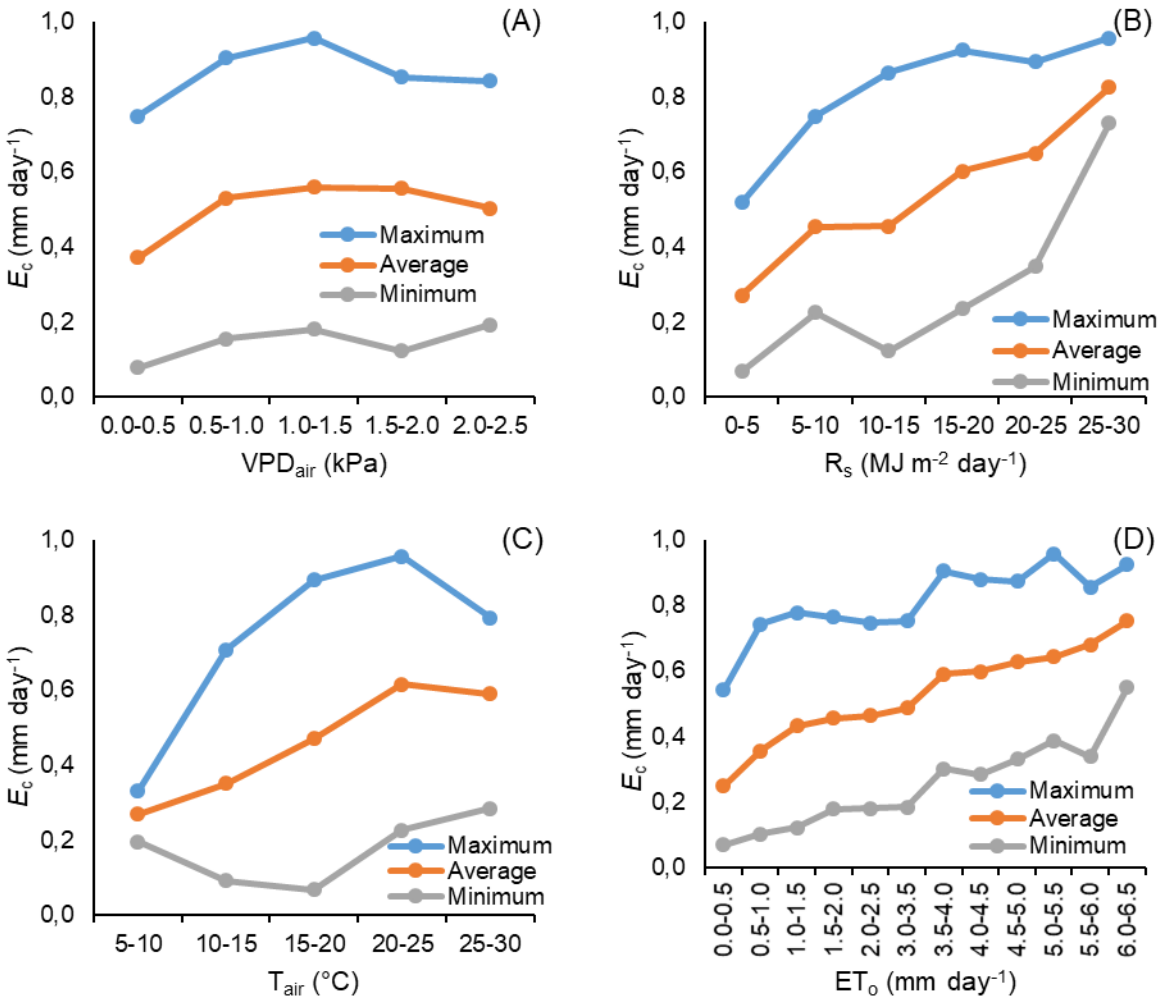


Figure 4.12: Average, maximum and minimum transpiration (E_c) of intermediate bearing macadamias in response to (A) vapour pressure deficit (VPD$_{air}$), (B) solar radiation (R$_s$), (C) air temperature (T$_{air}$), and (D) reference evapotranspiration (ET$_o$) across two cropping seasons stretching from 16 August 2017 to 5 August 2019

Hydraulic limitations typically lead to strict stomatal control under periods of high evaporative demand (Prado and Maurel, 2013; Martínez-Vilalta and Garcia-Forner, 2017), and would imply that macadamias have an upper limit to E_c. This study has confirmed that this is indeed the case in macadamias, with $E_{c\,max}$ in both orchards being reached when ET$_o$ rates exceeded 3.5 mm day^{-1}. Increases in ET$_o$ above 3.5 mm day^{-1} led to no further increase in E_c. The similarity in this response between the two orchards, with contrasting sizes, could suggest that this is either a species or cultivar specific trait, seeing that studies on citrus (Villalobos et al., 2009) and olive (Gucci et al., 2000, Tognetti et al., 2002) have shown within species differences in canopy conductance, and therefore also E_c, when grown under the same set of environmental conditions. Although this study has not investigated such potential differences, determining these thresholds for a range of macadamia cultivars could prove to be of great value to the macadamia industry by improving site selection based on environmental suitability of certain cultivars, whilst also providing more insight into the differences in water use and dry matter accumulation between cultivars.

4.1.4.2 Stomatal responses to environmental variables

In order to further explain the response of macadamia E_c to changing weather variables, more in depth studies on leaf gas exchange and leaf water potentials were conducted. This was deemed important to understand the ecophysiology of this relatively understudied crop and to ensure that the correct modelling approach was chosen. As gas exchange includes the entry of CO_2 into leaves it is also important to understand the link between stomatal conductance and photosynthesis.

Light-saturated rate of net CO_2 assimilation (A_{max}) reached optimum levels when leaf temperature ranged from 20-30°C, declining thereafter, with significantly lower A_{max} measured at leaf temperatures above 35°C compared to the optimum range between 20 and 30°C (Figure 4.13 A). In response to increasing VPD_{leaf}, A_{max} reached a maximum between 1.0-2.5 kPa (Figure 4.13 B), declining at higher VPD_{leaf}. A similar response was observed between g_s and VPD_{leaf}, with g_s reaching a maximum between 1.0-2.5 kPa, where after it declined in a similar manner to that of A_{max} in response to increasing VPD_{leaf} (Figure 4.13 C). The relationship between A_{max} and g_s (Figure 4.13 D) was non-saturating under the measured values of g_s.

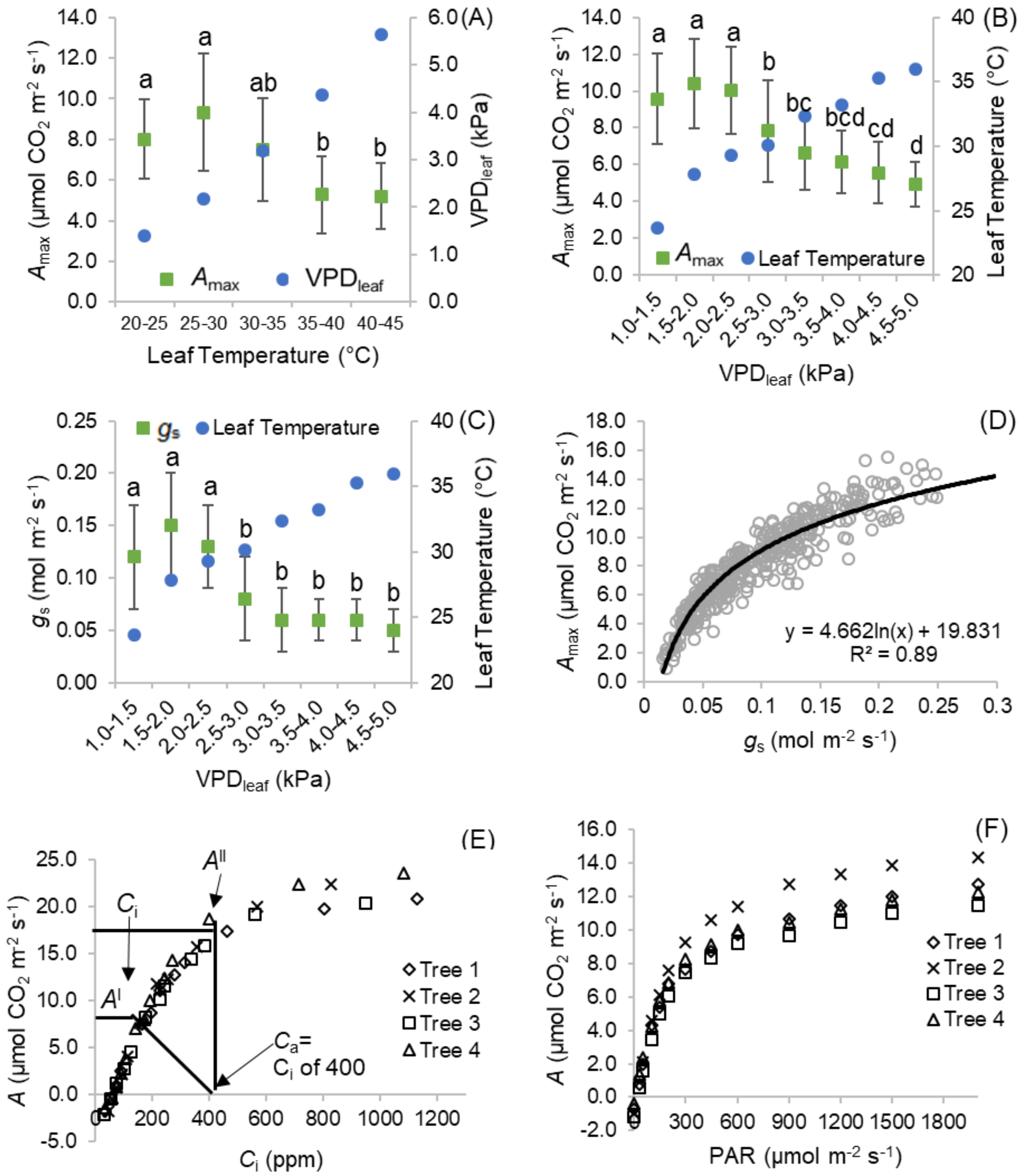


Figure 4.13: Response of A_{max} to increasing (A) T$_{leaf}$ (N= 500) and (B) VPD$_{leaf}$ (N= 500), (C) the response of g_s to VPD$_{leaf}$ (N= 500), and (D) the response of A_{max} to g_s (N= 500). (E) Representative responses of A to intercellular CO$_2$ concentration (C_i) showing the method used to calculate stomatal limitations ($l = (A^{II} - A^{I})/A^{II}$) as outlined by Long and Bernacchi (2003) of four experimental trees (N= 51) measured on 2017/12/07. (F) Response of A to PAR in fully sun-exposed leaves of four trees (N= 52) measured on 23 March 2017. Means followed by the same letter are not significantly different (p = 0.05) as analysed using repeated measures ANOVA. Data from Figures A-D were pooled data obtained from several measurement campaigns.

In response to increasing internal CO2 concentration (C_i), A increased linearly up to approximately 180 µmol mol^{-1}, after which the response flattened out during the shift from the

CO_2-limited region to the RuBP-limited region (Figure 4.13 E). At C_i concentrations above 400 µmol mol^{-1} the mean A was approximately three times higher (17.16 µmol m^{-2} s^{-1}) than the mean value of A^l (A at C_i when C_a= 400 µmol mol^{-1}), which was approximately 6.64 µmol m^{-2} s^{-1} (Figure 4.13 E). Stomatal limitation as calculated from these response curves amounted to approximately 33% of all possible limitations to photosynthesis. Macadamias reached A_{max} at PAR levels of >900 µmol m^{-2} s^{-1} (examples of photosynthetic light response curves are given in Figure 4.13 F). Mean A_{max} obtained from light response curves (8.77 ± 2.49 µmol m^{-2} s^{-1}) was comparable to mean seasonal spot measurements of A_{max} (8.34 ± 1.21 µmol m^{-2} s^{-1}) made at PAR levels of 1500 µmol m^{-2} s^{-1}.

Seasonal mean A_{max} of macadamias, obtained from spot measurements of leaf gas exchange in this study, was 8.34 µmol CO_2 m^{-2} s^{-1}, which is similar to values reported by Huett (2004) (8-10 µmol CO_2 m^{-2} s^{-1}). Net assimilation rates for macadamia were low compared to temperate, deciduous fruit and nut crops, such as apple, pear, plum, pecan and almond, all of which have mean A_{max} values greater than 15 µmol CO_2 m^{-2} s^{-1} (Flore and Lakso, 1989). Compared to other evergreen subtropical crops, such as citrus, macadamia seems to be slightly lower in terms of both A_{max} and g_s (Syvertsen et al., 2003). This could be partly attributed to slightly higher estimated stomatal limitations of macadamia (33%) than that of citrus (23.3%) (Jifon and Syvertsen, 2003), but various non-stomatal limitations also seem to result in lower assimilation rates.

4.1.4.3 Water relations

Pre-dawn leaf water potentials throughout the duration of the trial revealed only minimal variation, with a mean value of -0.13 ± 0.04 MPa in the MB orchard and -0.12 ± 0.06 MPa in the IB orchard (Figure 4.14). This suggests that neither orchard experienced prolonged periods of water stress. The analysis of diurnal trends in VPD_{air}, E_c and sun exposed leaf water potential ($\psi_{sun\ leaf}$) in the MB orchard revealed that during the course of a day (selected days shown in Figure 4.15), VPD_{air} increased to a maximum around 13:00 in summer (2016/12/08), between 12:00 and 13:00 in autumn (2017/04/15, 2018/04/18) and around 12:00 in winter (2017/07/14) (Figure 4.15 A). On these days, mean $\psi_{sun\ leaf}$ was reached between 10:00-11:00 daily, with a mean minimum value of -1.21 ± 0.22 MPa (Figure 4.15 B). Thereafter, $\psi_{sun\ leaf}$ recovered gradually to a mean value of -0.73 ± 0.21 MPa at 15h00. Consecutive days of measurements confirmed that ψ_{leaf} recovered completely during the night, with ψ_{pd} of consecutive days being similar (data not shown). Leaf water potentials lower than -2.0 MPa were rarely recorded throughout the duration of the trial. Midday $\psi_{sun\ leaf}$ remained relatively constant across all measurement days, despite distinctly different environmental conditions (Figure 4.15 A & B).

Whole tree E_c showed an approximate linear increase from 8:00-11:00 daily, where after E_c remained relatively constant as $\psi_{\text{sun leaf}}$ started to decrease from 11:00 onwards (Figure 4.15 C). Diurnal trends in $\psi_{\text{sun leaf}}$ and g_s, measured on the same leaf confirmed that the lowest value for $\psi_{\text{sun leaf}}$ and highest value for g_s typically occurred between 10:00 and 11:00 (Figure 4.16 A). This corresponded to a VPD_{leaf} of approximately 2.1-2.9 kPa (Figure 4.16 B).

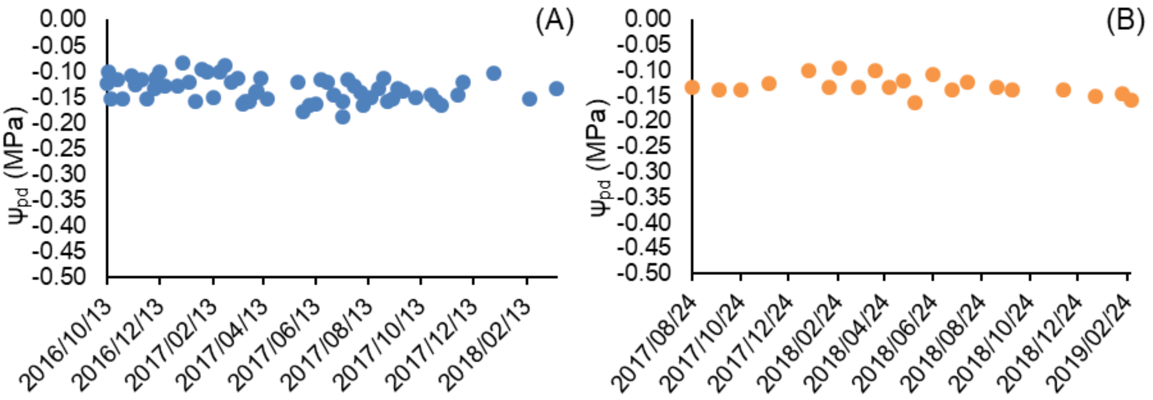


Figure 4.14: Pre-dawn leaf water potential (ψ_{pd}) measured in (A) the mature bearing macadamia orchard (N=60) and (B) intermediate bearing orchard (N=21) throughout the trial. Stress is believed to occur at pre-dawn leaf water potentials less than -0.5 MPa based on research from Stephenson (2003).

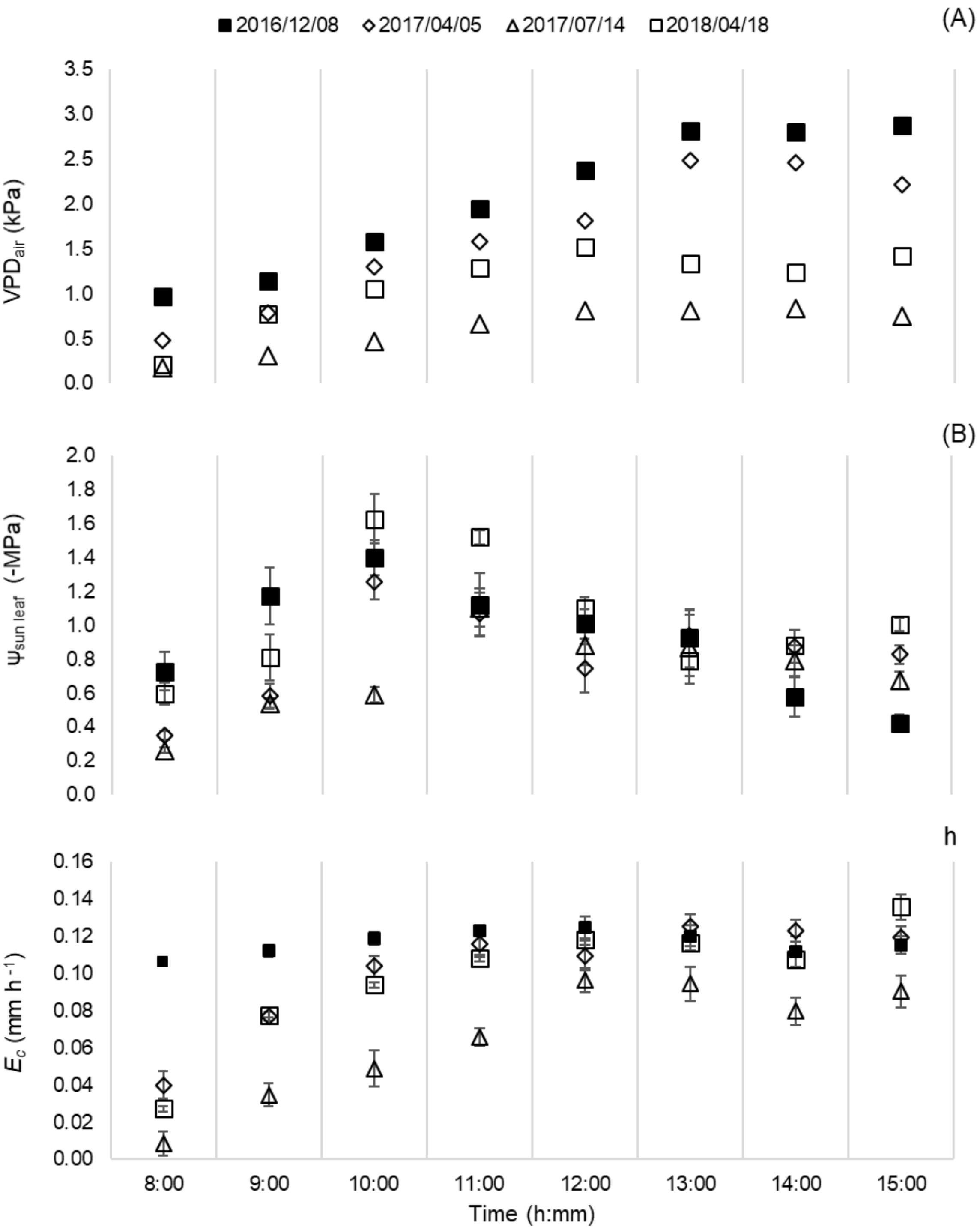


Figure 4.15: Diurnal progression of (A) air vapour pressure deficit (VPD_{air}), (B) sun exposed leaf water potential ($\psi_{sun\ leaf}$) obtained from random canopy sampling, and (C) whole tree transpiration rate (E_c) for four measurement days with contrasting weather conditions. Measurements of $\psi_{sun\ leaf}$ (N = 384) and E (N = 128) are means of four trees (± standard deviation) in the mature bearing orchard.

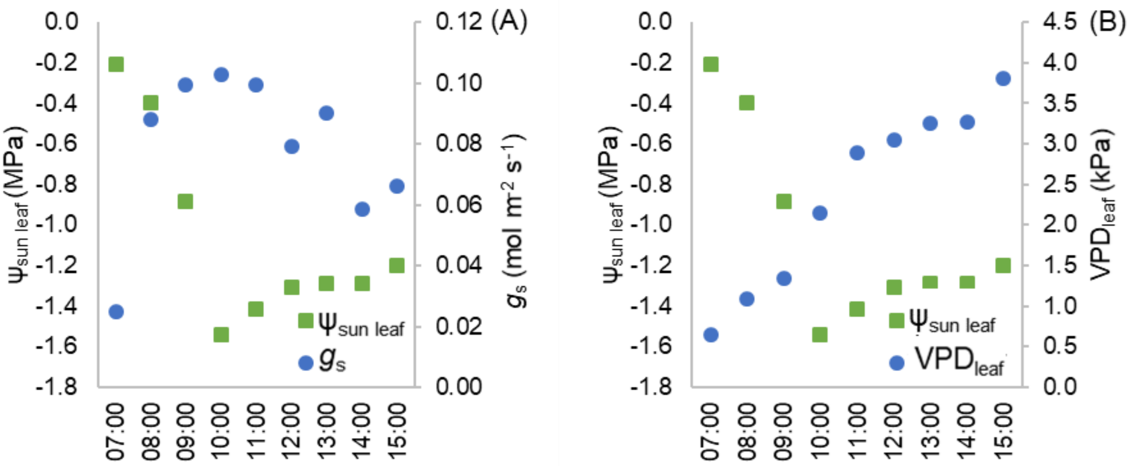


Figure 4.16: The diurnal trends in (A) $\psi_{\text{sun leaf}}$ and g_s and (B) $\psi_{\text{sun leaf}}$ and VPD_{leaf}, measured on the same leaf (2017/07/13) in the mature bearing orchard.

The seasonal mean of whole tree hydraulic conductance ($k_{\text{soil-leaf}}$) was estimated at 3.44 ± 2.13 mmol m^{-2} s^{-1} MPa^{-1}, with a mean conductance at the stem-leaf interface ($k_{\text{stem-leaf}}$) of 7.43 ± 5.05 mmol m^{-2} s^{-1} MPa^{-1}, and a mean conductance at the soil-stem interface ($k_{\text{soil-stem}}$) of 7.85 ± 4.48 mmol m^2 s^{-1} MPa^{-1} (Figure 4.17 A). However, large variation in hydraulic conductance was found, with estimates varying between individual trees and between consecutive days of measurements (Figure 4.17 A). An analysis of the diurnal variation of the various components of the hydraulic pathway revealed that both $k_{\text{soil-leaf}}$ and $k_{\text{soil-stem}}$ increased slowly until 10:00, where after the increase was more rapid (especially $k_{\text{soil-stem}}$), before slowly decreasing after 15:00 (Figure 4.17 B). In contrast, $k_{\text{stem-leaf}}$ increased rapidly until 08:00, then decreased rapidly from 8:00-10:00, before increasing from 11:00 onwards until 14:00 (Figure 4.17 B). Maximum g_s was reached between 8:00-11:00, after which g_s decreased rapidly. The mean $k_{\text{soil-leaf}}$, obtained from the inverse of the slope of the linear relationship (Figure 4.17 C) between whole tree E_c and $\psi_{\text{sun leaf}}$ was slightly higher (3.95 ± 2.24 mmol m^{-2} s^{-1} MPa^{-1}) than that determined from Equation [19] (3.44 ± 2.13 mmol m^{-2} s^{-1} MPa^{-1}). There was a positive linear relationship between leaf specific conductance (k_L) and g_s (Figure 4.17 D).

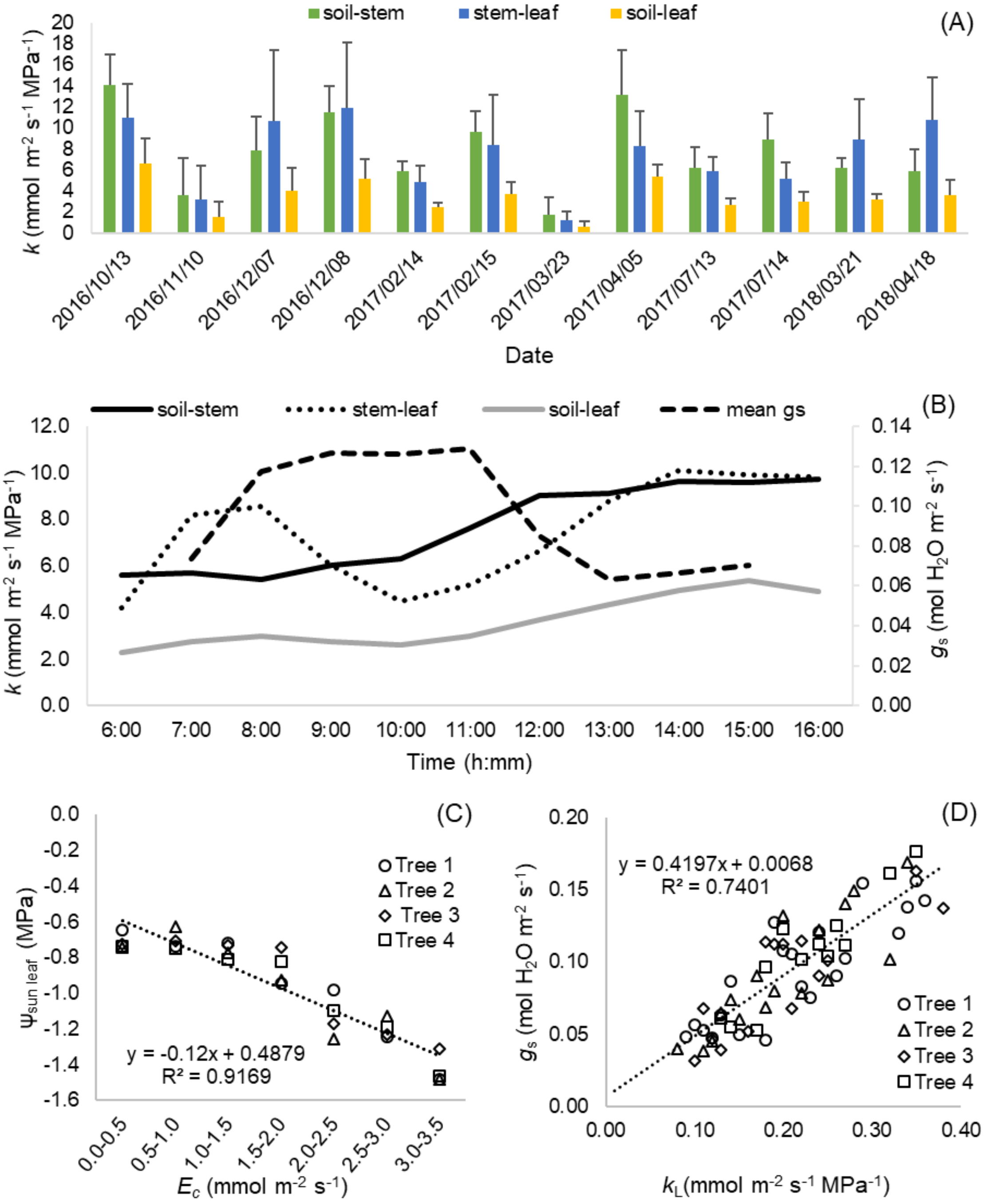


Figure 4.17: Means (± standard deviation) of (A) daily seasonal and (B) diurnal progression of individual components of hydraulic conductance, including soil to stem ($k_{\text{soil-stem}}$), stem to leaves ($k_{\text{stem-leaf}}$), whole tree hydraulic conductance ($k_{\text{soil-leaf}}$) of four study trees (N = 102) and mean stomatal conductance (g_s) from random spot measurements made during the same measurement day (N = 52). (C) Linear relationship between mean sun leaf water potential ($\psi_{\text{sun leaf}}$) and mean whole tree transpiration rate (E_c) for four study trees on 18 April 2018. (D) Linear relationship between mean leaf specific conductance (k_L) and mean stomatal conductance g_s for four study trees measured on 13 July 2017.

Stomatal limitations to macadamia leaf exchange are largely attributed to the predominantly isohydric behaviour of the crop, which was confirmed by diurnal $\psi_{\text{sun leaf}}$ which rarely reached levels lower than -2.0 MPa, despite rather contrasting environmental conditions, resulting in a range of atmospheric evaporative demands, during measurements and non-limiting soil water conditions (Figure 4.15). Strict stomatal control in macadamias resulted in the maintenance of favourable $\psi_{\text{sun leaf}}$, irrespective of atmospheric evaporative demand. Lloyd et al. (1991) found similar results, with $\psi_{\text{sun leaf}}$ of both irrigated and non-irrigated macadamias being very similar over a 2-month period and rarely reaching levels below -1.5 MPa. There were, however, differences in g_{s} between the two treatments, with g_{s} in the non-irrigated treatment dropping significantly to maintain ψ_{leaf}. The maintenance of high ψ_{leaf} through stomatal closure is believed to be an underlying hydraulic safety factor used to avoid xylem cavitation under high evaporative demands (Schultz, 2003, Sperry, 2000) and suggests that there is a hydraulic limitation to water flow through certain segments within the tree (Gleason et al., 2016).

The report by Lloyd et al. (1991) of high hydraulic conductance of macadamia trees relative to most other fruit trees seems to be at odds with the isohydric nature of the tree. However, results from this study suggest a lower value for $k_{\text{soil-leaf}}$ than those reported by Lloyd et al. (1991), which possibly reflects different techniques for estimating $k_{\text{soil-leaf}}$. The values from this study ($k_{\text{soil-leaf}}$ = 3.44 ± 2.13 mmol m^{-2} s^{-1} MPa^{-1}), using whole tree transpiration, are more comparable with other fruit tree species, such as apple (4.4 mmol m^{-2} s^{-1} MPa^{-1}, Cohen and Naor (2002)) and kiwifruit (2.44-3.83 mmol m^{-2} s^{-1} MPa^{-1}, (Clearwater et al., 2004)). Importantly, the separation of the hydraulic pathway from the soil to the stem and from the stem to the leaf, provided more insight into the hydraulic characteristics of macadamia trees and suggested slightly lower conductance in the stem to leaf pathway, than the soil to stem pathway throughout the season. This was confirmed through the analysis of the diurnal progression of $k_{\text{stem-leaf}}$ and $k_{\text{soil-stem}}$, which revealed that there was a reduction in $k_{\text{stem-leaf}}$ in the morning (Figure 4.17 B), which roughly corresponded with an increase in g_{s}. This suggests that as stomata open, water held within storage tissues in the leaf is lost through transpiration. As there was a negligible time lag between transpiration estimated via sap flow and evapotranspiration estimated using Eddy Covariance measurements (data not shown), it was assumed that the storage capacity in the trees was low and thus transpiration at the start of the day would have depended predominantly on stored water in the leaves. After the depletion of these stored water reserves, and increased transpiration rates, significant resistance to water flow occurs within the stem to leaf interface. From this point onwards results suggest that resistance within the stem to leaf interface places significant constraints on macadamia leaf gas exchange, by means of changes in leaf water status, as demonstrated in ponderosa pine by Hubbard et al. (2001). This is complemented by the linear relationship between k_{L} and g_{s} (Figure 4.17 D), which is not only indicative of near isohydric behaviour, but also suggests that a reduction in bulk leaf water status, or even a single portion of the leaf as a result of reduced k_{L}, could lead to reduced g_s. According to Hubbard et al. (2001) this slight reduction in g_s returns ψ_{leaf} to its original levels and the continuous nature of this response in both time and space results in a near constant ψ_{leaf} irrespective of atmospheric conditions.

Although results from this study suggest that macadamias are predominantly isohydric and exhibit strict stomatal control in response to increasing VPD_{leaf}, these responses were not consistent throughout the duration of the trial. The observed variation of both g_s and A_{max} in response to increasing VPD_{leaf} corresponded to the absence or presence of fruit on trees.

4.1.5 TRANSPIRATION DURING DIFFERENT PHENOLOGICAL STAGES

Although prevailing weather conditions remain the major factor controlling E_c, results from this study have suggested that E_c varies during different phenological periods, especially during periods of high and low sink strength. Throughout the study period, E_c in both the MB and IB orchards, increased from a minimum at flower initiation to a maximum at flowering (Table 4.4). Daily E_c then decreased slightly during the nut set period, where after E_c rates continually increased in both orchards to the seasonal maxima throughout the nut growth to the summer flush period.

Table 4.4: Average (± standard deviation) daily transpiration rates for the mature bearing (MB) and intermediate bearing (IB) macadamia orchards during different phenological and management periods across consecutive cropping seasons, as outlined in Table 4.1. Means followed by the same letter are not significantly different (p = 0.05) as analysed using one-way repeated measures ANOVA, in each of the orchards.

Phenological Stage	Transpiration MB (mm day^{-1})	Transpiration IB (mm day^{-1})
Pre-flowering	0.75 ± 0.24 ^{a}	0.37 ± 0.15 ^{a}
Flowering	1.01 ± 0.23 ^{b}	0.51 ± 0.12 ^{b}
Nut Set	0.87 ± 0.27 ^{abc}	0.45 ± 0.15 ^{abc}
Spring Flush	0.91 ± 0.28 ^{bc}	0.46 ± 0.17 ^{abc}
Premature Nut Drop	0.95 ± 0.25 ^{bc}	0.55 ± 0.15 ^{b}
Nut Growth	1.03 ± 0.15 ^{b}	0.62 ± 0.10 ^{b}
Summer Flush	1.12 ± 0.24 ^{b}	0.63 ± 0.16 ^{b}
Oil Accumulation	0.99 ± 0.12 ^{b}	0.57 ± 0.15 ^{b}
Harvest	0.74 ± 0.30 ^{ac}	0.50 ± 0.12 ^{bc}
Flower Initiation	0.77 ± 0.12 ^{ac}	0.38 ± 0.10 ^{ac}
Pruning & Winter Rest	0.68 ± 0.18 ^{a}	0.33 ± 0.08 ^{a}

During the summer flush period, trees transpired on average 1.1 mm day^{-1} for the MB orchard and 0.6 mm day^{-1} for the IB orchard. These rates were approximately 0.2 mm day^{-1} higher than the average spring E_c of 0.9 mm day^{-1} for the MB orchard and 0.1 mm day^{-1} higher than the average seasonal E_c of 0.5 mm day^{-1} in the IB orchard. The increase during the summer vegetative flush period could be attributed to the increase in ET_o and canopy size, but could also be partially attributed to the combined sink strength of developing fruit and vegetative growth. There was, however, no difference in daily ET_o during spring and the summer vegetative flush period. Although increases in canopy size of each orchard cannot be eliminated as a factor causing increases in E_c during the summer flush period, transpiration rates during both the flowering and nut set period (Table 4.4) were not significantly lower than E_c rates measured during the spring and summer vegetative flush periods, although average LAI was greater during the flush periods (Figure 4.18).

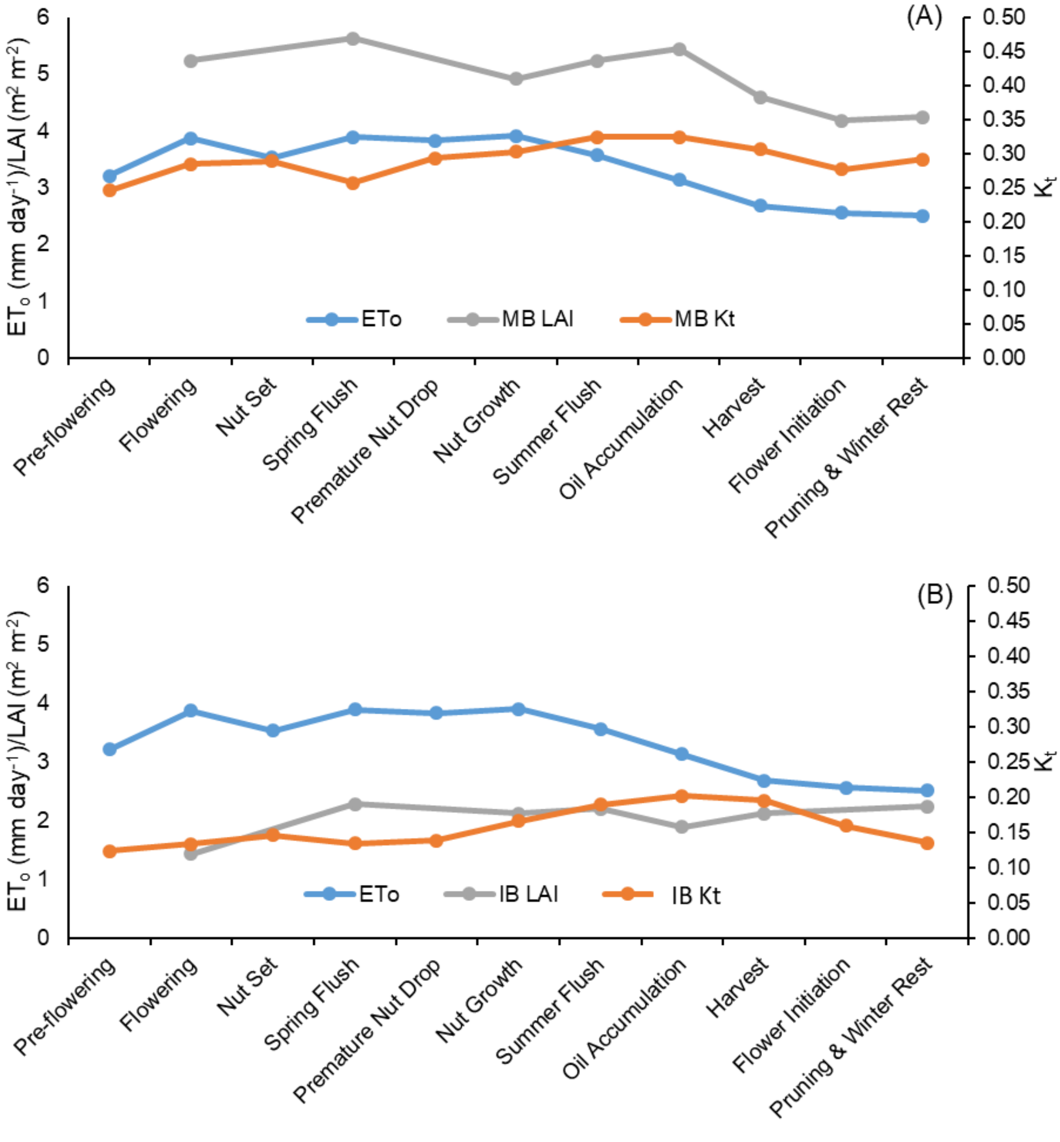


Figure 4.18: Average daily reference evapotranspiration (ET_o), leaf area index (LAI), and transpiration crop coefficients (K_t) for (A) mature bearing (MB) and (B) intermediate bearing (IB) macadamia orchards measured during different phenological periods.

The results from this study are supported by anecdotal evidence from growers, who have observed an increase in water use during flowering (Table 4.4). It is commonly believed that this increase in E_c is as a result of transpiration by the flowers themselves. Although this cannot be ruled out at the moment, it is more likely that the increase in E_c at this time is a response to increased R_s, $VPD_{air,}$ and ET_o (Figure 4.1) during the onset of spring. However, it is surprising that average K_t during the flowering period was 10% higher in the MB orchard and remained constant in the IB orchard compared to that of the spring flush period, even though ET_o was similar to that measured during the spring flush period (Table 4.4), and LAI of both MB and IB orchards were approximately 10% less during the flowering period. This observation would suggest that given the fact that average ET_o was similar between the two aforementioned periods and that increases in canopy size did not occur, increased K_t during flowering could possibly be attributed to direct water loss from flowers, which ultimately increased measured E_c. This 25% increase in daily E_c rates would undoubtedly cause observable increases in water use as reported by growers, which would be exacerbated by higher levels of soil evaporation (not measured in this study), due to increased solar radiation reaching the orchard floor following winter pruning and the lack of substantial increases in canopy size before the onset of spring.

During the harvesting to pre-flowering periods, average daily E_c rates were approximately 0.2-0.4 mm day^{-1} lower compared to average spring and summer E_c rates (Table 4.4) in both MB and IB orchards. This decrease in E_c from the summer flush period to the harvesting and post-harvest period occurred in conjunction with a decrease in both canopy size and seasonal decreases in ET_o (Figure 4.18). During the autumn and winter period, ET_o was on average 2.2 mm day^{-1} and was approximately 1.5 mm day^{-1} less than the average ET_o during the summer period (Figure 4.19). The weather variable leading to the greatest decrease in ET_o is the reduction in total daily R_s (Figure 4.19), which was approximately 30% lower compared to the seasonal average of 16.5 MJ m^{-2} day^{-1}. Reduced total daily R_s was as a result of shorter day lengths during winter and autumn, which subsequently lead to reduced total daily $E_{c.}$

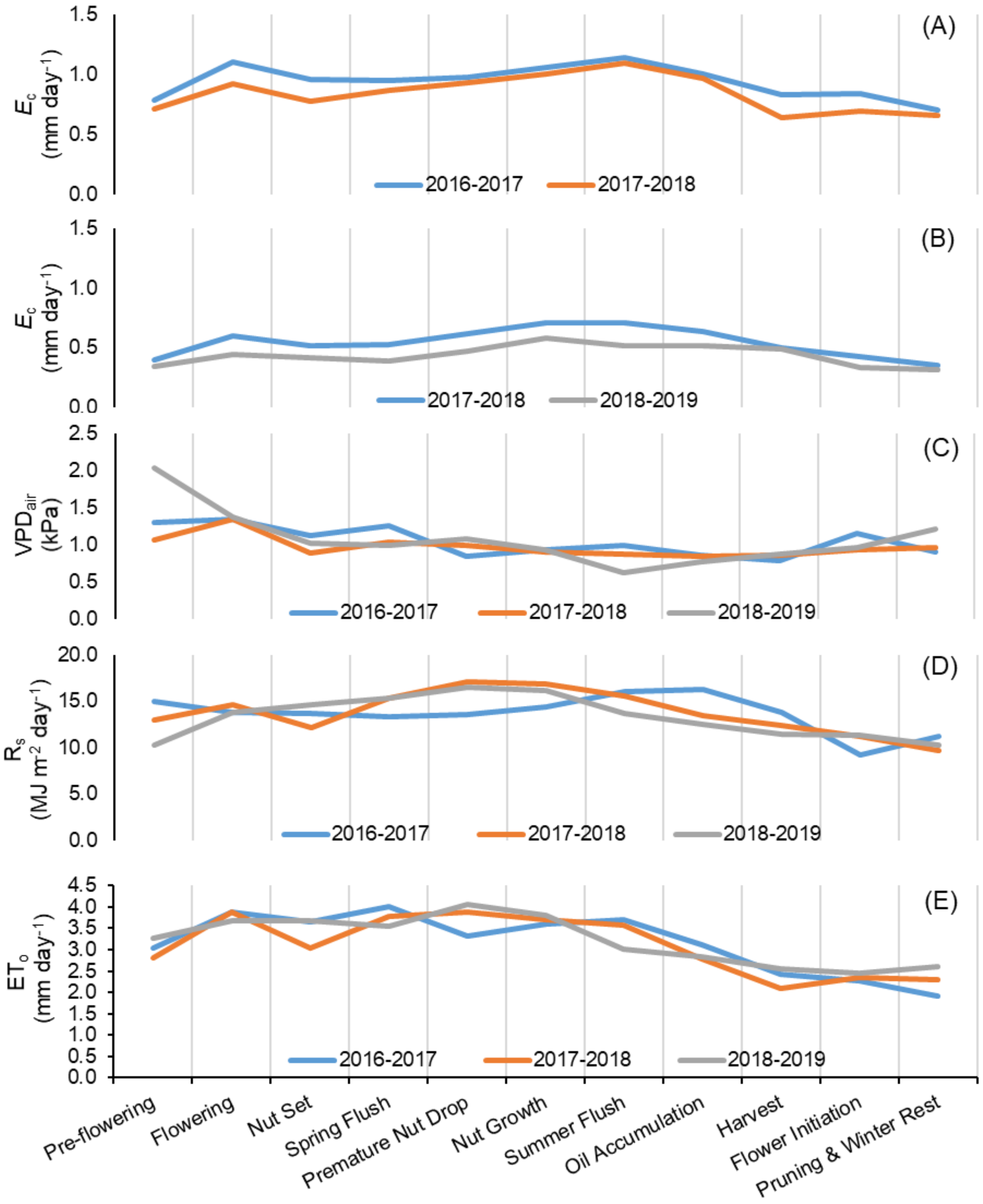


Figure 4.19: Daily averages of transpiration (E_c) in the (A) mature bearing (MB) and (B) intermediate bearing (IB) macadamia orchards and accompanying daily average (C) air vapour pressure deficit (VPD_{air}), (D) solar radiation (R_s), and (E) reference evapotranspiration (ET_o) during each phenological stage across three consecutive cropping seasons.

Results from this study complement currently recommended industry management practices, where growers reduce irrigation volumes during the harvesting period until the pre-flowering period. During these periods, average daily E_c rates were lower than average seasonal daily E_c rates. This significant decrease in E_c during the post-harvest period is in part due to slight decreases in canopy size as a result of applications of exogenous ethylene (Ethephon) during harvest, which is known to cause leaf drop, followed by maintenance pruning directly after harvest. The combination of these two practices resulted in 5-10% reduction in canopy size in the MB and IB orchards. These reductions in canopy size coincided with observed decreases in E_c, but it is highly unlikely that these slight reductions in canopy size alone would be responsible for the observed decreases in E_c. A reduction in canopy size, achieved through pruning, aims to increase radiation penetration into the tree canopy and decrease canopy height. This should theoretically lead to increased solar radiation interception by previously shaded leaves, which will subsequently lead to increased leaf gas exchange (Huett, 2004) and therefore compensate for some of the loss in canopy size and subsequently have a smaller impact on E_c. It is therefore more likely that the observed decreases in E_c during the post-harvest period is attributed to decreased atmospheric evaporative demand during late autumn and winter. During these periods, ET_o was on average 40% less than that of average ET_o during the summer period which led to a 20-30% decrease in average daily E_c in both orchards over multiple seasons.

Not only do these reduced E_c rates during the post-harvest period complement current management practices, it also provides some more insight into the results of Stephenson et al. (2003), which showed that during the floral initiation period, which roughly corresponds with the harvest and pruning/winter rest period in this study, mild water stress had no significant effect on yield and quality of macadamias. This could be due to the relatively low E_c during this period, which even under conditions of mild water stress and slight stomatal closure, would have been sufficient to sustain whole tree photo-assimilate requirements during this period. In combination with the results from Stephenson (2003), the results from this study would suggest that growers could potentially reduce irrigation by 20-30% from the summer norm during the post-harvest period.

4.1.5.1 Influence of fruit on leaf gas exchange

In order to attempt to explain the change in transpiration during low and high sink strength periods, more in depth studies of gas exchange were conducted during low and high sink strength periods. Mean A_{max} varied throughout the data collection period between a minimum of 6.03 µmol m^{-2} s^{-1} (2016/08/09) and a maximum of 11.21 µmol m^{-2} s^{-1} (2017/12/08) (Table 4.5). Intermediate A_{max} values were recorded on the other measurement dates. Differences in A_{max} and g_s throughout the season typically agreed with significant differences in mean T_{leaf}

and $\mathrm{VPD}_{\mathrm{leaf}}$, However, these differences were not consistent throughout the season. Despite similar $\mathrm{VPD}_{\mathrm{leaf}}$ on 2016/08/09 and 2017/03/23, A_{max} and g_{s} were significantly higher in March than August. This variation in A_{max} and g_{s} corresponded to the presence of oil accumulating fruit in March, as opposed to August when the trees were in flower (Figure 4.4).

Table 4.5: Mean light saturated net CO_2 assimilation rate (A_{max}), stomatal conductance (g_{s}), leaf-to-air vapour pressure deficit ($\mathrm{VPD}_{\mathrm{leaf}}$), leaf temperature ($T_{\mathrm{leaf}}$) and the corresponding daylight (6:00-18:00) air vapour pressure deficit ($\mathrm{VPD}_{\mathrm{air}}$) and air temperature ($T_{\mathrm{air}}$) for spot measurements. Measurement dates falling within the fruiting period are denoted by a *. Means in columns were separated by LSD at 5% when $P \leq 0.05$ according to repeated measures ANOVA.

Date	*N*	A_{max} (μmol CO_2 m^{-2} s^{-1})	g_{s} (mol m^{-2} s^{-1})	$\mathrm{VPD}_{\mathrm{leaf}}$ (kPa)	T_{leaf} (°C)	$\mathrm{VPD}_{\mathrm{air}}$ (kPa)	T_{air} (°C)
2016/08/09	140	6.03 c	0.05 c	3.2 ab	31.0 b	1.7 b	21.9 c
2016/10/13	23	7.88 bc	0.11 b	1.4 c	22.2 d	0.6 d	17.4 d
***2017/03/23**	**26**	**8.64 b**	**0.12 b**	**3.5 a**	**34.6 a**	**2.3 a**	**27.9 a**
2017/05/11	21	8.43 b	0.10 b	2.6 b	32.3 b	2.3 a	25.2 b
***2017/12/08**	**38**	**11.21 a**	**0.15 a**	**1.7 c**	**26.8 c**	**1.2 c**	**21.6 c**
Average		7.48	0.08	2.77	30.02	1.6	22.4

Although A_{max} during fruiting (F) periods remained higher than A_{max} during non-fruiting (NF) periods at similar leaf temperatures, the difference was only significant within the 25-35°C range (Figure 4.20 A). Mean light saturated net CO_2 assimilation rate during F periods was significantly higher than A_{max} during NF periods within the 1.0-2.0 kPa and 2.5-3.5 kPa $\mathrm{VPD}_{\mathrm{leaf}}$ ranges (Figure 4.20 B). During F periods, g_{s} was significantly higher compared to g_{s} during NF periods at $\mathrm{VPD}_{\mathrm{leaf}}$ ranging from 1.5-3.5 kPa (Figure 4.20 C). The majority of higher A_{max} and corresponding g_{s} values were obtained during the F period (Figure 4.20 D). Higher A values were achieved for similar C_{i} levels during F periods compared to NF periods (Figure 4.20 E). However, responses of A to increases in PAR (Figure 4.20 E) were similar between F and NF periods. These results suggest that macadamias have the capability to maintain g_{s} for longer under high evaporative demands during fruit bearing periods than during non fruit bearing periods.

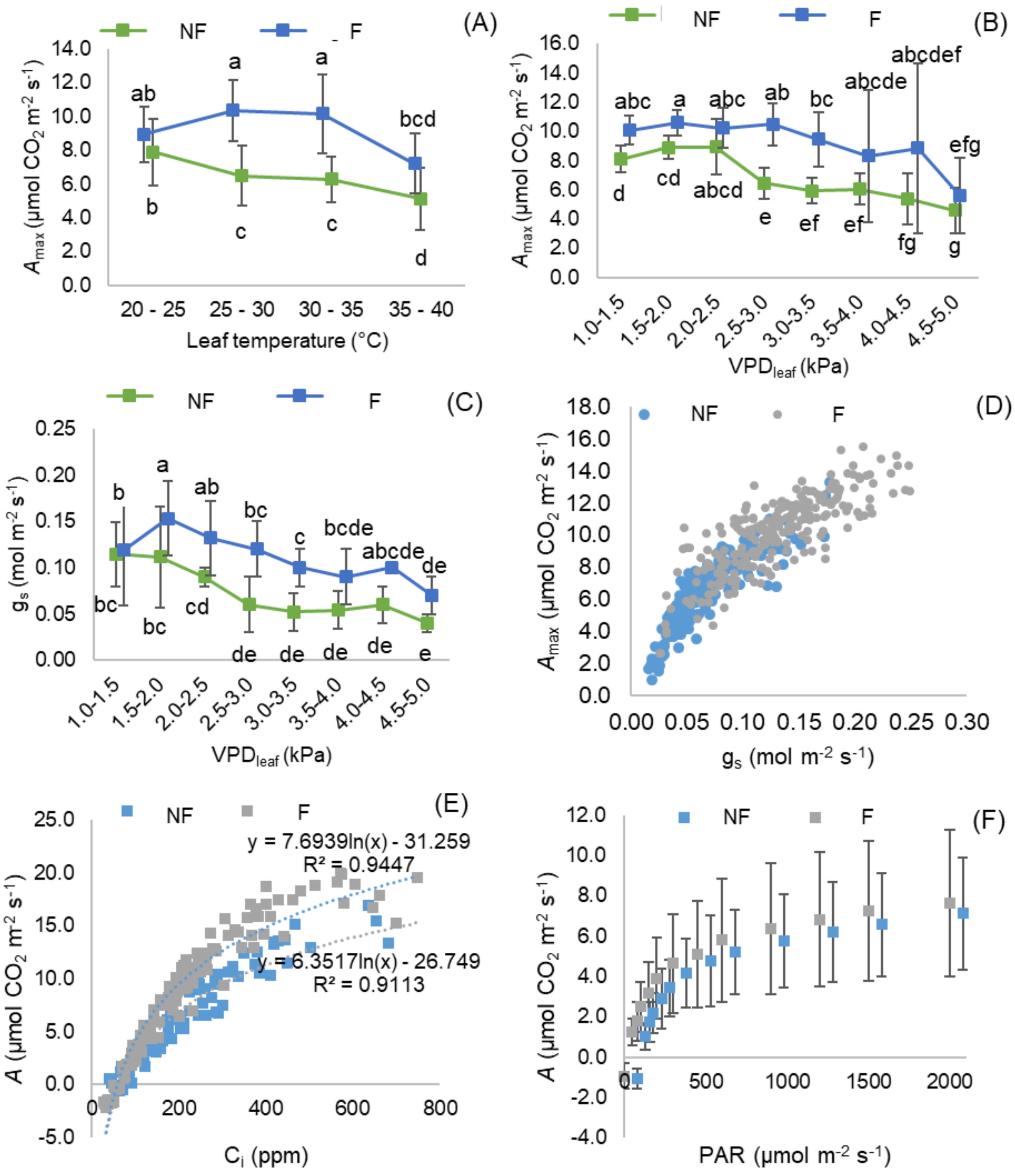


Figure 4.20: Response of A_{max} to increasing (A) T_{leaf} and (B) VPD_{leaf}, and (C) the response of g_s to VPD_{leaf}, and (D) the response of A_{max} to g_s during non-fruiting (NF) (N= 261) and fruiting (F) (N= 239) stages. (E) Responses of A to intercellular CO_2 concentration (C_i) during non-fruiting stages (N= 78) and fruiting stages (N= 138) stages. (F) Response of A to PAR in fully sun-exposed leaves of all experimental trees during non-fruiting stages (N= 368) and fruiting stages (N= 272) stages. Means were separated by LSD at 5% when P<0.05 according to repeated measures ANOVA

Mean values of A_{max} and g_s, and associated T_{leaf}, T_{air}, VPD_{leaf} and VPD_{air} from spot gas exchange measurements are shown in Table 4.6. Mean air temperature was 3.6°C higher during F periods compared to NF periods (with no difference in mean VPD_{air}), yet leaf temperature was 1.6°C lower during F periods (Table 4.6). A greater g_s during F periods was therefore associated with a lower T_{leaf} and VPD_{leaf}. Parameters derived from A/C_i curves ($V_{c\,max}$, J_{max}, TPU, R_d and l) measured at similar T_{leaf} and VPD_{leaf}, for NF and F periods, are also shown in Table 4.6. Estimates of $J_{max,}$ and TPU were higher during F periods compared to NF periods (Table 4.6). Mitochondrial respiration rate (R_d) was lower for periods of F compared to periods of NF. No differences were found between the two periods for $V_{c\,max}$ and l. No significant differences were found between F and NF periods for the parameters derived from the photosynthetic light response curves (Table 4.6).

Given the significant assimilate demand by the oil storing fruit of macadamia (Stephenson et al., 1989), an upregulation of photosynthesis during fruit bearing periods is not only likely but also necessary. Whilst the upregulation of A_{max} in response to the presence of fruit observed in this study can be linked to the concomitant increase in g_s, it is also most likely linked to reduced mitochondrial respiration rates and increased Calvin cycle kinetics, as J_{max} and TPU were higher during fruiting periods (Table 4.6). Similar increases in g_s and/or A_{max} in response to crop load have been noted in a number of fruit crops (Naor, 2001, Pretorius and Wand, 2003, Silber et al., 2013), with Sade and Moshelion (2014) suggesting a switch between isohydric and anisohydric behaviours over the course a season as a result of shifts in hydraulic and stomatal regulation in response to sink strength. It is therefore plausible that macadamias do not follow a purely isohydric water management strategy, but rather a more plastic isohydric strategy, which depends on the presence or absence of developing nuts.

Unfortunately, the mechanisms by which stomata respond to sink strength are not well understood. Whilst Hölttä et al. (2017) proposed a steady state stomatal model balancing gas exchange with plant hydraulics and source-sink flux, Mitchell et al. (2017) linked an increase in ABA with the build-up of non-structural carbohydrates in source tissue, which lead to a reduction in g_s. A dual role for ABA in reduced g_s was suggested Pantin et al. (2013), with a direct impact on guard cells and an indirect action through reduced k_L by decreasing water permeability of the leaf vascular tissue. Finally, Sade and Moshelion (2014) suggest that aquaporins play an important role in controlling leaf water status and therefore whether a plant will behave in a more isohydric or anisohydric fashion.

Table 4.6: Average values and standard deviations (SD) for light saturated net CO_2 assimilation rate (A_{max}), stomatal conductance (g_s), maximum velocity of Rubisco for carboxylation ($V_{c\ max}$), maximum rate of electron transport (J_{max}), rate of triose phosphate use (TPU), mitochondrial respiration rate (R_d) and stomatal limitation (l), leaf temperature (T_{leaf}), daylight (6:00 am to 6:00 pm) air temperature, leaf-to-air vapour pressure deficit (VPD_{Leaf}), air vapour pressure deficit (VPD_{air}), light compensation point (LCP), apparent quantum efficiency (AQE) and day respiration rate between periods of high and low sink strength. The parameters $V_{c\ max}$, J_{max}, TPU, R_d, l, LCP, AQE and day respiration rate were obtained from analysis of A/C_i and PAR response curves at T_{leaf} ranging from 25-30°C. Averages were separated by LSD at 5% when $P \leq 0.05$. N is the number of measurements.

	N	High Sink (Average ± SD)	*N*	Low Sink (Average ± SD)
		Spot Measurements		
A_{max} ($\mu mol\ CO_2\ m^{-2}\ s^{-1}$)	228	10.27 ± 2.23^a	196	6.58 ± 2.00^b
g_s ($mol\ m^{-2}\ s^{-1}$)	228	0.13 ± 0.05^a	196	0.07 ± 0.03^b
T_{leaf} (°C)	228	28.66 ± 2.27^b	196	30.28 ± 3.45^a
T_{air} (°C)		23.58 ± 1.36^a		19.93 ± 2.59^b
VPD_{leaf} (kPa)	228	1.91 ± 0.61^b	196	2.97 ± 0.80^a
VPD_{air} (kPa)		1.04 ± 0.40^a		1.37 ± 0.62^a
		A/C_i Response Curve Analysis		
$V_{c\ max}$ ($\mu mol\ m^{-2}\ s^{-1}$)	9	72.80 ± 14.31^a	13	55.92 ± 25.51^a
J_{max} ($\mu mol\ m^{-2}\ s^{-1}$)	9	90.24 ± 10.39^a	13	73.35 ± 12.86^b
TPU ($\mu mol\ m^{-2}\ s^{-1}$)	9	6.53 ± 1.05^a	13	4.77 ± 0.78^b
R_d ($\mu mol\ m^{-2}\ s^{-1}$)	9	0.35 ± 0.25^b	13	1.01 ± 0.45^a
l (%)	9	35.23 ± 8.96^a	13	29.24 ± 9.32^a
		PAR Response Curve Analysis		
LCP ($\mu mol\ PAR\ m^{-2}\ s^{-1}$)	7	7.73 ± 5.83^a	13	11.01 ± 9.81^a
AQE ($mol\ mol^{-1}$)	7	0.05 ± 0.01^a	13	0.03 ± 0.02^a
Day respiration rate ($\mu mol\ m^{-2}\ s^{-1}$)	7	0.37 ± 0.24^a	13	0.33 ± 0.30^a

4.1.6 WATER USE EFFICIENCY AND WATER USE PRODUCTIVITY

The details of all quality parameters determined from the average of the four measurement trees in the MB orchard, during each season, are provided in Table 4.7. Furthermore, the selling price and gross on-farm income of macadamias (less processor costs) was calculated based on the average price per grade and style and is displayed in

Table 4.8. Dry in shell (DIS) yield per tree in the 2016/2017 was slightly higher than in 2017/2018, which also translated into a difference in kernel mass. Yields in both years were fairly high with over 6 t ha^{-1} recorded in both years, which is above the industry norm. Crackout % for both seasons was on average 35%, which is slightly above the industry norm of 30-34%. First grade kernel % was slightly higher in 2016/2017 (90% vs 87%), but % whole kernel was slightly higher in 2017/2018 (36% vs 28%).

Table 4.7: Average macadamia yield and quality obtained from four measurement trees for two consecutive seasons stretching across the period of 10 August 2016 to 9 August 2017 (2016/2017 season) and 10 August 2017 to 9 August 2018 (2017/2018 season).

	2016/2017 Season		**2017/2018 Season**	
Parameter	**kg tree^{-1}**	**kg ha^{-1}**	**kg tree^{-1}**	**kg ha^{-1}**
Dry In Shell (DIS) Weight	21.5	6708.0	19.5	6072.4
Shell Weight	14.2	4427.3	12.5	3886.3
Total Kernel Weight	7.9	2461.7	7.0	2186.1
First Grade Kernel Weight	7.17	2237.0	6.1	1901.9
Second Grade Kernel Weight	0.4	124.8	0.6	181.4
Whole Kernel Weight	2.0	615.4	2.2	699.5
Halve Kernel Weight	3.9	1206.2	2.7	830.7
Kernel Bits & Pieces Weight	1.3	418.5	1.2	371.6

Average prices per kg of kernel were slightly higher in 2017/2018 than 2016/2017 and as expected the price per kg varied quite considerably depending on the grade, from R222 for first grade whole kernel to R142 for second grade kernel. This highlights the importance of quality for growers in order to achieve maximum profits. When considering WUE and WUP (calculated based on orchard *transpiration*), these parameters were very similar for the two seasons. WUE was 1.92-1.97 kg m^{-3} when considering nut in shell and 0.69-0.72 kg m^{-3} when considering kernel. WUP was R117-R118 m^{-3} of water transpired (Table 4.9). Thus, although WUE is fairly low, WUP is fairly high due to the high price of nuts. These WUE values for macadamias are considerably higher than those reported for mature pecan trees in New Mexico and South Africa, which varied between 0.15 kg m^{-3} to 0.31 kg m^{-3} (nut in shell) (Ibraimo et al., 2016, Miyamoto, 1990, Sammis et al., 2004). On average its takes 513 L to produce a kg of nut in shell macadamias.

Table 4.8: Average industry macadamia prices per kilogram according to grade and style

	2016/2017 Season			2018/2019 Season		
Grade and Style	**R kg^{-1}**	**R tree^{-1}**	**R ha^{-1}**	**R kg^{-1}**	**R tree^{-1}**	**R ha^{-1}**
First Grade						
Whole Kernel	R222.00	R437.90	R136,623.24	R228.00	R511.20	R159,494.65
Half Kernel	R192.00	R742.29	R231,594.85	R204.00	R543.15	R169,463.07
Kernel Bits & Pieces	R188.00	R252.16	R78,675.29	R201.00	R239.42	R74,697.54
Second Grade Kernel	R142.00	R56.80	R17,721.60	R153.00	R88.98	R27,760.73
Total Income		R1,489.15	R464,614.99		R1,382.74	R431,415.98
Gross Income (Less Processing Costs)		R1,283.18	R400,352.35		R1,196.29	R373,242.60

Table 4.9: Parameters used in calculation of transpiration water use efficiency (WUE) and water use productivity (WUP) across two cropping seasons for a mature macadamia orchard.

	2016/2017 Season	2017/2018 Season
Total Transpiration (mm)	340	316
Total Transpiration (m^3)	3400	3160
Total Dry in Shell Nut Yield (kg ha^{-1})	6708.0	6072.4
Total Kernel Yield (kg ha^{-1})	2461.7	2186.1
Total Net Income (R ha^{-1})	R400 352.35	R373 242.60
WUE (kg m^{-3}) – In Shell	1.97	1.92
WUE (kg m^{-3}) – Kernel	0.72	0.69
WUP (R m^{-3})	117.75	118.11

4.1.7 CONCLUSIONS

Despite the rapid expansion of irrigated macadamia production, information regarding water use of the crop is lacking. In order to provide producers with water use guidelines which are applicable to a range of environments, this study examined the mechanisms and driving variables of macadamia water use to select and parameterize water use models. This study has therefore provided valuable insight into the seasonal water use dynamics of macadamias.

Not only has it shown that macadamias have substantial stomatal and non-stomatal limitations to net CO_2 assimilation, it has shown that the crop is predominantly isohydric in nature, a trait which has a significant effect on the E_c of macadamias. Furthermore, it has revealed that macadamia phenology, in particular the presence of oil storing fruits, can have a significant effect on crop physiology which resulted in seasonal variations of E_c, which were unaccounted for by variations in the major driving variables of macadamia E_c being canopy size and atmospheric evaporative demand.

Fairly low net CO_2 assimilation (A) rates were obtained for macadamias in this study, especially compared to other subtropical evergreen crops, such as citrus and olive. These low A values could largely be explained by both stomatal and non-stomatal limitations to A, but could also relate to the hydraulic limitation identified in the leaf to stem interface. Non-stomatal limitations in macadamias, which include previously demonstrated low mesophyll conductance (g_m) and light limitations within the internal leaf space, is attributed to the sclerophyllous nature of macadamia leaves. Stomatal limitations to A accounted for approximately one third of the total limitation to carbon assimilation in macadamias. Understanding stomatal behaviour, and more specifically stomatal conductance (g_s), was therefore essential to understanding the relationship between carbon gain and water lost through transpiration. Macadamia g_s is carefully controlled in response to increasing leaf vapour pressure deficit (VPD_{leaf}), with a decline in g_s being observed when VPD_{leaf} exceeded 2.50 kPa. Strict stomatal control was accompanied with nearly constant $\psi_{sun\ leaf}$, which is typical of isohydric water management strategies in plants. Isohydric behaviour is often linked to an underlying hydraulic limitation, which necessitates strict leaf level control of g_s which could possibly reflect a need to avoid hydraulic failure as a result of xylem embolism. An examination of hydraulic conductance within macadamias has showed that although whole tree hydraulic conductance is comparable with other tree crops, there is a significant hydraulic limitation within the stem to leaf interface. This hydraulic limitation most likely leads to decreases in relative water content within the leaf space, directly resulting in decreased g_s under conditions of high VPD_{leaf}.

The distinct stomatal behaviour shared between predominantly isohydric tree crops, creates an interesting scenario when examining E_c. It raises the question that if macadamias are predominantly isohydric, and display strict leaf level control of g_s under conditions of high VPD_{leaf}, would E_c respond in a similar fashion? This study suggests that this is exactly what happens in macadamias. Under conditions of non-limiting soil water, macadamia E_c increased linearly with air vapour pressure deficit (VPD_{air}) and reference evapotranspiration (ET_o) at low atmospheric evaporative demands (VPD_{air} < 0.8 kPa and ET_o <0.13 mm day^{-1}), but at higher atmospheric evaporative demands the rate of increase in macadamia E_c decreased, suggesting that macadamia E_c is a water supply controlled system. Supply controlled E_c implies that the rate of water supply to the leaves is lower than the atmospheric evaporative demand. It could be argued that a supply controlled system is synonymous with crops which follow a predominantly isohydric water management strategy, given that isohydricity largely stems from a hydraulic limitation within crops, which is managed through strict stomatal control of water loss. Nevertheless, responses of E_c to a range of weather variables were consistent between the orchards examined in this study.

Differences in the magnitude of E_c were observed between the two orchards examined. The distinguishing factor between the two orchards was canopy size, with trees in the mature bearing (MB) orchard being approximately double the size of trees, on a LAI basis, within the intermediate bearing (IB) orchard. The smaller trees in the IB transpired transpired approximately 50% less than the larger trees in the MB orchard when exposed to the same set of weather conditions, confirming that E_c is significantly influenced by canopy size. A similar situation was found when comparing the IB and NB orchards. This implies that in order to accurately model water use of macadamia orchards, both stomatal control over transpiration and canopy size need to be considered.

4.2 MODELLING MACADAMIA WATER USE

4.2.1 PARAMETERIZATION AND VALIDATION OF A CROP COEFFICIENT MODEL

Average transpiration crop coefficients (K_t) of the MB macadamia orchard (0.34), determined over two consecutive seasons, was approximately double that of the IB orchard (0.18). The large difference between the K_t values of the two orchards is mostly attributed to the large differences in canopy size, with trees in the IB orchard being approximately 60% smaller than those in MB orchard. A positive linear relationship ($R^2 = 0.71$) was also apparent between the daily K_t values of the MB and IB orchards obtained during the 2017/18 season (Figure 4.21 A). The slope of the linear regression equation can therefore be used as an indication of the fraction of E_c attributed to physical or physiological attributes of the crop. The slope of the relationship, being 0.62, would suggest that E_c of IB orchards is 62% that of the MB orchard due to differences in physical attributes of canopies.

Transpiration crop coefficients from both orchards varied substantially throughout the study period (Figure 4.21). In the MB orchard, K_t reached a maximum in March and April in the 2016/17 and 2017/18 seasons, with an average maximum K_t of 0.46. This was approximately double that of maximum K_t from the IB orchard during April of both the 2017/18 and 2018/19 seasons. In both orchards, K_t increased from a low in September to a seasonal maximum in April before again declining to a minimum in late August/beginning September of the following season. Considering that K_t normalizes for environmental conditions, increases in K_t from September to April during each season would suggest that increases in K_t follow increases in canopy size, given the fact that during this period, two vegetative flushes would have occurred. Similarly, the decrease in K_t from April to September would have been as a result of decreases in canopy size as a result of pruning. Although this cannot be ruled out in both these orchards, it should be noted that pruning only commenced in June of all of the seasons, yet substantial decreases in K_t were already evident from the end of April (Figure 4.21). These observed decreases in K_t also indicates that increases in E_c were not as rapid as the increases in ET_o, further emphasising that E_c in macadamias is more supply limited than demand limited under conditions of high ET_o. Supply limited E_c implies that the rate of water supply to the leaves is lower than the vapour pressure gradient out of the leaf, which is dictated by atmospheric evaporative demand.

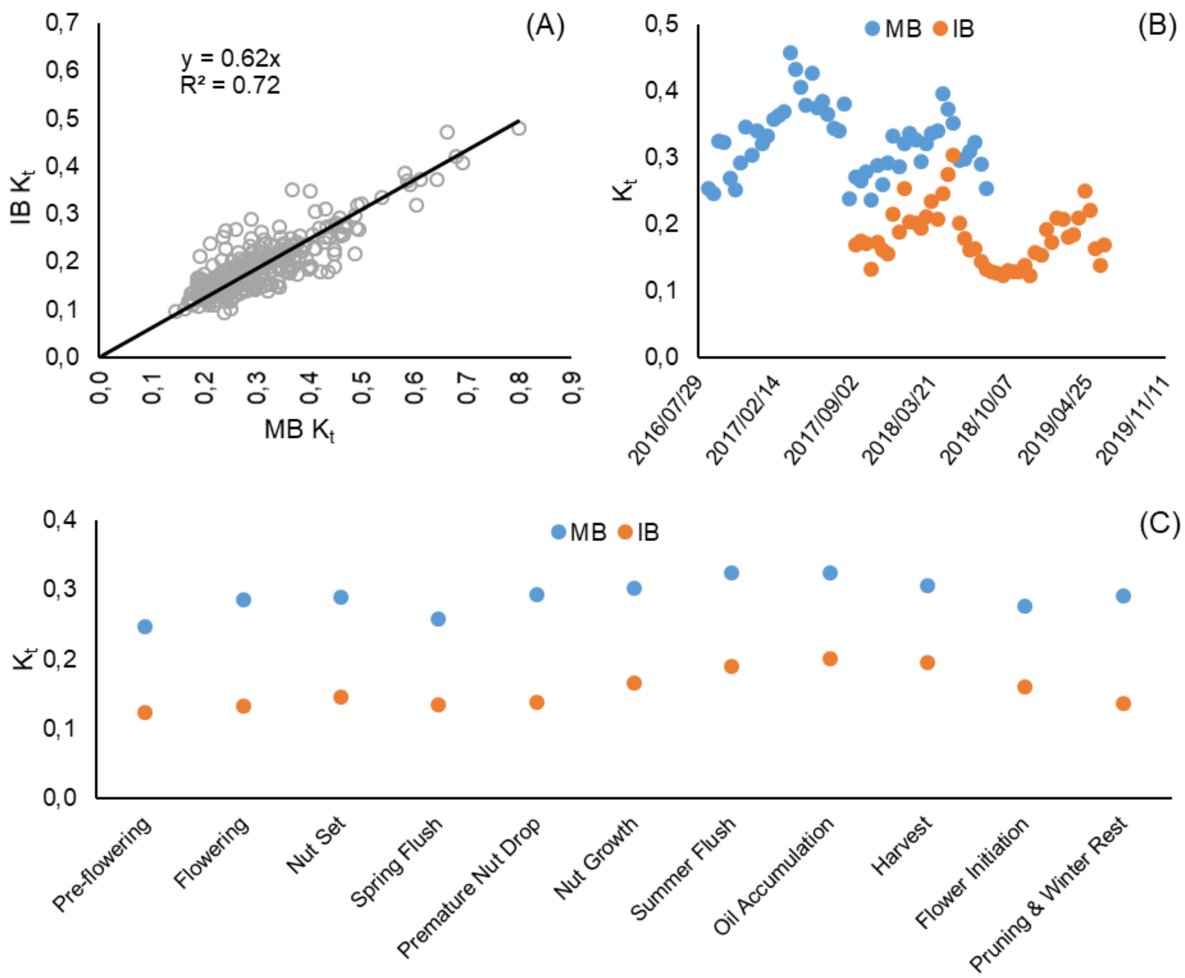


Figure 4.21: (A) Linear relationship between daily transpiration coefficients (K$_t$) of mature bearing (MB) and intermediate bearing (IB) macadamias determined during the 2017/2018 season. (B) Fortnightly averaged K$_t$ values for the MB and intermediate bearing IB macadamia orchards measured throughout the duration of the trial. (C) Average K$_t$ values for the MB and IB macadamia orchards determined during the respective phenological periods recorded throughout the duration of the trial.

The increases in K$_t$ from September to April of each season also roughly coincides with increases in nut growth and development, with increases in K$_t$ tending to reach a maximum just before harvest (April), before decreasing again directly after harvest. The increase in K$_t$ observed in both orchards during the fruit development phase (periods post premature nut drop to harvest), occurred without substantial increases in LAI (Figure 4.21) and throughout this period there was a continuous decline in ET$_o$, which would suggest that E_c increased more during these periods relative to increases in ET$_o$. These increases in E_c could therefore be mediated by increased stomatal and therefore also canopy conductance in the presence of developing fruit. These decreases in K$_t$ following harvest occurred before any physical reductions in canopy size were made. Directly following the harvest period (i.e. the flower initiation period), average K$_t$ over two consecutive seasons was 10% less in the MB orchard and 40% less in the IB orchard compared to K_t estimated during the harvest period, yet there was only a small difference in ET_o (3% lower during flower initiation) and LAI (2% lower during flower initiation) compared to the harvest period (Figure 4.18). This sudden reduction in K_t without significant reductions in canopy size could be indicative of physiological control over E_c during different phenological stages.

As a result of the need to take into account stomatal control over transpiration the approach of Allen and Pereira (2009) was tested in the mature and intermediate macadamia orchards. This approach adjusts crop coefficients for the size of the canopy (effective fractional cover and tree height), local weather condition that may differ from standard conditions and the degree of stomatal control over transpiration relative to most agricultural crops. Comparisons between measured and simulated daily K_t values obtained during the model parameterization and validation periods, using single r_{leaf} and r_s values (Table 3.10) are displayed in Figure 4.22 for the MB orchard and Figure 4.23 for the IB orchard. Poor parameterization and validation of daily K_t derived from the FAO-56 dual crop coefficient model was observed in both the MB (Figure 4.22) and IB orchard (Figure 4.23), with K_t being significantly overestimated by the model, as indicated by the model statistics. This suggests that the degree of stomatal control over transpiration is not constant over a season and may vary depending on the prevailing weather conditions, which influences the ratio of E_c to ET_o. This is not surprising given the response of g_s to VPD demonstrated in this study.

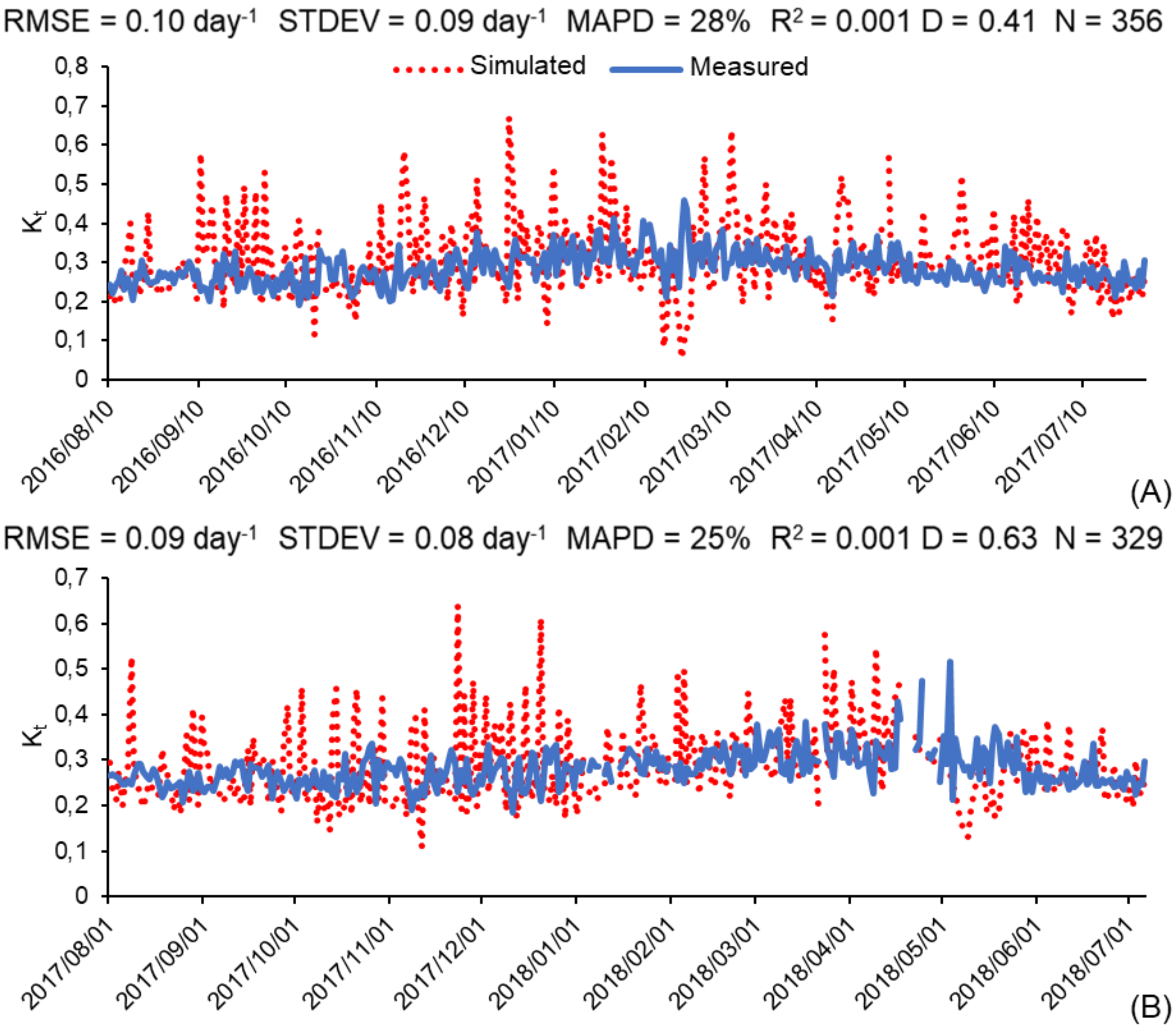


Figure 4.22: Comparison between daily measured and simulated transpiration crop coefficients (K_t) for the mature bearing (MB) orchard during the (A) parameterization and (B) validation of the FAO-56 dual crop coefficient model using a single r_{leaf} value. Missing data is due to missing solar radiation data as a result of equipment failure.

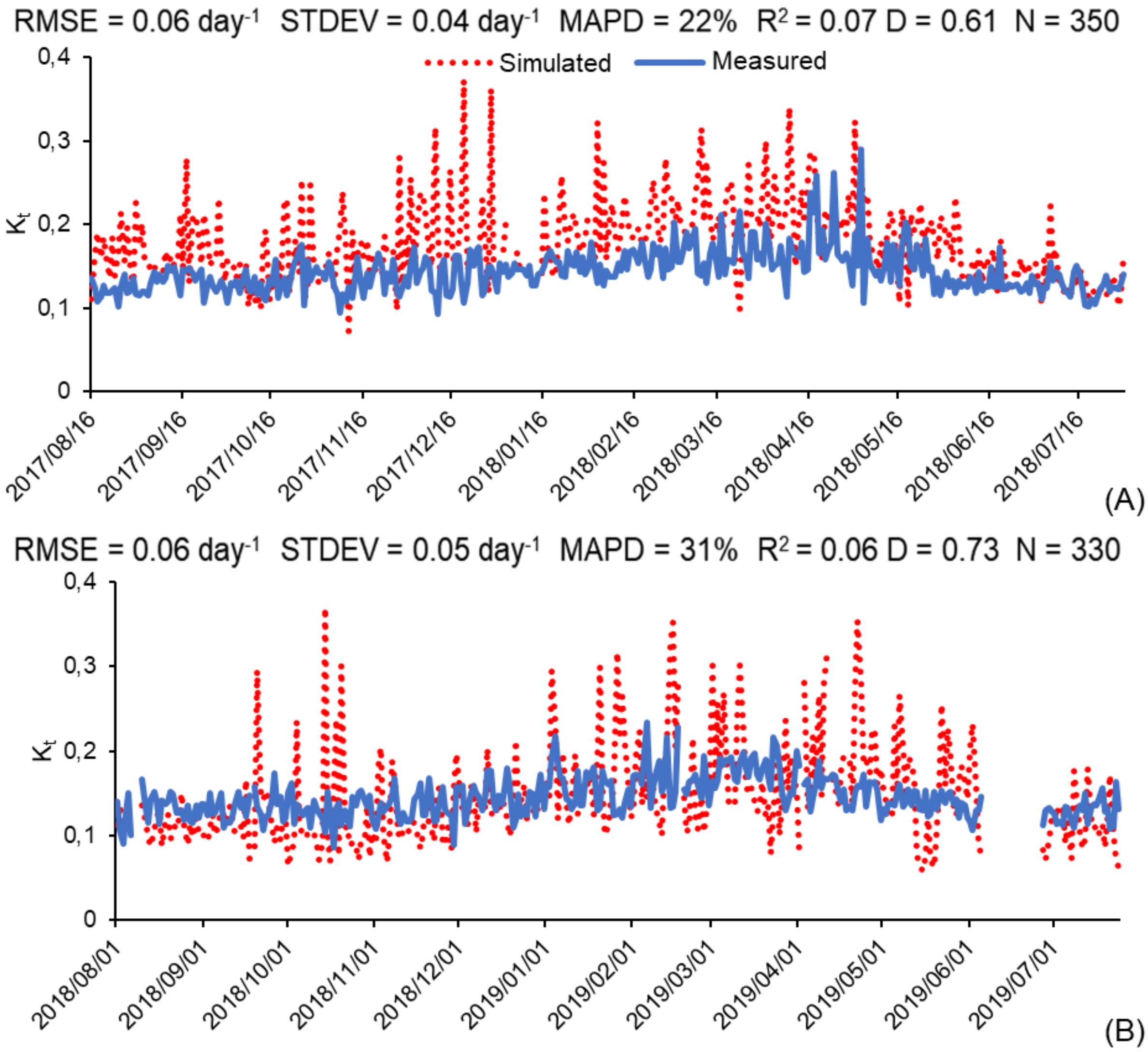


Figure 4.23: Comparison between daily measured and simulated transpiration crop coefficients (K_t) for the intermediate bearing (IB) orchard during the (A) parameterization and (B) validation of the FAO-56 dual crop coefficient model using a single r_s value. Missing data is due to missing solar radiation data as a result of equipment failure.

In both orchards RMSE, R^2, MAPD and D observed between measured and simulated daily K_t were outside the criteria of acceptability for model validation and parameterization (RMSE > half the standard deviation of the measured data, MAPD >20% and R^2 and D below 0.8). As expected, the poor parameterization of the FAO-56 dual crop coefficient model to simulate daily K_t, whilst using a single seasonal r_{leaf} and r_s value, resulted in equally poor estimates of daily E_c in the MB (Figure 4.24) and IB (Figure 4.25) macadamia orchards during the parameterization and validation phases.

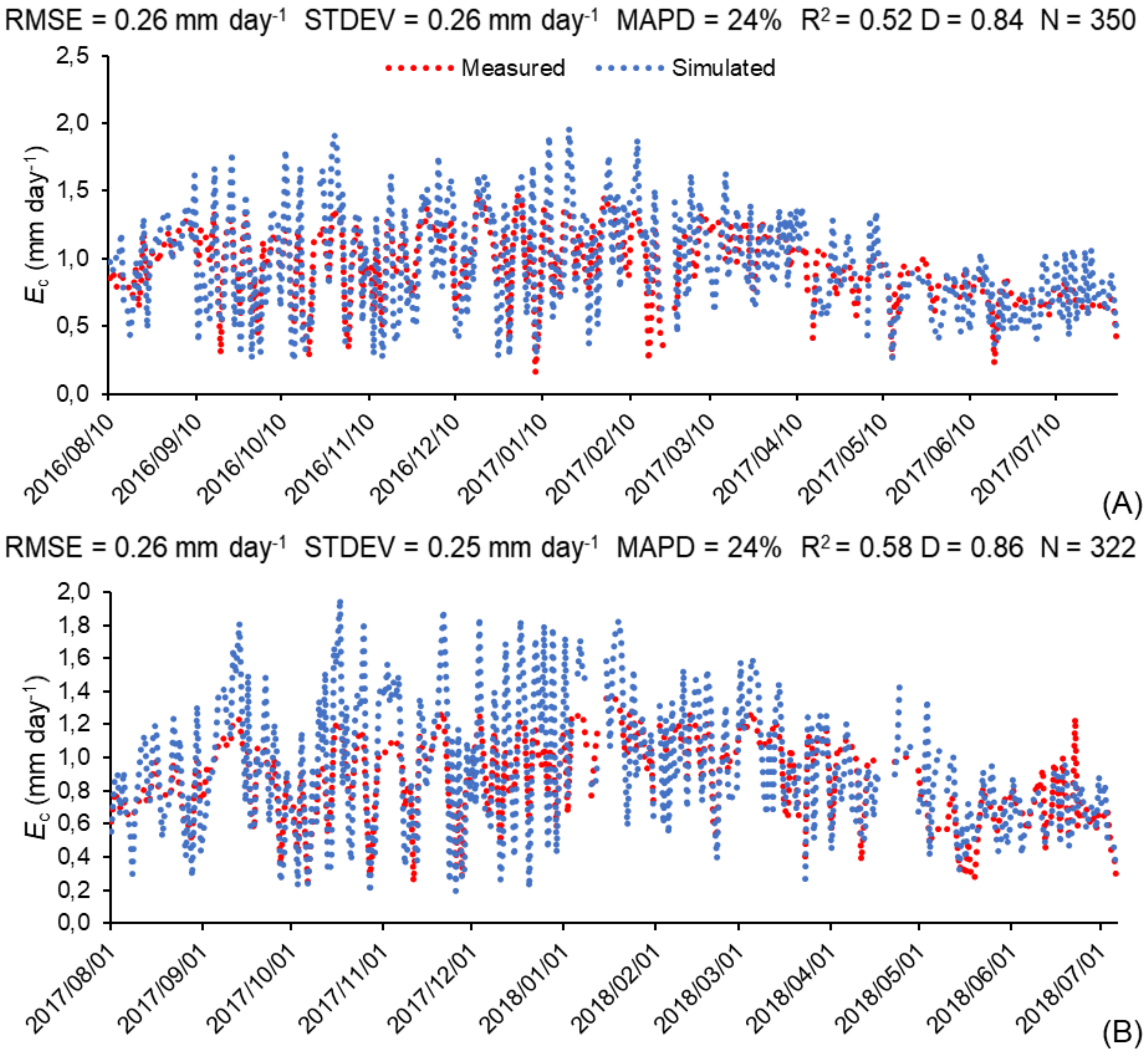


Figure 4.24: Comparison between daily measured and simulated transpiration (*E_c*) for the mature bearing (MB) orchard during the (A) parameterization and (B) validation of the FAO-56 dual crop coefficient model using a single r_{leaf} value. Missing data is due to missing solar radiation data as a result of equipment failure.

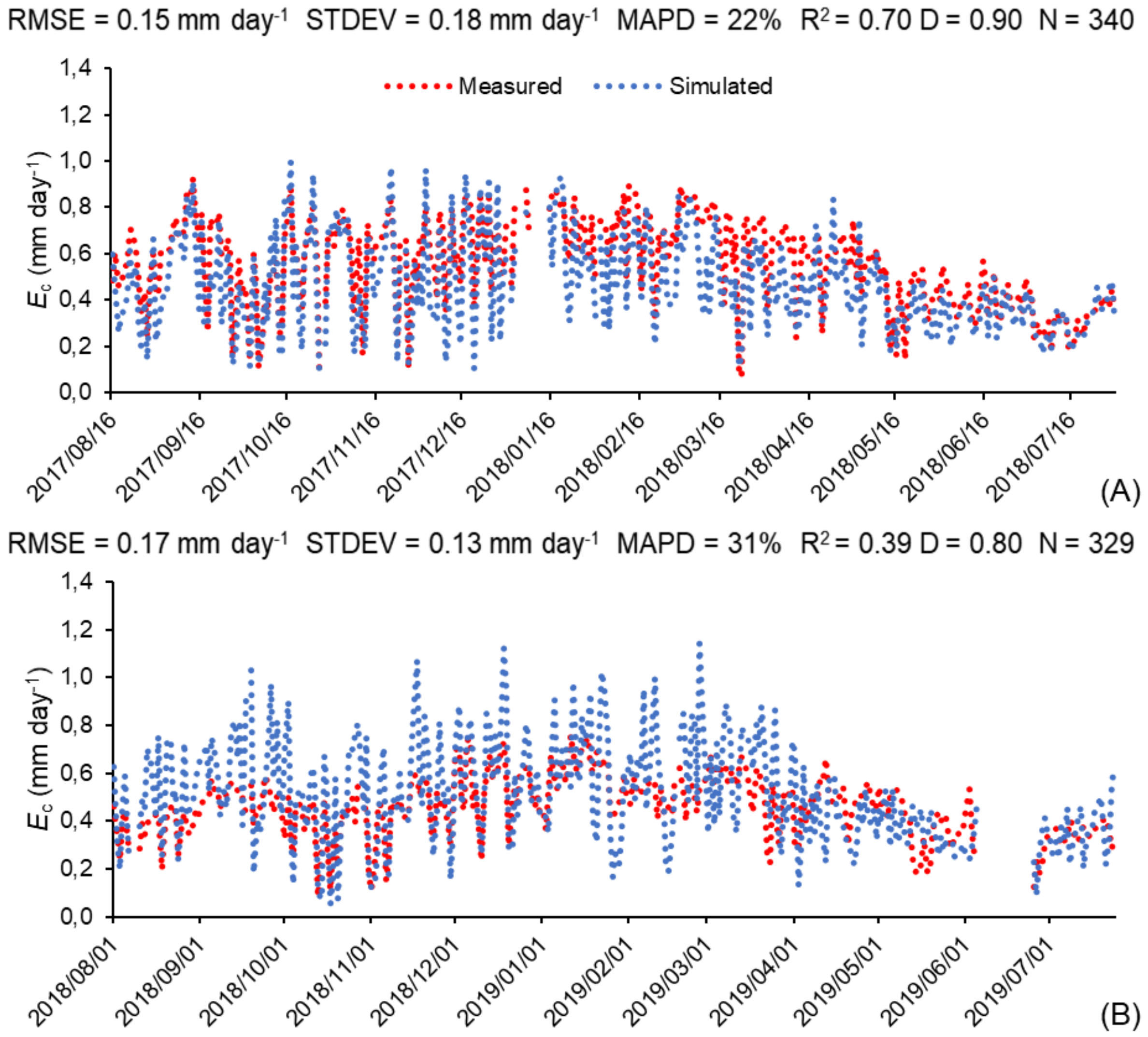


Figure 4.25: Comparison between daily measured and simulated transpiration (*E*c) for the intermediate bearing (IB) orchard during the (A) parameterization and (B) validation of the FAO-56 dual crop coefficient model using a single r_s value. Missing data is due to missing solar radiation data as a result of equipment failure.

In both orchards, model criteria when using a single r_{leaf} and r_s value, were not met for comparisons between measured and simulated daily E_c during both the model parameterization and validation phase. RMSE was outside the stipulated criteria during both the parameterization and validation phase, which suggest that standard deviation between the measured and simulated values of daily E_c in each of the data sets used was rather high. The largest discrepancies between the measured and simulated daily K_t and E_c largely stem from the underestimation of both daily K_t and E_c at low ET_o (<2.5 mm day^{-1}) and overestimation of K_t and E_c at high ET_o (>4.0 mm day^{-1} in the MB orchard and >4.5 mm day^{-1} in the IB orchard) (Figure 4.26 A-D).

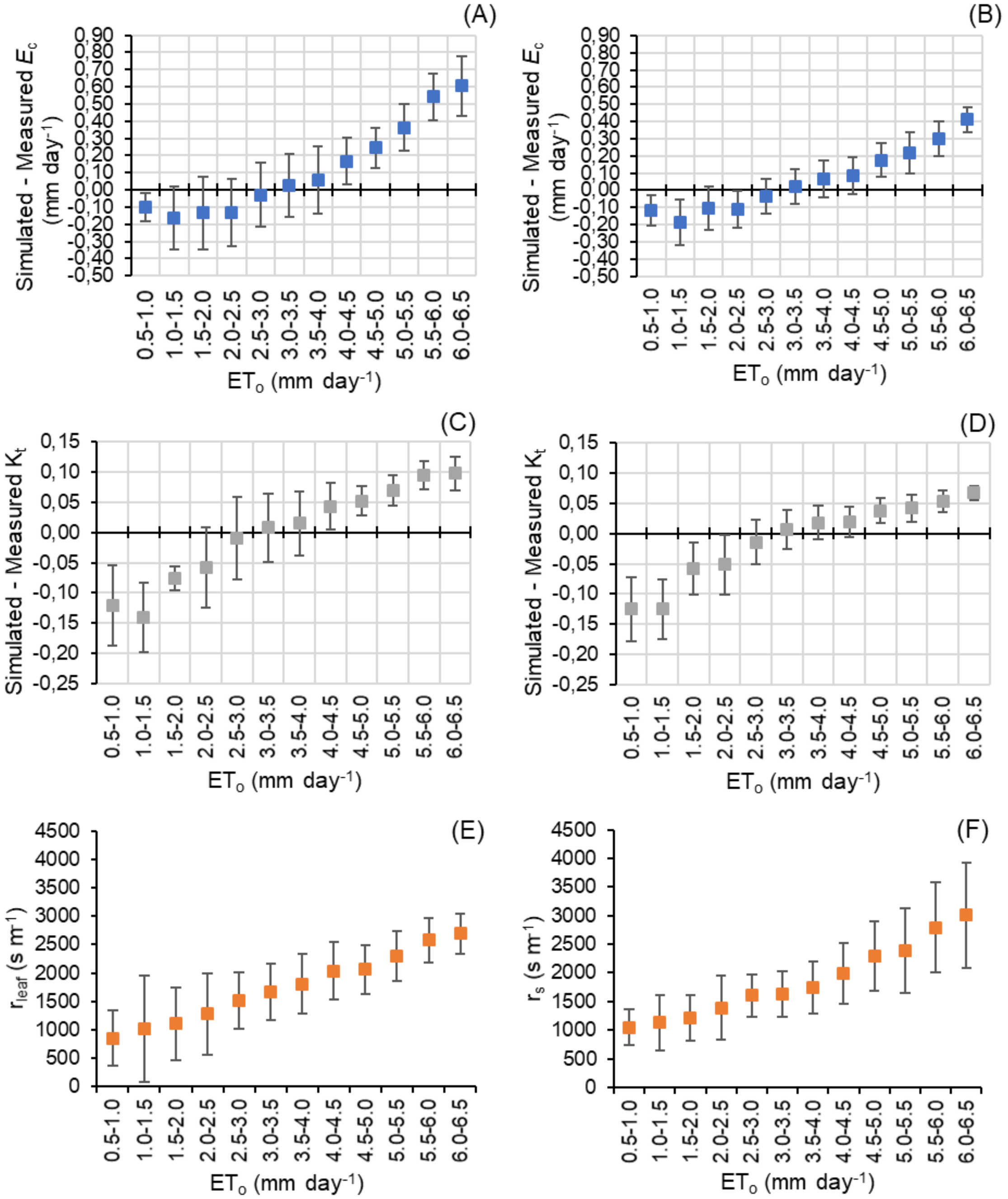


Figure 4.26: Average (± standard deviation) difference between simulated and measured daily transpiration (E_c) and daily transpiration crop coefficients (K_t) throughout a range of daily reference evapotranspiration (ET_o) rates for the mature bearing (MB) (A, C) and intermediate bearing (IB) (B, D) orchards during model validation of the FAO-56 dual crop coefficient model. Average (± standard deviation) of calculated (E) leaf resistance (r_{leaf}) for the mature bearing (MB) orchard and (F) surface resistance (r_s) using Equations [29] and [30] for the intermediate bearing (IB) orchard in response to a range of ET_o

Poor model performance on a daily basis was, however, expected seeing that the major assumption of the FAO-56 approach is that E_c is a demand limited process, whilst in macadamia E_c is more a supply limited process, with maximum E_c reached when ET_o exceeds

3.5 mm day^{-1}. Therefore, on days where ET_o exceeded 3.5 mm day^{-1}, daily simulated macadamia E_c would be overestimated, as measured E_c, would have increased at the same rate as ET_o and would rather remain either constant or even decline slightly. Similarly, on days where ET_o was less than 2.5 mm day^{-1}, simulated macadamia E_c was slightly underestimated in relation to measured E_c. This was confirmed in both macadamia orchards (Figure 4.26 C & D), with large differences observed between simulated and measured K_t at ET_o <2.5 mm day^{-1}.

Although the discrepancies between measured and simulated daily K_t and E_c could be due to a range of factors, this is most likely due to the use of a single average value of r_{leaf} and r_s for the entire validation period. Calculated r_{leaf} and r_s for macadamias in this study revealed that although an approximate linear relationship exists between ET_o and either calculated r_{leaf} or r_s, a large amount of variability in calculated r_{leaf} and r_s was observed throughout the range of daily ET_o (Figure 4.26 E-F). A substantial amount of variability is therefore lost in the averaging of r_{leaf} values across a season, as is the case when using a single seasonal value. Multiple estimates of r_{leaf} were therefore tested in an attempt to improve model accuracy. The results from this analysis are presented in Table 4.10 and Table 4.11.

In both the MB and IB orchards the use of multiple r_{leaf} and r_s values failed to improve the accuracy of the FAO-56 dual crop coefficient model to simulate daily values of both K_t and E_c. Although multiple values tended to decrease MAPD and increase R^2, RMSE and D remained similar and were unsatisfactory for modelling purposes. The high RMSE in the model parameterization and validation of K_t and E_c, in both the MB and IB orchards, tend to suggest that data points obtained from the model simulation were not well concentrated around the line of best fit. Nevertheless, results presented would suggest that the FAO-56 dual crop coefficient model could not be successfully parameterized and would subsequently lead to poor estimations of daily values of both K_t and E_c of independent data sets.

Table 4.10: Statistical evaluation of the FAO-56 dual crop coefficient model during model parameterization and validation of daily transpiration coefficients (K_t) and daily transpiration (E_c) using single and multiple values of leaf resistance (r_{leaf}) calculated for the mature bearing (MB) macadamia orchard (Table 7.2). Statistical parameters include the number of observations used (*N*), root mean square error (RMSE), mean absolute percentage difference (MAPD) index of agreement (D) of Willmott (1982), and coefficient of determination (R^2).

	Mature Bearing Macadamia Orchard									
	Parameterization K_t					Validation K_t				
	N	RMSE	MAPD (%)	D	R^2	*N*	RMSE	MAPD (%)	D	R^2
Single	353	0.10	28	0.47	0.001	329	0.09	25	0.64	0.001
Two	353	0.10	28	0.47	0.001	329	0.09	25	0.63	0.001
Quarterly	353	0.10	27	0.47	0.001	329	0.09	25	0.61	0.01
Monthly	353	0.10	26	0.53	0.03	329	0.10	27	0.60	0.01
	Parameterization E_c					Validation E_c				
	N	RMSE (mm day^{-1})	MAPD (%)	D	R^2	*N*	RMSE (mm day^{-1})	MAPD (%)	D	R^2
Single	350	0.26	24	0.84	0.52	322	0.26	24	0.86	0.59
Two	350	0.26	24	0.84	0.53	322	0.27	24	0.86	0.58
Quarterly	350	0.26	24	0.84	0.50	322	0.27	25	0.85	0.55
Monthly	350	0.25	23	0.85	0.54	322	0.29	26	0.84	0.52

Table 4.11: Statistical evaluation of the FAO-56 dual crop coefficient model during model parameterization and validation of daily transpiration coefficients (K_t) and daily transpiration (E_c) using single and multiple values of bulk canopy resistance (r_s) calculated for intermediate bearing (IB) macadamia orchard (Table 7.2). Statistical parameters include the number of observations used (N), root mean square error (RMSE), mean absolute percentage difference (MAPD), index of agreement (D) of Willmott (1982), and coefficient of determination (R^2).

	Intermediate Bearing Macadamia Orchard									
	Parameterization K_t					Validation K_t				
	N	RMSE	MAPD (%)	D	R^2	*N*	RMSE	MAPD (%)	D	R^2
Single	350	0.07	22	0.60	0.07	330	0.06	32	0.72	0.04
Two	350	0.07	22	0.60	0.07	330	0.06	32	0.72	0.04
Quarterly	350	0.06	22	0.60	0.07	330	0.06	32	0.73	0.06
Monthly	350	0.06	22	0.61	0.07	330	0.06	31	0.74	0.06
	Parameterization E_c					Validation E_c				
	N	RMSE (mm day^{-1})	MAPD (%)	D	R^2	*N*	RMSE (mm day^{-1})	MAPD (%)	D	R^2
Single	340	0.14	22	0.90	0.70	329	0.17	32	0.81	0.35
Two	340	0.13	22	0.90	0.70	329	0.17	32	0.81	0.35
Quarterly	340	0.14	22	0.90	0.70	329	0.17	32	0.80	0.37
Monthly	340	0.15	22	0.90	0.70	329	0.18	32	0.81	0.39

From the results, it is clear that the large daily variation in r_{leaf} and r_s, in relation to ET_o, leads to poor performance of the FAO-56 dual crop coefficient model to simulate daily K_t and E_c. Seeing that poor model performance was observed on a daily time step, the accuracy of the FAO-56 dual crop coefficient model was assessed on longer time steps (i.e. monthly or seasonally). Accurate estimates of monthly or seasonal K_t and E_c would allow for the FAO-56 dual crop coefficient model to be used as a strategic irrigation planning and water licencing tool in macadamias. A single value of r_{leaf} and r_s (Table 3.10) was therefore used in conjunction with monthly and seasonally averaged ET_o and RH_{min} to determine monthly and seasonal estimates of K_t. Monthly and seasonal E_c was estimated by using monthly and seasonal totals of ET_o and multiplying these totals with derived K_t values for each of the respective periods. The comparisons between monthly and seasonally measured and simulated K_t and E_c, using a single value of r_{leaf} and r_s, is presented in Figure 4.27 for the MB and Figure 4.28 for the IB orchard.

Monthly and seasonally measured and simulated K_t and E_c showed a substantial increase in accuracy compared to simulations on a daily basis. In both the MB and IB orchard all statistical criteria were met, and differences between measured and simulated K_t and E_c were relatively small. The substantial increases in accuracy observed at this time scale, is largely attributed to compensatory errors, which ultimately mask any under or overestimations observed on a daily basis. For example, average ET_o throughout the entire measurement period ranged from 2.5 mm day^{-1} in winter to 4.0 mm day^{-1} summer, which is within the ET_o range where the model simulated K_t and E_c most accurately (Figure 4.26).

Regardless of increased model accuracy, the FAO-56 dual crop coefficient model slightly underestimated both K_t and E_c on a monthly and seasonal basis in the MB orchard. In contrast, the model slightly overestimated K_t and E_c in the IB orchard from July to December and slightly underestimated both K_t and E_c from January to May during the period of model validation. In both the MB and IB orchards K_t and E_c were consistently underestimated during autumn (March-April), a period which coincides with nut maturation and oil accumulation, which has been shown to cause an upregulation in E_c unrelated to increases in ET_o. In this study the model underestimated E_c during the autumn period by 4.0 mm in the MB orchard and 2.5 mm in the IB orchard. Although a single value of r_{leaf} and r_s was used in these assessments, it should be noted that both r_{leaf} and r_s was substantially lower in April (Table 3.10) compared to the single r_{leaf} and r_s used in the assessment. Substituting only r_{leaf} and r_s in April, with lower values (Table 3.10) resulted in less of an underestimation in both E_c and K_t (data not shown). Lower r_{leaf} and r_s values during April would lead to increases in F_r, $K_{t\,full}$ and subsequently K_t

and E_c. Decreases in r_{leaf} and r_s in April implies that an upregulation in stomatal conductance occurs during this period, which was reported in this study.

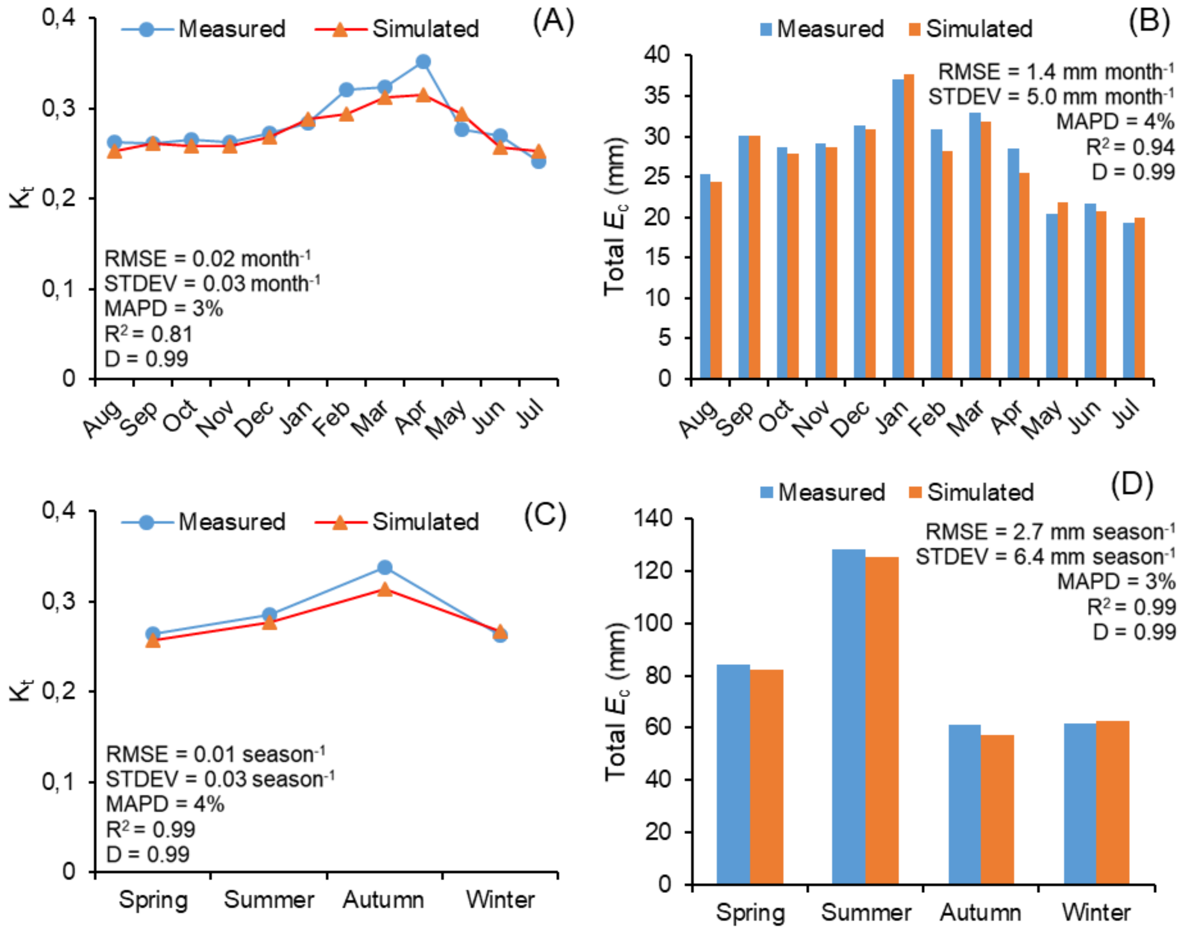


Figure 4.27: Comparison between monthly (A, B) and seasonally (C, D) measured and simulated transpiration crop coefficients (K_t) and transpiration (E_c) for the mature bearing (MB) orchard during the model validation phase (2017/08/01-2018/07/31) of the FAO-56 dual crop coefficient model using a single r_{leaf} value

Regardless of the slight variances between measured and simulated values of K_t and E_c, the FAO-56 dual crop coefficient model by Allen and Pereira (2009) provided fairly accurate estimates of both K_t and E_c on a monthly or seasonal basis. Total E_c measured in the MB orchard during the period of model validation (2017/08/01-2018/07/31) was 335 mm and was only 8 mm more than that simulated using the FAO-56 dual crop coefficient model (327 mm). In the IB orchard the total measured seasonal E_c differed by 1 mm from that of the simulated value, being 170 mm measured compared to the 171 mm simulated by the model. This analysis of the FAO-56 dual crop coefficient model would therefore suggest that poor model performance is to be expected if the model is to be used for daily estimates, but model performance is satisfactory if used for estimates of monthly or seasonal K_t and E_c.

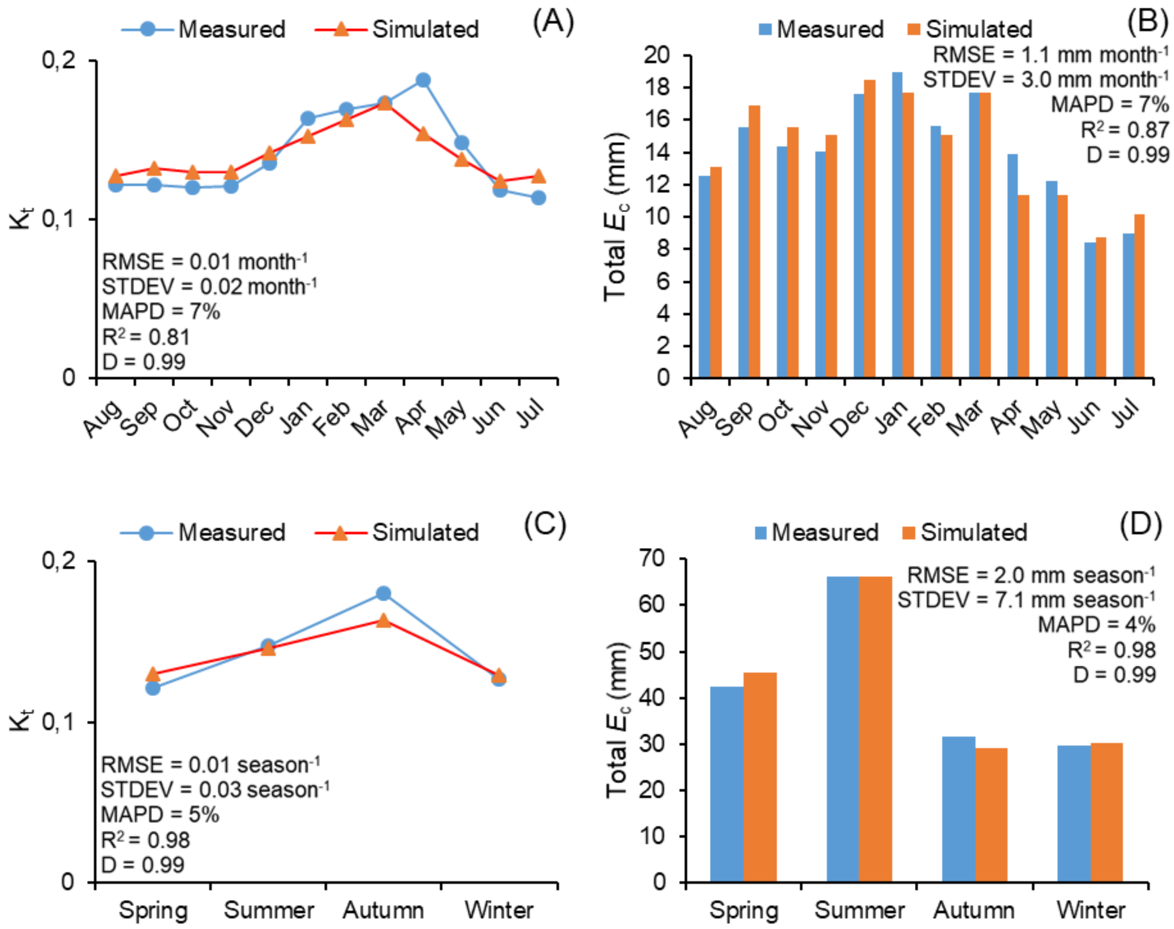


Figure 4.28: Comparison between monthly (A, B) and seasonally (C, D) measured and simulated transpiration crop coefficients (K_t) and transpiration (E_c) for the intermediate bearing (IB) orchard during the model validation phase (2018/08/01-2019/07/31) of the FAO-56 dual crop coefficient model using a single r_s value.

4.2.2 PARAMETERIZATION 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

The successful use of the Penman-Monteith equation to estimate E_c requires reliable measurements or estimates of both g_a and g_c. Calculated g_a throughout the duration of the trial, yielded a daytime (08:00 to 17:00) average value of 75 ± 31 mm s^{-1} in the MB orchard and 37 ± 19 mm s^{-1} in the IB orchard. These values, although high, were similar to values of g_a measured (average 68 mm s^{-1}) during a window period of eddy covariance measurements in the MB orchard when using windspeed above the canopy and friction velocity determined using the 3D sonic anemometer, as described by Kumagai et al. (2004). Average daytime (08:00 to 17:00) calculations of g_c, using the Penman-Monteith equation during the model parameterization period (2016/09/15-2017/01/15), were rather low (0.7 mm s^{-1} in the MB orchard), with the absolute maximum calculated g_c obtained during this period being 1.2 mm s^{-1} in the MB orchard. Following the successful parameterization of the Jarvis-type g_c model (Equation [34]), it was determined that maximum g_c ($g_{c\ max}$) in the MB orchard was 1.2 mm s^{-1} (Table 4.12). Maximum calculated and parameterized values of g_c were similar, implying that $g_{c\ max}$ obtained through least squares regression analysis was a fair measure of maximum g_c. Both maximum and average calculated g_c values were substantially lower than those reported by Villalobos et al. (2013) 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}). These low g_c values calculated for macadamia mostly stems from the low E_c rates recorded in both MB and IB orchards in this study, compared to these crops.

Table 4.12: Optimised parameters for Equation [34] to Equation [38] used to model canopy conductance (g_c). Parameters were generated through non-linear least squares regression analysis using data from the mature bearing (MB) macadamia orchard.

Parameter	Value
$g_{c\ max}$ (mm s^{-1})	1.2076
k_{D1} (kPa)	-0.1377
k_{D2} (kPa)	-0.3178
k_T (°C)	22.54
k_R (W m^{-2})	17.83
R^2	0.83

Estimated (calculated from the inverted Penman-Monteith equation) daytime average g_c across the study period was 0.7 mm s^{-1} in the MB orchard, and 0.3 mm s^{-1} in the IB orchard, and were similar to average modelled g_c. Although the Jarvis-Steward g_c (Equation [34]) model provided satisfactory estimates of g_c during the model parameterization phase (Figure 4.29 A), model acceptability criteria were not met during the validation phase in both orchards (Figure 4.29 B & C). The discrepancies between simulated and measured g_c, largely stems from the observed seasonal variation of measured g_c (Figure 4.29 D & E). Measured g_c reached a maximum during summer, where after g_c declined gradually from the end of

February until reaching a minimum in winter (Figure 4.29 D & E). The seasonal variation in measured g_c is, however, expected given that both R_s and T_{air} are lower, and VPD_{air} is slightly higher during the winter months compared to summer months (Figure 4.29 F).

Modelled g_c tended to follow a similar seasonal trend, but some discrepancies between measured and modelled g_c were evident throughout the trial. In the MB orchard, there was a substantial overestimation of g_c from May to October, which coincides with significant changes in canopy size, as a result of pruning, as well as physiological changes brought about by fruit removal. In April, a period where E_c was shown to be significantly higher without significant increases in canopy size and atmospheric evaporative demand, g_c was underestimated by ~20%. Similar results were observed in the IB orchard during the April period. The model, however, tended to underestimate g_c from March-May and October-December, whilst overestimating g_c in the July-August period. In the IB orchard, the discrepancies between measured and modelled g_c was largely attributed to increases and decreases in canopy size. These observations imply that g_c is sensitive to changes in LAI, and $g_{c\ max}$ would need adjustment throughout the season in order to obtain accurate estimates of g_c in macadamias.

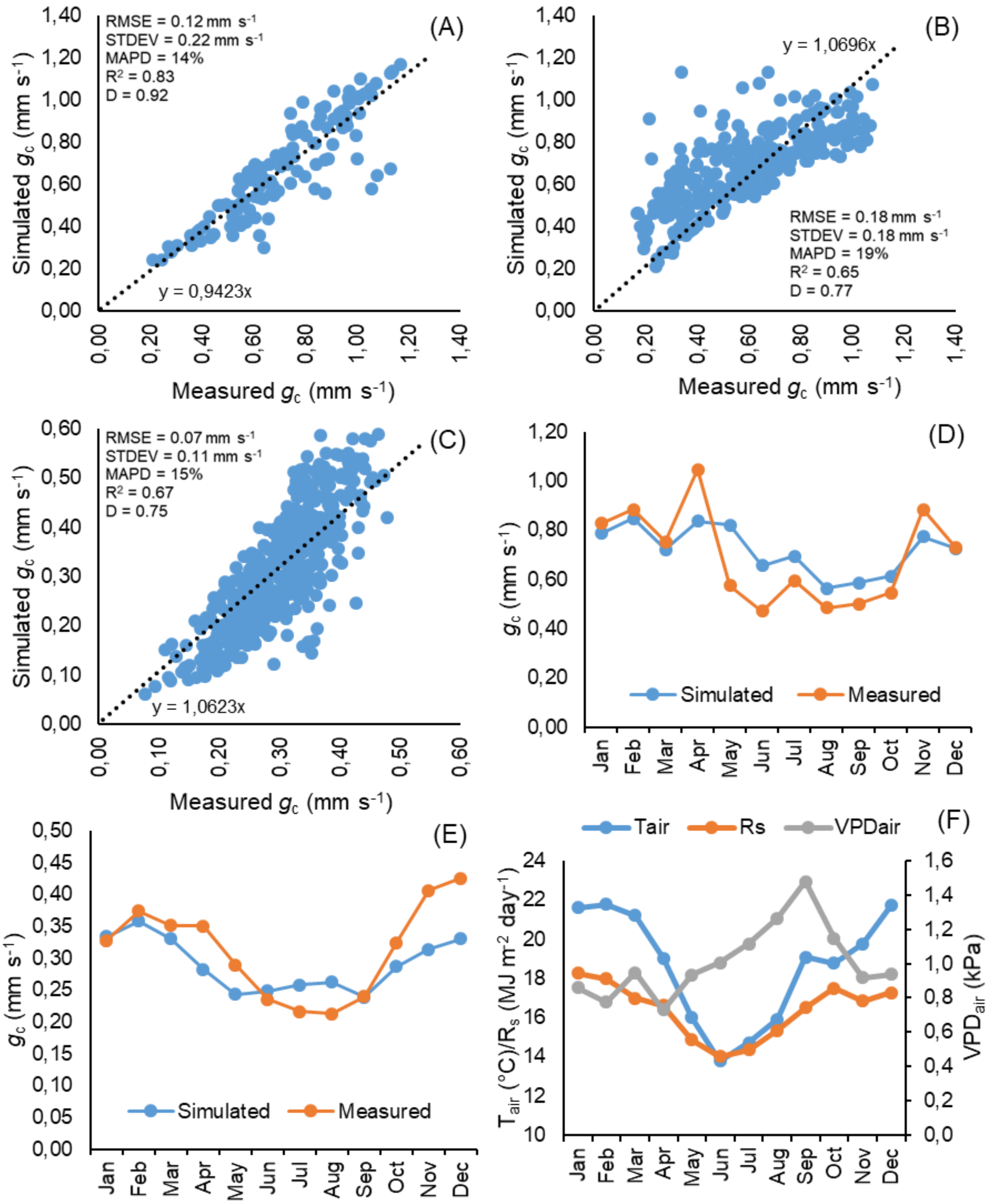


Figure 4.29: Hourly measured (calculated by inverting the Penman-Monteith equation) and simulated (using Equation [34]) daily averaged canopy conductance (g_c) for the mature bearing (MB) orchard during the (A) model parameterization phase (2016/09/15-2017/01/15), (B) validation phase (2017/08/16-2018/08/06) and (C) during the model validation phase (2017/09/30-2019/04/30) in the intermediate bearing (IB) orchard. Average monthly measured and simulated g_c in the (D) MB and (E) IB orchard and (F) monthly average weather variables including air temperature (T_{air}), solar radiation (R_s) and air vapour pressure deficit (VPD_{air}).

Nevertheless, due to the low g_c measured for macadamias in this study, especially in relation to the high estimated g_a, the average calculated decoupling coefficient (Ω) (Jarvis & McNaughton, 1986) for both orchards in this study equalled 0.08. This would imply that macadamia canopies are well coupled to the atmosphere. The strong degree of coupling observed in this study, is characteristic of tall, rough crops, where windspeed is sufficient to cause sufficient mixing of the atmosphere resulting in high g_a (Jarvis and McNaughton, 1986). This has been demonstrated in a range subtropical fruit tree crops, with Ω <0.15 in citrus (Marin and Angelocci, 2011, Marin et al., 2016) and olive (Tognetti et al., 2009). Similar results have also been for macadamia, with Ω reported by Ibraimo (2018) being <0.25. Well coupled canopies would suggest that g_c responds to bulk atmospheric conditions, which is evident from Figure 4.29, and would imply that changes in g_c would result in changes in E_c. The response of E_c to varying atmospheric conditions, should therefore be similar to the response of g_c to the same set of atmospheric conditions.

Based on results from this study, failing to account for the effect of LAI on g_c, would lead to decreased accuracy in simulations of E_c. This was evident in this study, with estimated total daily E_c using unadjusted $g_{c\ max}$ in combination with the Penman-Monteith equation (Equation [31]), yielding a good correlation between measured and simulated E_c in the MB orchard during the model parameterization phase (Figure 4.30 A). However, when $g_{c\ max}$ was left unadjusted during the model validation phase (2017/08/16-2018/08/06), the model failed to produce acceptable estimations of E_c in the MB orchard (Figure 4.30 B). Poor model performance was largely as a result of overestimations of E_c during spring (August-September 2017) and winter periods (June-July 2018). Similar results were found for the IB orchard (Figure 4.31).

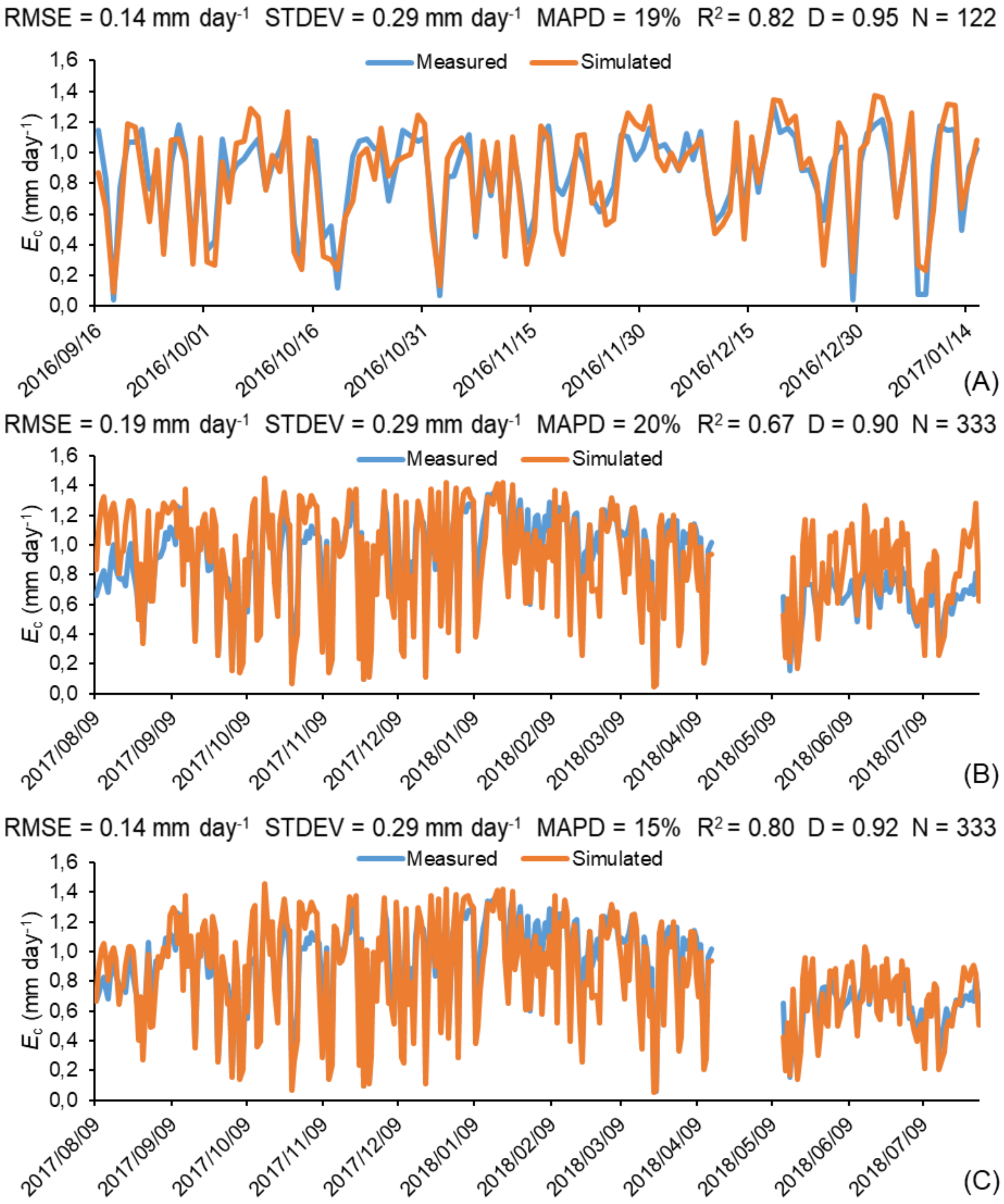


Figure 4.30: Comparison between hourly measured and simulated, transpiration (E_c) totalled on a daily basis, for the mature bearing (MB) orchard during the (A) parameterization phase (2016/09/15-2017/01/15) and validation (2017/08/16-2018/08/06) phase of the canopy conductance model using an (B) unadjusted and (C) adjusted maximum canopy conductance ($g_{c\ max}$). Missing data is due to missing solar radiation data as a result of equipment failure

These overestimations in the MB orchard most likely stem from the overestimation of $g_{c\ max}$ for these periods, which in turn was linked to a decrease in LAI compared to that used during the model parameterization phase. Average LAI during the model parameterization phase was 5.4 $m^2\ m^{-2}$ compared to 4.3 $m^2\ m^{-2}$ before spring of 2017, and 4.4 $m^2\ m^{-2}$ during the winter of 2018. The decrease in LAI observed in the MB orchard was as a result of pruning, with the intention of increasing radiation penetration into canopies, whilst also reducing tree height. Parameterization, of especially $g_{c\ max}$, during the period when LAI was higher could therefore have resulted in a higher $g_{c\ max}$, as a result of the higher E_c linked to the higher LAI, thereby leading to an overestimation during spring and winter in the MB 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). The importance of accounting for canopy size in the $g_{c\ max}$ estimate was confirmed, as adjusting $g_{c\ max}$ using LAI (Equation [41]) lead to increased model accuracy (Figure 4.30 C), with RMSE being 0.14 mm day^{-1}, R^2>0.8 and D>0.9, which were all well within the modelling acceptability criteria.

The IB orchard had LAI of 1.8 $m^2\ m^{-2}$ during the 2017-2018 season and an average LAI of 2.2 $m^2\ m^{-2}$ during the 2018-2019 season and following downward adjustment of $g_{c\ max}$, which equalled the LAI ratio between the MB and IB orchard, the model provided reasonable estimates of E_c for the IB orchard over the two model validation periods (Figure 4.31 A & B). During the first validation phase (2017/09/30-2018/07/31), all statistical criteria for acceptable model accuracy were met, with RMSE being 0.07 mm day^{-1} and both R^2 and D exceeding 0.8. During the second validation phase (2018/08/10-2019/04/30) RMSE and R^2 were, however, outside of the specified criteria. The largest variation between simulated and measured E_c in the IB orchard was observed from the start of January 2019 to the end of April 2019. Although no noticeable changes in LAI occurred at this time, the period coincided with the oil filling and nut maturation. Variable stomatal and transpirational responses to environmental variables have been demonstrated in this study, which would imply that model performance would be influenced by physiological changes unaccounted for by model parameters. The removal of this specific period from the model validation phase in the IB orchard led to a substantial increase in statistical parameters, with RMSE decreasing to 0.07 mm day^{-1} and both R^2 and D exceeding 0.8.

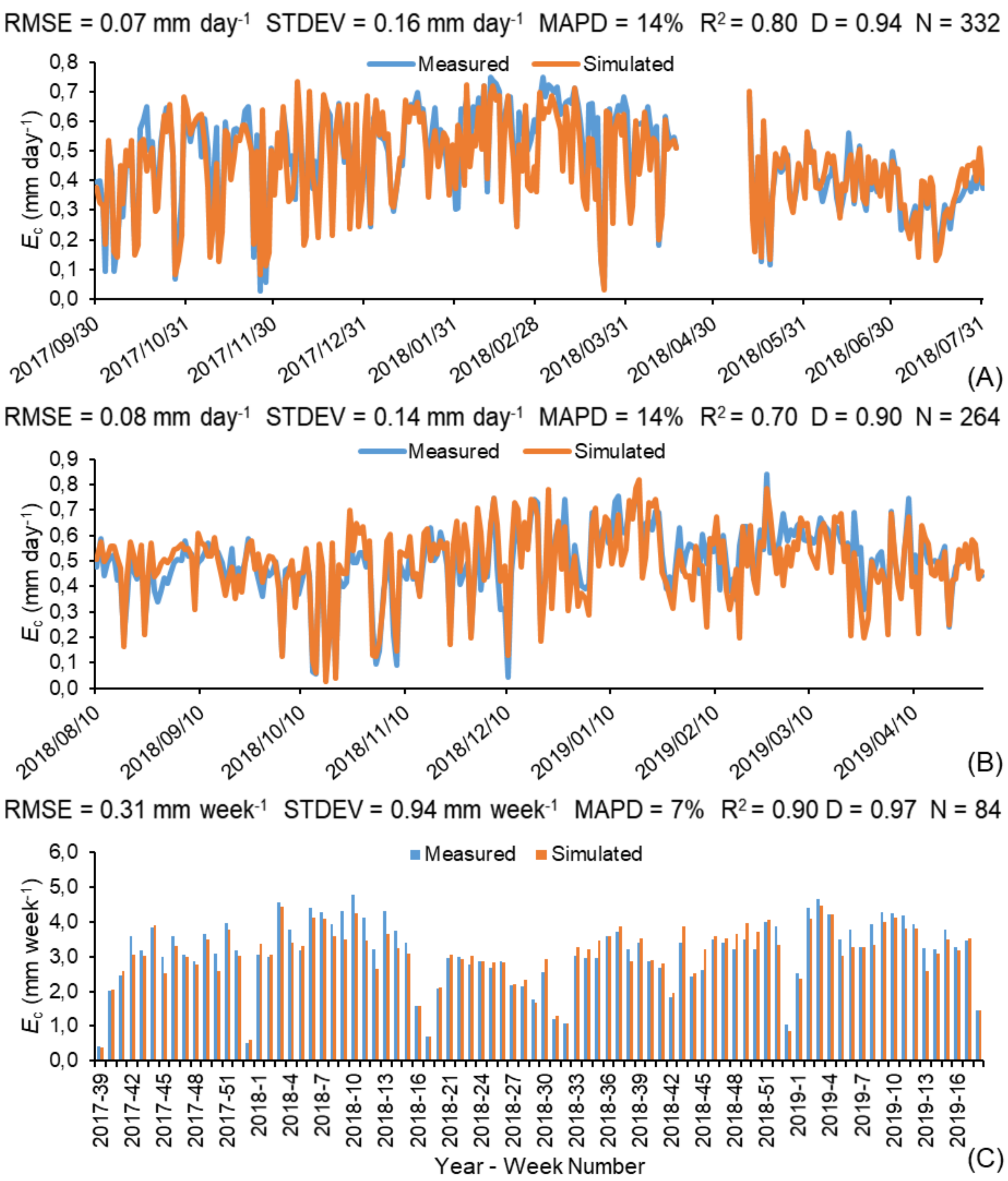


Figure 4.31: Comparison between hourly measured and simulated transpiration (E_c) totalled on a daily basis, for the intermediate bearing (IB) orchard during the (A) first validation (2017/09/30-2018/07/31) and (B) second validation (2018/08/10-2019/04/30) phase and (C) hourly measured and simulated weekly totalled transpiration (E_c) throughout both validation periods of the canopy conductance model using adjusted maximum canopy conductance ($g_{c\ max}$). Missing data is due to missing solar radiation data as a result of equipment failure

Seeing that similar discrepancies between measured and simulated E_c were found during the January 2018-March 2018 period in both the MB (Figure 4.30) and IB (Figure 4.31) orchards, it was proposed that the removal of these periods from the model validation period would lead to increased model performance. The removal of these periods, only led to a slight improvement in statistical parameters in both the MB and IB orchard (data not shown), which was largely as a result of missing hourly solar radiation data during April 2018, which is a period during which the model tends to significantly underestimate g_c (Figure 4.29). Given that improvements in model accuracy were achieved by removing the January-April periods from analysis, the error in estimated E_c during this period is most probably linked to poor estimates of g_c, which was attributed to physiological upregulation of g_s which was not accounted for during parameterisation of the g_c model.

The accuracy of the g_c model in the IB orchard was also improved once hourly estimated E_c values were totalled on a weekly basis, with RMSE being 0.31 mm week^{-1}, and both R^2 and D exceeding 0.9. Accurate estimates of E_c over a weekly period provide irrigators with sufficient information to assess irrigation practices retrospectively and make adjustments accordingly in the following week. Although accurate estimates of E_c could be achieved using the Penman-Monteith (Monteith and Unsworth, 1990) equation, it required accurate estimates of both g_c and g_a. In this study reasonable estimates of g_c could be obtained in two orchards of varying canopy size using the Jarvis (1976) model, provided that $g_{c\ max}$ was adjusted for canopy size, using measurements of LAI (Equation [42]). 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, not always fair to compare estimates of g_a between studies, as a number of factors, including tree height and prevailing windspeed, influence estimates of g_a. Nevertheless, McNaughton and Jarvis (1983) suggested that in the case of well-ventilated canopies, such as orchards, the role of g_a is far less critical than g_c in determining E_c. Studies on olive by Villalobos et al. (2000) and Orgaz et al. (2007) support this supposition, as these authors demonstrated that 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, a phenomenon 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.

Given that this study is the first to successfully parameterize the g_c Jarvis model (Jarvis, 1976) for macadamias, it is unclear if the model parameters (Table 4.12) used in this study would be transferable to other orchards and environments. Even if these parameters are transferable, the difficulty in obtaining accurate measurements of LAI used to scale $g_{c\ max}$ makes this modelling approach less favourable compared to the model by Whitley et al. (2009), which only requires an estimate of $E_{c\ max}$. The accuracy of the Whitley et al. (2009) model has, however, not been established in macadamias, but if proven to be accurate could be a simplified alternative for the combined approach using the Jarvis (1976) model and Penman-Monteith (Monteith and Unsworth, 1990) equation to determine transpiration volumes.

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 model suggested by Whitley et al. (2009) requires similar parameterization to that of the canopy conductance model. This model was successfully parameterized, with model variables used in the simulation of E_c presented in Table 4.13. Parameterization through non-linear least squares regression analysis yielded a maximum E_c ($E_{c\ max}$) rate of 0.17 mm h^{-1} and was exactly the same as maximum hourly measured E_c in the MB orchard. There was also no difference between the daily maximum E_c measured (1.5 mm day^{-1}) in the MB orchard and that simulated by the model. Daily maximum E_c measured in this study was similar to that found in olive (1.1-2.3 mm day^{-1}) (Masmoudi et al., 2010, Rousseaux et al., 2009, Santos et al., 2007), implying that E_c measurements in this study were reasonable.

Table 4.13: Optimised parameters for Equation [40] used to model transpiration (E_c). Parameters were generated through non-linear least squares regression analysis using data from the mature bearing (MB) macadamia orchard

Parameter	**Value**
$E_{c\ max}$ (mm h^{-1})	0.174
K_{e1} (kPa)	1.672
K_{e2} (kPa)	0.618
k_T (^oC)	44.36
k_R (W m^{-2})	12.46
R^2	0.82

During the parameterization phase (2016/09/16-2017/02/15) of the Whitley et al. (2009) model, the model simulated daily E_c in the MB orchard with a high degree of accuracy, as all the statistical criteria were met during this phase (Figure 4.32 A). The model also provided reasonable estimates of daily E_c in the MB orchard during the model validation phase (2017/08/09-2018/07/31) (Figure 4.32 B), only underestimating total seasonal transpiration by 5 mm, whilst meeting all the statistical criteria for acceptable model accuracy. Seeing that

$f_{\mathrm{c\ eff}}$ varied little between the model parameterization and validation period, no adjustment in $E_{\mathrm{c\ max}}$ was needed in the MB orchard to achieve reasonable estimates of E_{c}.

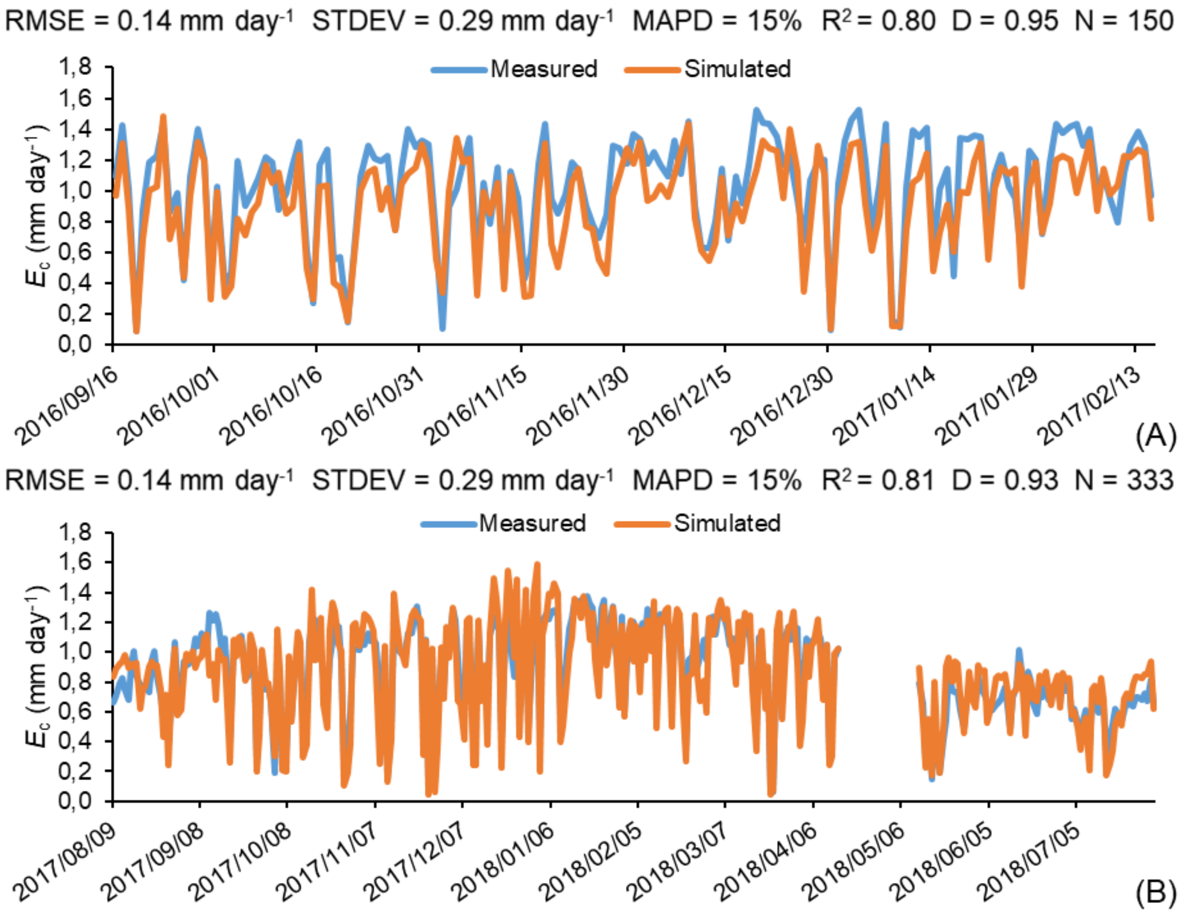


Figure 4.32: Comparison between hourly measured and simulated transpiration (E_{c}) totalled on a daily basis for the mature bearing (MB) orchard during the (A) parameterization (2016/09/16-2017/02/15) and (B) validation (2017/08/16-2018/08/06) of the Whitley et al. (2009) model. Missing data is due to missing solar radiation data as a result of equipment failure.

Adjustments in $E_{\mathrm{c\ max}}$ were, however, required in the IB orchard to achieve reasonable estimates of daily E_{c} given the large changes in $f_{c\ \mathrm{eff}}$ during the measurement period. The Whitley et al. (2009) model met model accuracy criteria during the first model validation phase in the IB orchard (Figure 4.33 A). During this phase, RMSE was 0.07 mm day^{-1} and both R^2 and D exceeded 0.8. Model performance was similar during the second validation phase in the IB orchard (Figure 4.33 B), with the exception of R^2 which was lower (R^2 = 0.65). Similar to the g_{c} model, the Whitley et al. (2009) model was most inaccurate from the start of January to the end of March, when E_{c} was underestimated on a daily basis. This period corresponds to the nut maturation and oil filling period in macadamias, during which increases in E_{c} have been reported without corresponding increases in atmospheric evaporative demand. Removal of this period from the model validation phase resulted in substantial improvements in statistical parameters, with RMSE decreasing to 0.05 mm day^{-1} and R^2 exceeding 0.8, whilst D was greater than 0.95.

The Whitley et al. (2009) model also provided reasonable estimates for hourly simulations of E_c totalled on a weekly basis (Figure 4.33 C), with RMSE being 0.36 mm week^{-1} and both R^2 and D exceeding 0.8. The model, however, slightly underestimated total E_c over a close to two year period by 10 mm, which given the fact that the model requires only a few easily measurable parameters, with the exception of $E_{c\ max}$, is rather exceptional. The successful parameterization and validation of the model in this study provides an alternative approach to the parameter intensive g_c model, but given that an independent data set in a different climatic region was not available for evaluating this model, the approach should be used with caution.

The model by Whitley et al. (2009) should, however, be well suited to crops which are well coupled to the atmosphere and exert strong stomatal control over transpiration. The model assumes that there is a maximum transpiration rate, which is not exceeded, and is only achieved under optimal environmental conditions. The premise of the model is therefore in line with the behaviour of an isohydric crop, where leaf water potential is prevented from dropping below a critical level, by strictly controlling water loss through stomatal control, which would imply that the maximum rate of E_c would not be exceeded, irrespective of atmospheric evaporative demand.

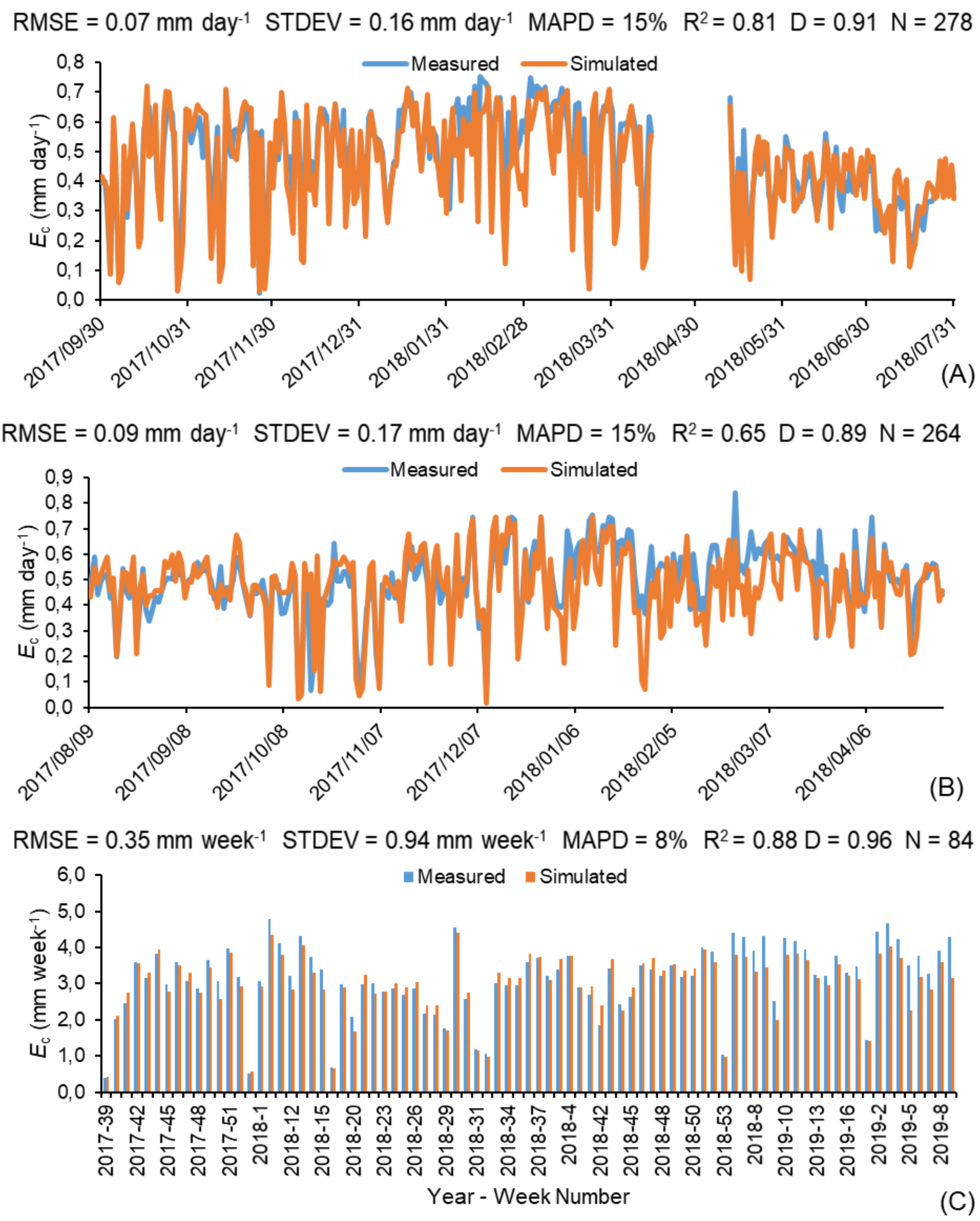


Figure 4.33: Comparison between hourly measured and simulated transpiration (*E*c) totalled on a daily basis for the intermediate bearing (IB) orchard during the (A) first validation (2017/09/30-2018/07/31) and (B) second validation (2018/08/10-2019/04/30) phase and (C) hourly measured and simulated weekly totalled transpiration (*E*c) throughout both validation periods of the Whitley et al. (2009) model. Missing data is due to missing solar radiation data as a result of equipment failure.

4.2.3 CONCLUSIONS

A number of models are available for estimation of transpiration, which differ greatly in complexity. One of the most commonly used models to estimate E_c is the FAO-56 dual crop coefficient approach which is based on the premise that E_c is a demand limited process. Macadamia E_c is, however, supply controlled, and this needs to be considered when trying to choosing a model for accurate estimates on fairly short time steps. As a result, it was proposed that a g_c modelling approach would be better suited to estimate macadamia E_c. These models, however, require reliable measurements or estimates of g_c and g_a to obtain accurate estimates of E_c, which are often difficult to determine, and are site/orchard specific. As a result, there is an opportunity to evaluate the accuracy of less parameter intensive models to estimate macadamia E_c, which would be more readily applied by a number of end users.

Given that macadamia E_c is a supply-controlled system, arising from strict stomatal control in response to increases in atmospheric evaporative demand, it was not surprising that the empirical FAO-56 dual crop coefficient model provided poor estimates of daily K_t and E_c. The discrepancies between measured and modelled K_t and E_c, stem from an overestimation of K_t and E_c at ET_o rates > 4.0 mm day^{-1}, and an underestimation of K_t and E_c when ET_o < 2.0 mm day^{-1}. These over and under estimations of K_t and E_c were largely due to the linear relationship between r_{leaf} and r_s and ET_o. The model, however, provided reasonable estimates of monthly and seasonal K_t and E_c in both the MB and IB orchard, which is most likely due to compensatory errors over the longer period of estimation. The ability of the FAO-56 dual crop coefficient model to simulate K_t and E_c over longer periods of time makes this model a valuable tool for water licencing authorities and strategic irrigation planning and management.

On a daily time step, the Jarvis-Steward g_c model in conjunction with the Penman-Monteith equation, provided reasonable estimates of E_c, but was shown to be particularly sensitive to seasonal changes in LAI. Only after adjustments in $g_{c\ max}$ using LAI, did the model provide accurate estimates of E_c in both orchards. The model, however, failed to provide accurate estimates of both g_c and E_c, by consistently under estimating g_c and E_c during specifically April, a period during which the presence of fruit has been shown to cause a significant upregulation in stomatal conductance and E_c, further reiterating the significant impact of phenology and physiology on macadamia E_c. It also emphasizes the fact that although a model, such as the Jarvis-Steward g_c model, is able to account for significant variability in environmental conditions, the model failed to account for physiological and phenological changes which significantly impact g_c and subsequently E_c.

Regardless of the possible limitation of the Jarvis-Steward type g_c model, estimates of g_c in macadamia orchards are rather low (0.3-0.7 mm s^{-1}) in relation to g_a (37-75 mm s^{-1}), confirming that macadamias are well coupled to the atmosphere ($\Omega = 0.08$). The high degree of coupling in macadamia implies that changes in g_c would lead to direct changes in E_c, which contributed to the success of a simplified E_c model. This model provided reasonable estimates of daily $E_{c,}$ without multiple adjustments for canopy size being needed within each of the orchards. The use of this simplified model, which performed comparably to the parameter intensive g_c model, provides both scientist and researchers with an alternative approach to estimate E_c in a range of macadamia orchards. Considering that this model provided accurate estimates of E_c on a daily or weekly basis, it could be used for irrigation scheduling, which would be of great value to the macadamia industry. It should, however, be emphasized that although this study has successfully parameterized three different E_c models, and alluded to the various possible limitations of these models, these models have not been tested in other orchards and environments. A large degree of uncertainty regarding the transferability of model parameters derived in this study, to other macadamia orchards therefore exists. For example, the use of the FAO-56 dual crop coefficient approach would be limited to environments where average ET_o is between 2.0-4.0 mm day^{-1}, whilst parameters such as $g_{c\ max}$ and $E_{c\ max}$ could vary between cultivars, thereby limiting widespread implementation of the mechanistic model evaluated in this study. Furthermore, before these models could be used to successfully schedule irrigation, soil evaporation needs to be accounted for in order to quantify total crop water use.

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

4.3.1 WEATHER VARIABLES

Understanding the weather conditions under which the trial was conducted is important when considering if any weather conditions may have been limiting to yield and quality of the macadamia trees. When assessing weather variables over a season (July to June), mean seasonal temperature was fairly similar between two of three production seasons, with the average daily temperature for the 2017/18 season being 18.27°C, whilst it was 18.63°C and 19.32°C for the 2018/19 and 2019/20 seasons respectively (Figure 4.34). The 1.05-1.31°C difference in average daily temperature between the 2019/20 season and 2017/18, 2018/19 seasons can be attributed to a much warmer July to November period for the 2019/20 season, with mean daily temperatures on average being 1.83°C higher than what was recorded for same period over the two previous seasons (Figure 4.34 A). Average daily temperatures were particularly high for July, October and November in the 2019/20 season, with mean daily temperatures being 3-4°C higher over these months compared to the previous two seasons. The highest average daily maximum temperatures were recorded over a four month period from December to March for all three seasons.

Average daily air vapour pressure deficit (VPD_{air}) was fairly similar between the three seasons, with an average VPD_{air} being 0.97 kPa, 0.98 kPa and 1.04 kPa over the 2017/18, 2018/19 and 2019/20 seasons respectively. The highest daily average VPD_{air} values were observed from August to October over all three seasons (Figure 4.34 B). Daily average VPD_{air} values recorded for July of the 2019/20 season were substantially higher (1.55 kPa) than what was recorded during the same time for the 2017/18 (1.05 kPa) and 2018/19 (0.85 kPa) seasons. Total reference evapotranspiration (ET_o) was similar for the 2017/18 (1190.4 mm), 2018/19 (1164.4 mm) and 2019/20 (1154* mm estimated) seasons (Figure 4.34 C). Average daily ET_o was also similar between the 2017/18 (3.26 mm/day), 2018/19 (3.19 mm/day) and 2019/20 (3.18 mm/day) seasons and highest daily ET_o values were recorded during September and October periods over all three seasons. Mean daily solar radiation was fairly similar for the 2017/18 (17.08 MJ m^{-2} day^{-1}), 2018/19 (16.17 MJ m^{-2} day^{-1}) and 2019/20 (16.83 MJ m^{-2} day^{-1}) seasons (Figure 4.34 D). The total annual rainfall was, however, substantially higher during the 2018/19 (894 mm) season compared to that of the 2017/18 (759.4 mm) and 2019/20 (759.2 mm) seasons (Figure 4.34 E). Rainfall followed a typical summer rainfall pattern over all three seasons but was well below the long term mean rainfall (854 mm) for the Nelspruit growing area for both 2017/18 and 2019/20 seasons.

The potential impact of weather conditions on trial results can be further evaluating by assessing average weather conditions experienced during each phenological stage for the duration of the water stress trial (Table 4.14). Air temperature from the nut sizing stage through to oil accumulation was significantly higher than during flowering and fruit set, except for the 2018/19 season during nut sizing. Despite the lower temperatures during flowering and nut set VPD_{air} was higher, possibly reflecting low rainfall (<40 mm for both seasons) at this time, resulting in low relative humidity. The hottest conditions occurred during shell hardening, which is not surprising as this stage occurred over December and January and was associated with high solar radiation and fairly high ET_o. However, this stage was also associated with significant rainfall, especially on the 2018/19 season (490 mm; Table 4.15) and as a result VPD was not as high as during flowering and nut set. Whilst, temperatures were still quite high during oil accumulation, VPD_{air} was fairly low and so was ET_o. This could be attributed to higher rainfall during this period, which would have resulted in higher relative humidity and more overcast conditions. Whilst there were clear differences in weather conditions between phenological stages, this is to be expected due to seasonal weather patterns. These differences were mostly consistent between seasons and any differences could largely be attributed to differences in rainfall between seasons

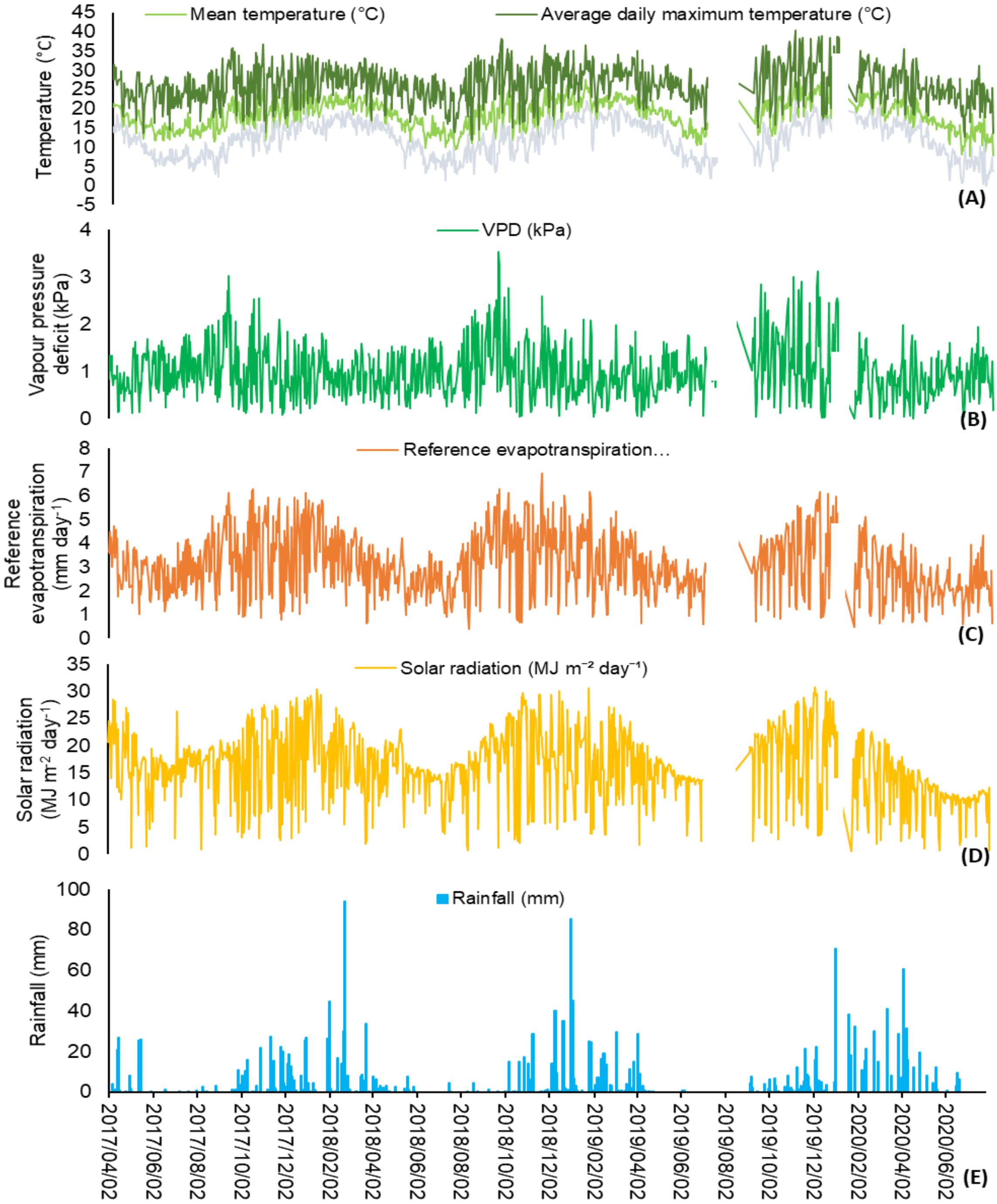


Figure 4.34: Maximum, minimum and mean air temperature (°C), (B) Air vapour pressure deficit (VPD_{air}) (kPa), (C) Reference evapotranspiration (mm day^{-1}), (D) Solar radiation (MJ m^{-2} day^{-1}) and (E) total daily rainfall (mm) obtained from an automatic weather station located close to the orchard over a three season period (01 April 2017 to 27 July 2020). Missing data is as a result of the failue of the logger battery.

Table 4.14: Weather data summary over the three-season trial period and during the different phenological stages of the mature orchard trial. Daily average values were used for air temperature (T_{air}), total incident solar radiation (R_s), air vapour pressure deficit (VPD_{air}) and total reference evapotranspiration (ET_o).

Phenological stage (Treatment)	Year	Timespan (days)	T_{air} (°C) (Av ± Std)	R_s (MJ m^{-2} day^{-1}) (Av ± Std)	VPD_{air} (kPa) (Av ± Std)	ET_o (mm) (Av ± Std)	Rain -ET_o (mm)
Seasons data	2017/18	365	18.27 ± 3.33	17.08 ± 5.87	0.97 ± 0.50	3.26 ± 1.24	-431
	2018/19	365	18.63 ± 3.90	16.17 ± 6.15	0.98 ± 0.56	3.19 ± 1.28	-270
	2019/20	365	19.32 ± 4.00	16.83 ± 6.68	1.04 ± 0.65	3.18 ± 1.23*	-395*
Flowering and nut set	2018/19	82	17.84 ± 3.90	16.52 ± 5.12	1.31 ± 0.74	3.44 ± 1.33	-267
	2019/20	80	18.06 ± 3.39	16.52 ± 6.38	1.35 ± 0.75	3.15 ± 1.08*	-198*
Nut sizing and pre-mature nut drop	2018/19	41	17.35 ± 2.76	18.55 ± 9.72	0.90 ± 0.53	3.53 ± 1.70	-19
	2019/20	67	22.07 ± 3.20	18.69 ± 8.31	1.23 ± 0.83	3.57 ± 1.51	-126
Shell hardening	2018/19	59	22.20 ± 2.35	16.55 ± 7.05	0.84 ± 0.51	3.48 ± 1.34	283
	2019/20	39	23.11 ± 2.58	18.60 ± 6.99	1.10 ± 0.65	3.76 ± 1.32*	22*
Oil accumulation	2018/19	81	21.30 ± 1.70	16.13 ± 5.79	0.75 ± 0.38	3.06 ± 1.03	14
	2019/20	71	20.37 ± 2.32	13.20 ± 5.63	0.70 ± 0.44	2.63 ± 1.08	96

**** Missing ET_o data for August 2019 and January 2020 was estimated by multiplying the mean value for the season with the total missing days.***

It is therefore unlikely that any extreme weather events throughout the trial would have caused a reduction in yield, which would have masked any differences between treatments. However, the higher rainfall in the 2018/19 season could have influenced the ease with which stress treatments were implemented from December through to early April (shell hardening and oil accumulation). Although plastic was placed under the trees to exclude rainfall from treatment trees, it was close to impossible to exclude if rain fell for prolonged periods or during heavy showers of rain. This would have resulted in the wetting of soil in stressed treatments, thereby interrupting the stress period. Alternatively, hotter temperatures in the 2019/20 season may have increased atmospheric evaporative demand at the start of the season, thereby possibly increasing the rate of soil water depletion from the soil and the quicker implementation of stress. However, other than these differences weather conditions in the three seasons were fairly similar and typical of the region.

4.3.2 SOIL WATER DEFICITS

Control trees were well irrigated according to a cycle determined by readings from a capacitance probe installed within the trial block. Soil water content, within the top 60 cm of the soil profile, was maintained between field capacity (FC) and permanent wilting point (PWP) over all three seasons (2017/18-2019/20) (Figure 4.35). According to the capacitance probe measurement (Figure 4.35), macadamias extracted water from within the top 60 cm of the soil profile. The withdrawal of water from this depth is supported by the findings of a whole tree excavation study by Firth et al. (2003), showing the taproot of a 12 year old grafted macadamia tree being 60 cm in length and the highest density of fibrous roots being within the top 40 cm of the soil profile. Similarly, an in-field lysimeter study by Stephenson et al. (2003) showed that unstressed trees extract water primarily from the top 70 cm of the soil profile. Since trees used in this study were grafted and of similar age (13 years old), it can be assumed that the root distribution, root density and water extraction patterns of unstressed trees were similar to those described by Firth et al. (2003) and Stephenson et al. (2003).

Irrigation frequency increased from June (pre-flowering) to April (harvest) over each of the three seasons, as observed by the spikes in relative soil moisture content in the top 20 cm of the soil profile (Figure 4.35). The time between irrigation intervals decreased during the flowering and nut set, and nut sizing and pre-mature nut drop phenological stages (July to November), which overlapped with periods of high environmental demand (ET_o) and low rainfall (Figure 11). Irrigation water was intentionally restricted over the dormant post-harvest (27 April) to pre-flowering (1 June) period of the 2019/20 season, where after soil water content was replenished to FC by the grower (as observed from the large spike in relative water content in August 2019 presented in Figure 4.35). This pre-meditated water restriction is a common water saving practice implemented by macadamia producers in the South African macadamia industry, based on findings made in other crops such as peaches (Marsal et al., 2003) and on findings made by Stephenson et al. (2003). Stephenson et al. (2003) found that mild water stress after crop maturity is unlikely to be detrimental to the following seasons yield and quality and that it may be beneficial to crop yield as one could potentially manipulate flushing patterns during critical stages.

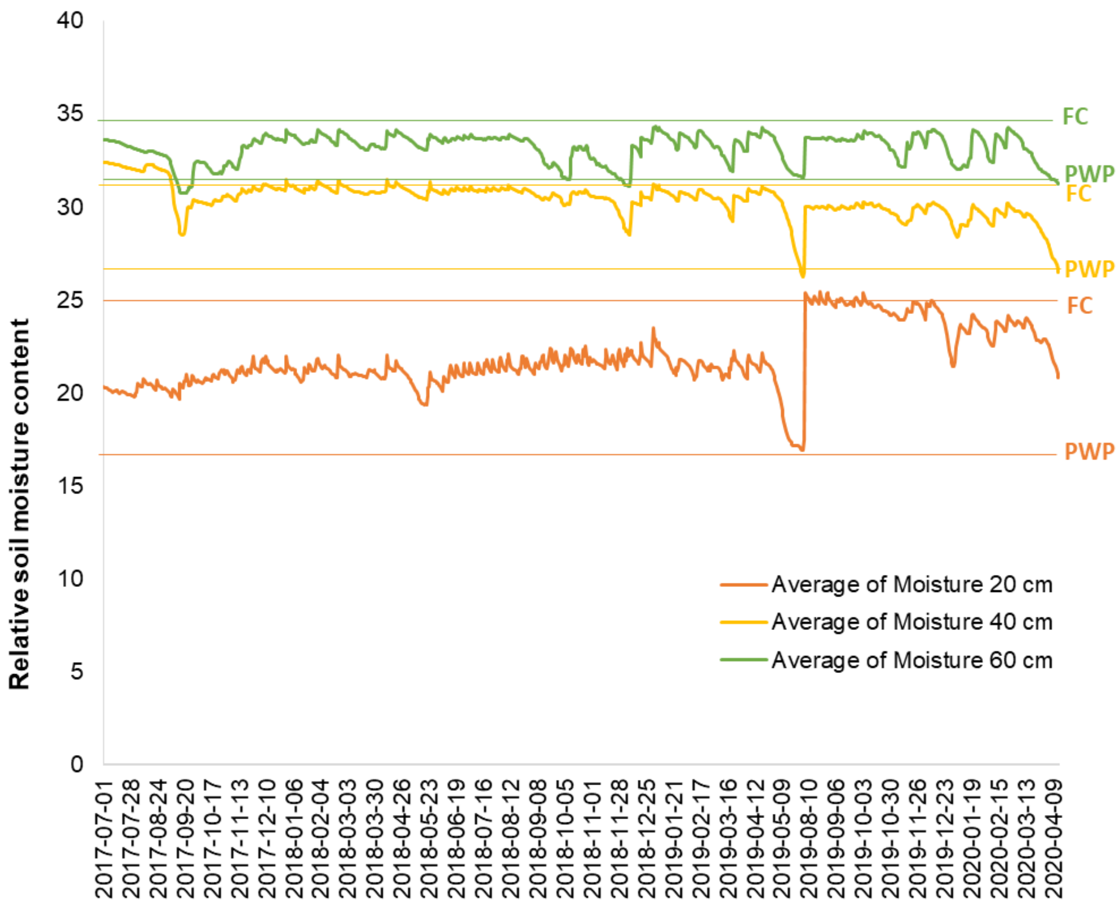


Figure 4.35: Relative soil moisture content at three different soil depths (cm) of the fully irrigated control treatment. Values were recorded in the mature orchard over a three season period (01 July 2017 to 04 April 2020). Field capacity (FC), Permanent wilting point (PWP)

Total ET_o exceeded total rainfall during most phenological stages over both the 2018/19 and 2019/20 seasons (Table 4.15). Rainfall was particularly low from May to October, meaning that supplementary irrigation was necessary to meet the full estimated ET requirement of the crop. The highest estimated irrigation requirements was observed during the flowering and nut set phenological period, where total crop evapotranspiration ($ET_c = ET_o \times K_c$) (based on a constant K_c = 0.65 recommended by Carr (2013)) exceeded total rainfall by 169.4 mm and 113.5 mm during the 2018/19 and 2019/20 seasons respectively (Table 4.15). However, total seasonal rainfall and irrigation was sufficient to meet the seasonal ET_c requirement of the control trees over all three seasons. The ET_c requirement of the control trees was also met by rainfall and irrigation during all seasons. In this study total seasonal rainfall and irrigation was sufficient to meet the seasonal ET_c requirement of the half irrigation treatment trees, over all three seasons. Similarly, total rainfall met the seasonal ET_c requirement of rainfed trees over both the 2018/19 and 2019/20 seasons, but rainfed trees were exposed to a 14 mm water deficit during the 2017/18 season (Table 4.15).

Despite rainfall and irrigation being sufficient to meet the seasonal ET_c requirement of both half irrigation and rainfed treatment trees, trees were subjected to substantial water deficits during the flowering and nut set phenological stage over both the 2018/19 and 2019/20 seasons. Water deficits of 140.5 and 83.8 mm were experienced by trees in the half irrigation treatment during the flowering and nut set phenological stage in the 2018/19 and 2019/20 seasons respectively, whilst rainfed trees were exposed to a water deficit of 169.4 and 113.5 mm during the same time (Table 4.15).

Table 4.15: Irrigation, rainfall reference evapotranspiration (ET_o) and crop reference evapotranspiration ($ET_c = ET_o \times K_c$ (K_c = 0,65 (Carr (2013)) summary for the mature bearing orchard over a three-season period (July 2017-July 2020) and during different treatment stages. Values in brackets represent the quantity of rain and irrigation water received by the control treatment during the respective phenological stage.

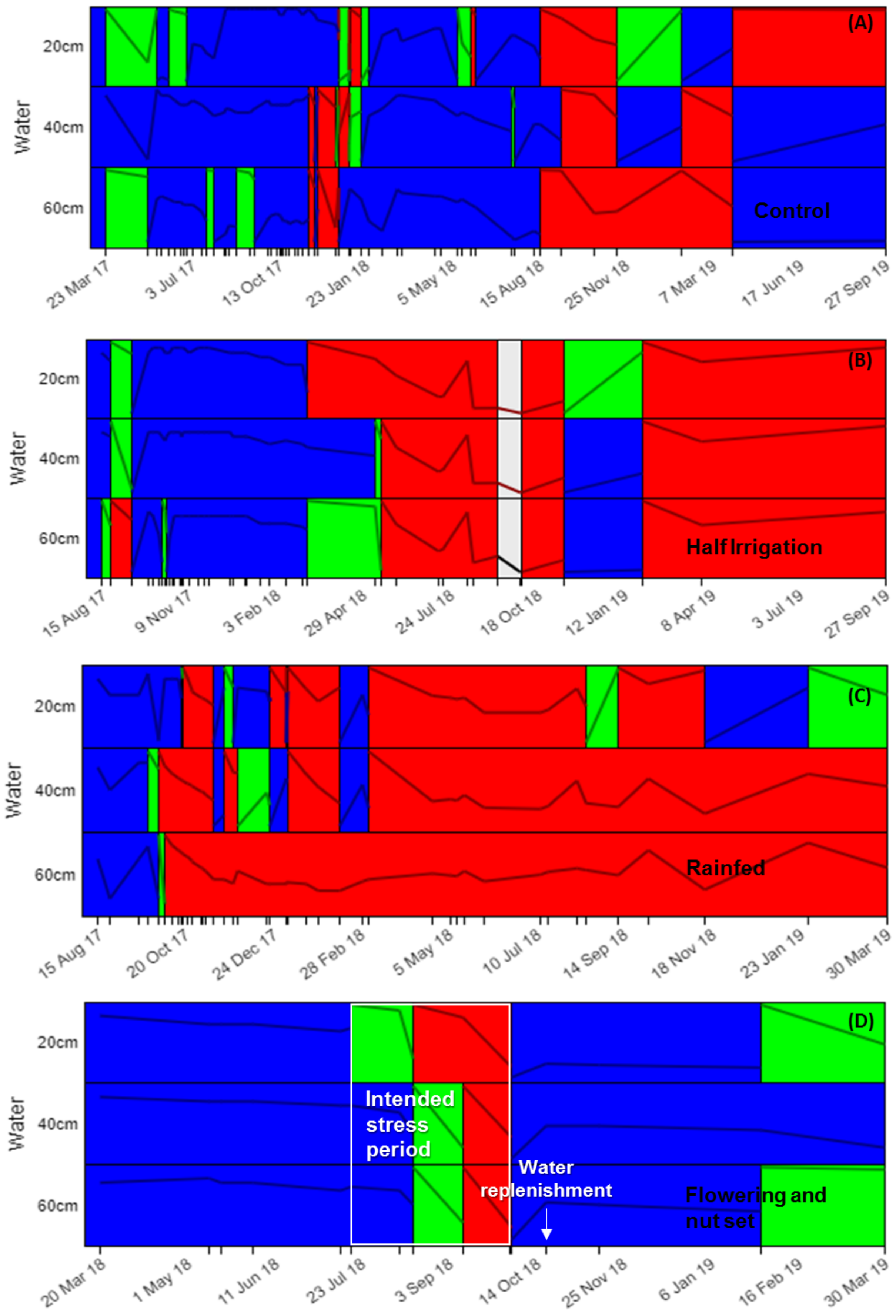
Phenology	Year	ET_o (mm)	Rain (mm)	Irrigation (mm)	Rain + Irrigation – ET_o (mm)	ET_o x K_c (mm)	Rain + Irrigation – ET_c (mm)
Control	2017/18	1190.4	759.4	160.6	-270.4	773.5	146.5
	2018/19	1164.4	894.0	156.0	-114.4	756.8	293.2
	2019/20	1154.0*	759.2*	177.8	-217.0	750.1	186.9
Half irrigation	2017/18	1190.4	759.4	80.3	-350.7	773.5	66.2
	2018/19	1164.4	894.0	78.0	-192.4	756.8	215.2
	2019/20	1154.0*	759.2*	88.9	-305.9	750.1	98.0
Rainfed	2017/18	1190.4	759.4	0	-431.0	773.5	-14.1
	2018/19	1164.4	894.0	0	-270.4	756.8	137.2
	2019/20	1154.0*	759.2*	0	-394.8	750.1	9.1
Flowering and nut set	2018/19	278.9	0 (11.8)	0 (57.8)	-278.9	181.2	-181.2
	2019/20	225.5*	0 (33.1)	0 (59.3)	-225.5	146.6	-146.6
Nut sizing and pre-mature nut drop	2018/19	145.0	0 (125.8)	0 (15.6)	-145.0	94.5	-94.5
	2019/20	283.0	0 (157.4)	0 (60.9)	-283.0	183.9	-183.9
Shell hardening	2018/19	205.8	0 (489.2)	0 (14.0)	-205.8	133.7	-133.7
	2019/20	218.6*	0 (241.3)	0 (10.9)	-218.6	142.1	-142.1
Oil accumulation	2018/19	248.0	0 (261.8)	0 (40.6)	-248.0	161.2	-161.2
	2019/20	184.5	0 (281.0)	0 (43.7)	-184.5	119.9	-119.9

**** Missing ET_o data for August 2019 and January 2020 was estimated by multiplying the mean value for the season with the total missing days.***

Rainfed trees were also exposed to a 26.5 mm water deficit during the nut sizing and pre-mature nut drop phenological stage of the 2019/20 season. Furthermore, through the exclusion of rainfall and restriction of irrigation water, treatment trees on which a mild water stress was implemented, were exposed to a calculated water deficit during all of the intended phenological stages, over both the 2018/19 and 2019/20 seasons (Table 4.15).

Soil matric potential readings over the 2017/18 and 2018/19 seasons were correlated with intended water deficits periods, as well as periods of high ET_o and low rainfall for all treatments in the mature orchard block (Figure 4.36). Measured soil matric potential readings, using Chameleon probes, of the control treatment ranged mainly (63% of readings) between 0 and -20 kPa throughout the course of both the 2017/18 and 2018/19 seasons, with some fluctuations in soil water content noted over the both seasons (Figure 4.36 A). Soil matric potential readings were substantially lower for the rainfed (Figure 4.36 C) and half irrigation treatments (Figure 4.36 B) over the both the 2017/18 and 2018/19 seasons, with 74% and 58% of the 48 chameleon readings being in the -50 kPa range for these treatments.

Furthermore, soil water content was successfully depleted during the flowering and nut set phenological stage (August-October 2018) (Figure 4.36 D), with matric potential readings exceeding -50 kPa from 10 September 2018 to the end of October 2018. The replenishment of soil water upon the completion of nut set resulted in the rapid increase in measured soil matric potential as subsequently observed on 2 October 2018 (Figure 4.36 D). Soil water content was similarly depleted during the remaining phenological stages which included nut sizing and pre-mature nut drop, shell hardening and oil accumulation stages (Figure 4.36 E, F, G). Water replenishment following these respective phenological stages was observed, due to a limited number of measurements after the completion of the different treatment stages. Following the completion of each treatment stage, all treatment replicates were irrigated according to the same irrigation cycle determined for the control treatment and similar water replenishment patterns would most likely have been observed. Rainfall and irrigation also exceeded total ET_c following the nut sizing and pre-mature nut drop, shell hardening and oil accumulation treatment stages (Table 4.15), which would also have contributed to ensuring adequate soil water replenishment following the stress treatment.


(A)
Water
20cm
40cm
60cm
Control
23 Mar 17
3 Jul 17
13 Oct 17
23 Jan 18
5 May 18
15 Aug 18
25 Nov 18
7 Mar 19
17 Jun 19
27 Sep 19
(B)
Water
20cm
40cm
60cm
Half Irrigation
15 Aug 17
9 Nov 17
3 Feb 18
29 Apr 18
24 Jul 18
18 Oct 18
12 Jan 19
8 Apr 19
3 Jul 19
27 Sep 19
(C)
Water
20cm
40cm
60cm
Rainfed
15 Aug 17
20 Oct 17
24 Dec 17
28 Feb 18
5 May 18
10 Jul 18
14 Sep 18
18 Nov 18
23 Jan 19
30 Mar 19
(D)
Water
20cm
40cm
60cm
Intended stress period
Water replenishment
Flowering and nut set
20 Mar 18
1 May 18
11 Jun 18
23 Jul 18
3 Sep 18
14 Oct 18
25 Nov 18
6 Jan 19
16 Feb 19
30 Mar 19

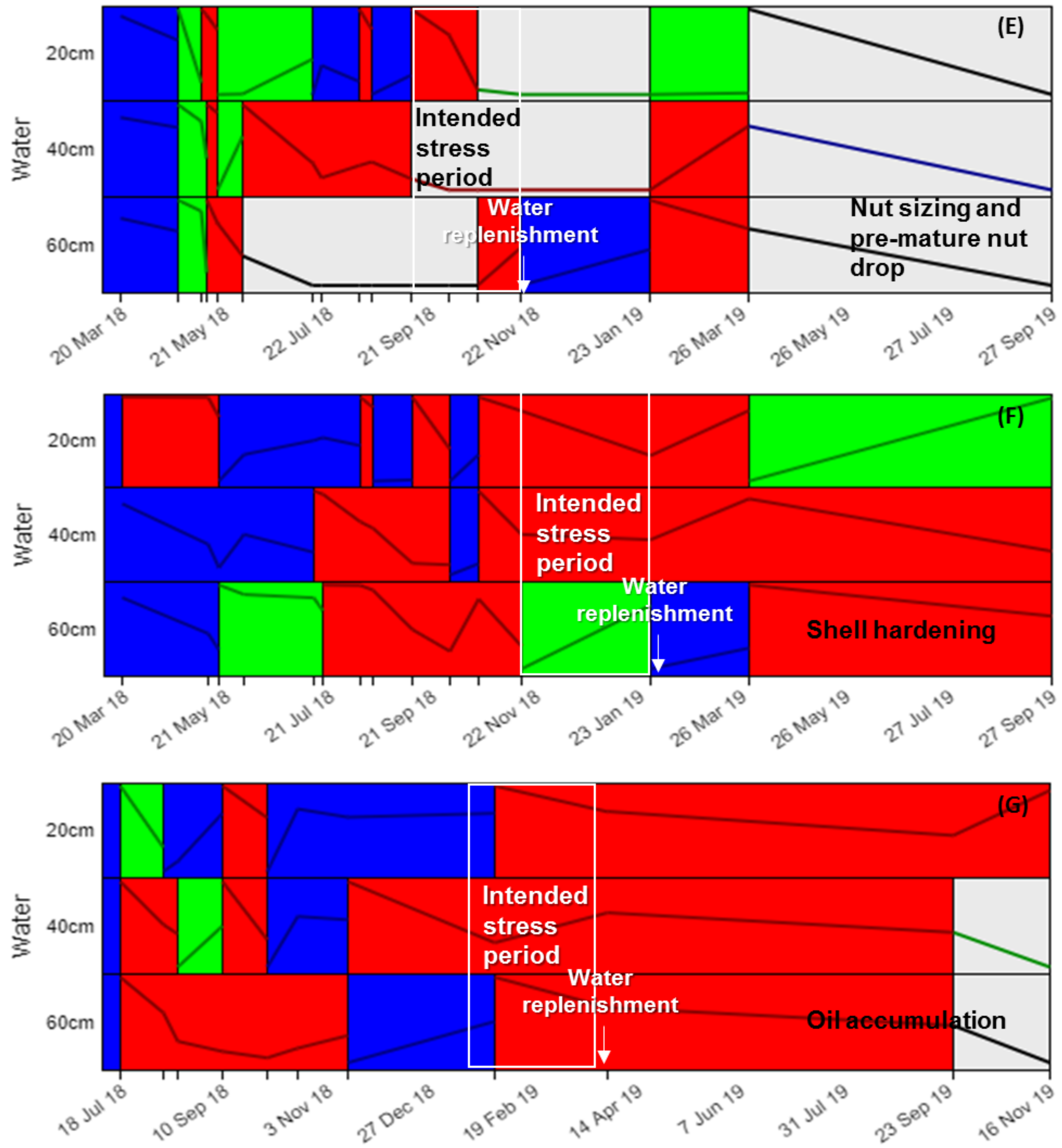


Figure 4.36: Soil water matric potential of seven different water stress treatments, which included (A) normal irrigation scheduled by the grower (control); (B) half irrigation; (C) no irrigation/rainfed; (D) water stress during flowering and nut set; (E) water stress during nut sizing and pre-mature drop; (F) water stress during shell hardening; and (G) water stress during oil accumulation measured at three different depths over the course of the 2017/18 and 2018/19 season (July 2017-April 2019). The measurement range included: Blue (0-20 kPa); Green (-20 to -50 kPa); Red (<-50 kPa); Grey (Unreadable). Solid lines represent relative trends in water extraction and replenishment

Soil matric potential measurements were primarily used to demonstrate that soil water was limiting during each of the four different phenological stages at which a water stress was implemented. Recommendations made by Stephenson and Searle (2014) suggests that soil water tension readings between -20 and -40 kPa at a 60 cm depth should be used as critical trigger points for deficit irrigation studies. Based on these recommendations, data presented in Figure 4.36, suggest that all treatments were exposed to mild water deficits during each of the intended phenological stages, as soil matric potential readings at all of the measured depths exceeded -40 kPa for a prolonged period (>4 weeks), during each of the treatment stages. Stephenson and Searle (2014), however, suggest that soil water replenishment trigger points should be fine-tuned for different soil types and tree rooting patterns and that these values should be validated through monitoring different physiological responses to developing water deficits.

4.3.3 THE EFFECT OF SOIL WATER DEFICITS ON PLANT WATER RELATIONS

One of the most common methods of evaluating the impact of water deficits on plant water relations is the use of predawn leaf water potentials (Ψ_{pd}) (Jones, 2004). Using Ψ_{pd} as an indicator of the level of crop water stress has been shown to be an accurate indicator of water deficit conditions in almond (Nortes et al., 2005), lime (Silva et al., 2005), plum (Intrigliolo and Castel, 2006), apple and walnut trees (Valancogne et al., 1996). At night, when transpiration is negligible, the plant continuously refills with water if there is a potential difference between the leaves and the soil, until an equilibrium is reached. An equilibrium between the leaves and soil usually occurs just before dawn. Hence, Ψ_{pd} is an indication of the plant water status at zero plant water flux and is considered to be in equilibrium with the soil water status of the plant root zone (Chone et al., 2001). Therefore, when Ψ_{pd} is highly negative, it is reasonable to assume that soil water potential is highly negative and vice versa. Under conditions of highly negative soil matric potential, Ψ_{pd} tends to be more negative than under conditions of higher (less negative) soil matric potential, mainly as a result of incomplete water replenishment of leaf tissues.

Similarly, water deficits confirmed by the decrease in soil matric potential during the different phenological stages, presented in Figure 4.36, resulted in a reduction in Ψ_{pd} during each of the respective phenological stages of this study (Figure 4.37). Similar trends in the reduction of the average Ψ_{pd} can be observed for trees stressed during nut sizing and pre-mature nut drop, shell hardening and oil accumulation over both seasons (Figure 4.37). Average minimum Ψ_{pd} levels reached during the nut sizing and pre-mature nut drop, shell hardening and oil accumulation phenological stages were, however, noticeably higher than the average Ψ_{pd} that was recorded for trees stressed during flowering and nut set, over both seasons. The higher

Ψ_{pd} levels observed during these stages could possibly be as a result of deep water extraction by trees during the rainy season, as opposed to the drier flowering period, with total ET_c greatly exceeding rainfall during the flowering and nut set phenological stage over both seasons (Table 4.15). Searle and Lu (2002) showed that soil water was depleted more gradually at depth than near the surface, which presumably provides a buffer against the onset of stress in deep rooted trees.

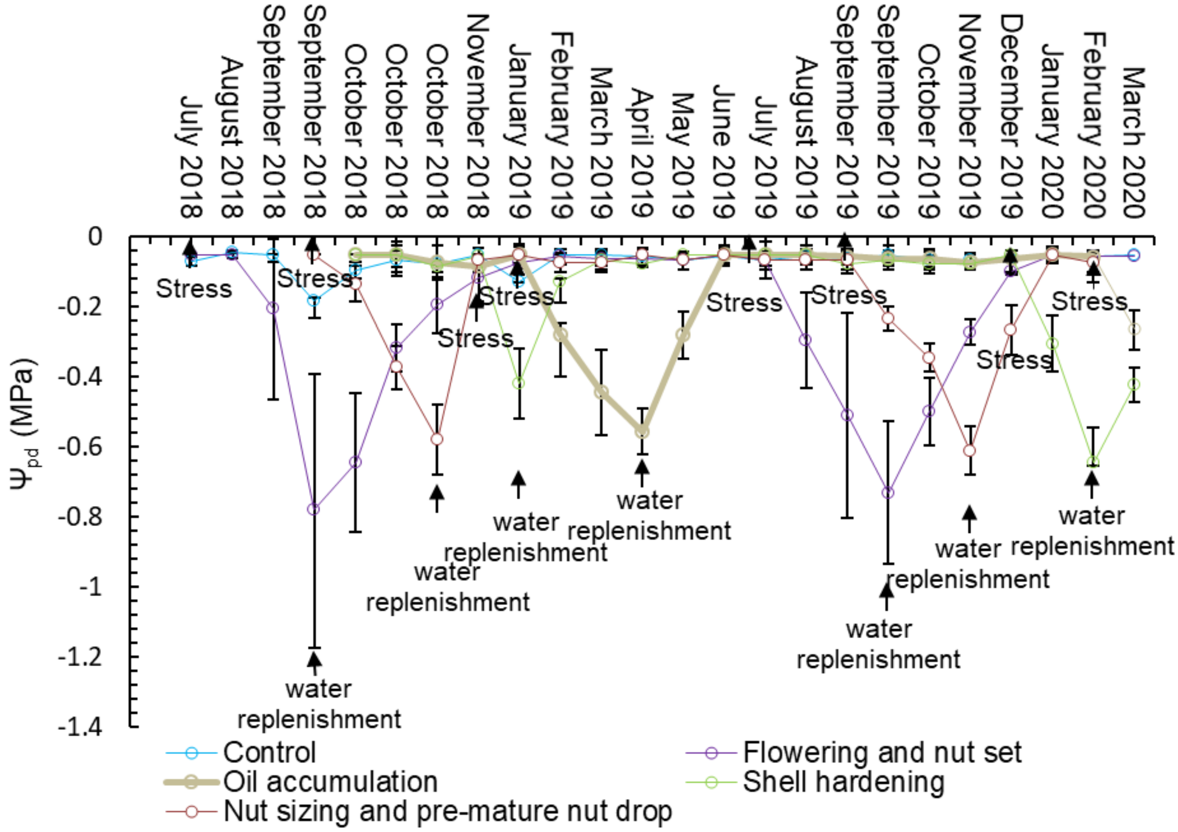


Figure 4.37: Average pre-dawn leaf water potential (Ψ_{pd}) (MPa) for nine measurement replicates per treatment over both the 2018/19 and 2019/20 seasons

The lower rainfall and higher ET_o during flowering and nut set, combined with the fact that irrigation is only managed within the top 60 cm of the soil profile (limited water replenishment >60 cm), can possibly explain the more negative values observed for control, half irrigation and rainfed treatments during the September-October period (Figure 4.38). As discussed above, ET_c exceeded rainfall and irrigation quantities in the control and half irrigation treatments during the flowering and nut set phenological stage, leading to a water deficit period. Therefore, limited water availability at depth (>60 cm) may have inhibited deep water extraction during these water deficits periods, leading to the slightly more negative Ψ_{pd} levels observed at this time. Differences between 2018/19 (-0.18 MPa) and 2019/20 (-0.06 MPa) Ψ_{pd}

levels recorded for the control treatment during the flowering and nut set phenological stage, can possibly be related to the grower replenishing the soil water content to FC, prior to flowering (1 June 2019), leading to some soil water reserves being available at depth (>60 cm) during the water deficit period. In addition, rainfall was more evenly distributed during the flowering and nut set period in the 2019/20 season with a total rainfall of 33.1 mm, as opposed to 11.8 mm during the 2018/19 flowering and nut set period, leading to more regular soil water replenishment within the top 20 cm of the soil profile.

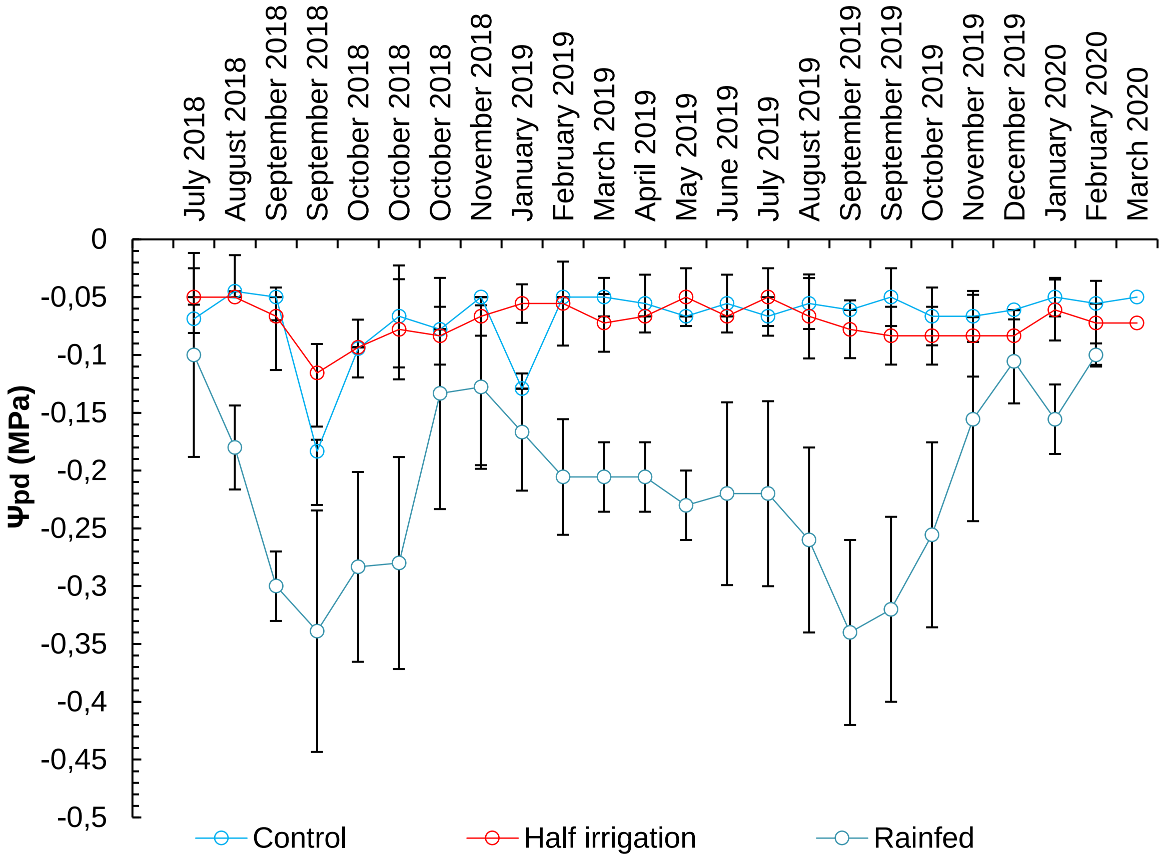


Figure 4.38: Average pre-dawn leaf water potential (Ψ_{pd}) (MPa) over nine measurement replicates for control, half irrigation and rainfed treatments, over both the 2018/19 and 2019/20 seasons

These findings are supported by Stephenson et al. (2003), who showed that soil water is rapidly depleted within the top 40 cm of the soil surface by the surface mat of roots of stressed trees. Stephenson et al. (2003) further showed water extraction by stressed trees to occur at greater depth (>130 cm) during a prolonged dry spell. Lloyd et al. (1991) also reported macadamia roots to have the ability to extract sufficient water at depth, even at low moisture contents. Hence, these abilities combined with possible water table replenishment by rain could have led to the observed higher Ψ_{pd} levels for trees stressed during nut sizing and pre-mature nut drop, shell hardening and oil accumulation. The study by Lloyd et al. (1991)

reported similar Ψ_{pd} levels (-0.05 to -0.1 MPa) for macadamia trees under well irrigated conditions, as those presented in this study. Despite occasional soil water depletion, Ψ_{pd} levels recorded over the 2018/19 and 2019/20 seasons seldom fell below -0.1 MPa in both the control and half irrigation treatments (Figure 4.38). Minimum Ψ_{pd} levels recorded during this study were, however, substantially lower (-1.2 MPa) (Figure 4.37) than what were reported by Lloyd et al. (1991). The authors reported a minimum Ψ_{pd} of approximately -0.22 MPa (-0.12 MPa more negative than the control) after a four month dry period in well drained red krasnozem (Hutton) soil. Average minimum Ψ_{pd} levels recorded over all treatments in this study (-0.61 MPa) was similar to the minimum Ψ_{pd} levels (-0.58 MPa) observed by Firth et al. (2003) in an unirrigated one year old macadamia orchard.

There was, however, substantial variation between the minimum Ψ_{pd} reached in the various treatment replicates, as indicated by the standard deviation (Figure 4.37), which can be attributed to variation in soil characteristics within the experimental block. Treatment replicates situated in the southern parts of the experimental block generally had higher (more positive) minimum Ψ_{pd} levels in comparison to treatment replicates in the northern sections. Due to a shallow soil profile and poor orchard drainage, treatment replicates in the southern parts of the experimental block were likely subjected to fluctuations in the soil water table, which would have led to occasional access by the tree to soil water and therefore the substantial variation observed between measured replicates.

4.3.4 THE EFFECT OF WATER STRESS ON MACADAMIA YIELD AND QUALITY

By using the universal accepted Ψ_{pd} approach as an indicator of the level of crop water stress, a decrease in Ψ_{pd} (increase in water stress) at various phenological stages appeared to have little effect on macadamia yield. For the 2018/19 season yield per tree, in terms of both nut in husk (NIH) and wet in shell (WIS), was not significantly different between different phenological stages, but all treatments differed relative to the control, with all treatments yielding significantly ($p \leq 0.05$) more fruit than the control (Figure 4.39). Similar findings have previously been reported in a lysimeter study by Stephenson et al. (2003), where trees stressed during floral initiation and floral development yielded more than the well-irrigated controls over a single season. Increased yield in the stressed treatments relative to the control could be related to possible improvements in tree health (root longevity) and improved nutrient use efficiency for trees subjected to some degree of water deficit. It is possible that by reducing irrigation to the various treatments waterlogged conditions were avoided in these treatments resulting in improved root growth and reduced disease incidence, which could both have led to improved yields. The possibility of the control being over-irrigated is supported by comparing the yield in the half irrigation treatment to treatments when trees were stressed at different phenological stages. When comparing treatment trees receiving half the normal irrigation, with those stressed at different phenological stage, trees receiving half the normal irrigation yielded significantly more ($p \leq 0.05$) than all the stress treatments. It is therefore possible that trees in the control were stressed due to excess water.

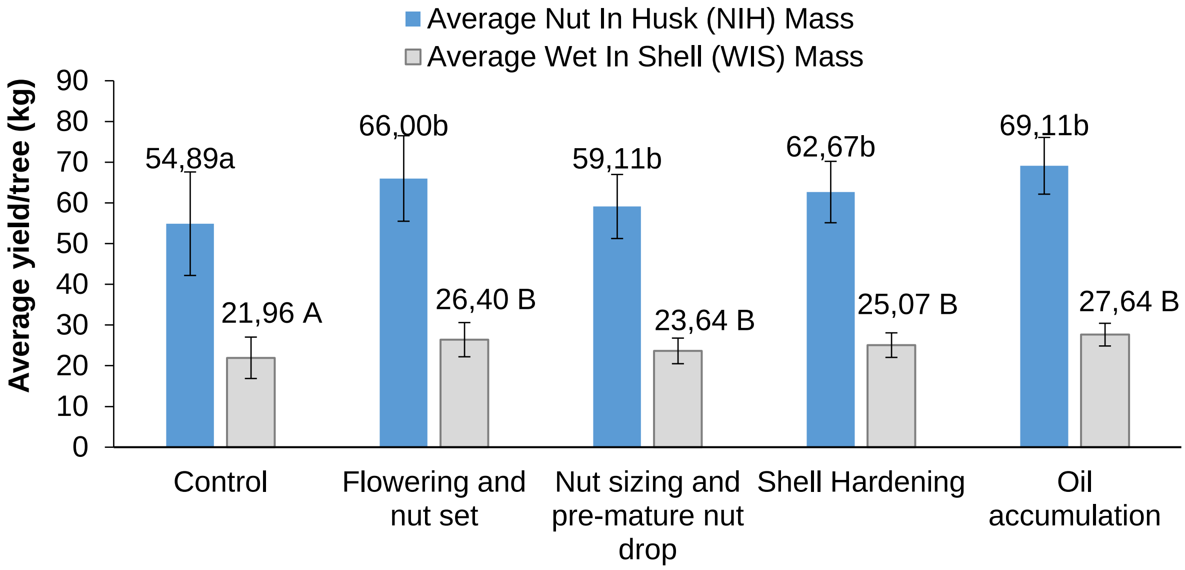


Figure 4.39: Average harvested nut mass (kg) per tree over nine measurement replicates per treatment for the 2018/19 season. Treatments with the same letter are not significantly different from each other ($p \leq 0.05$). NIH:WIS = 60:40

Yield increases in the stressed treatments could also be linked to a reduction in vegetative growth (although not measured in this study) during the respective phenological stages, as carbohydrate reserves previously partitioned to vegetative growth could potentially be assigned to the developing crop, which is the dominant sink (Stephenson et al., 1989). For example, Stephenson et al. (1986) showed that yields may be decreased by active vegetative growth in late spring. This, however, is unlikely as current photosynthesis would have also been affected by water deficit conditions, likely having an adverse effect on yield during the current or next phenological stage of the respective treatment. In fact, Stephenson and Gallagher (1989) concluded that managerial procedures affecting the availability of carbohydrate reserves are more likely to affect reproductive than vegetative growth. Stephenson et al. (2003) further showed that vegetative growth was supressed by a mild water stress (not observed in this study), where after trees responded to re-watering with a massive burst of vegetative growth. This again suggests that reduced vegetative growth during a specific phenological stage could possibly impact nut development at a later stage. For example, a delay in the early spring flush may have improved initial set, but re-watering would have resulted in vegetative growth during the next phenological stage, negatively affecting the trees in this treatment during nut sizing and pre-mature nut drop. This is, however, not supported by the findings of this study with all treatments showing improved yields relative to the control. Importantly, the level of stress achieved in this study needs to be considered in relation to the study by Stephenson et al. (2003). It is possible that only a mild water stress was achieved in this current study and Stephenson et al. (2003) concluded that, since improved yields can be achieved by a change in macadamia phenology, the cautious application of mild water stress may be useful to manipulate macadamia trees to achieve higher yields.

Water stress during nut sizing and premature nut drop is often associated with increased nut drop, potentially contributing to the natural weaning process of the tree (Stephenson and Gallagher, 1987). Nut sizing and pre-mature nut drop during the 2018/19 season further coincided with high VPD_{air} levels during late October and early November (Table 4.14), which with low water availability have been shown to significantly increase pre-mature nut abscission (Stephenson et al., 2003). In an earlier study, Stephenson and Gallagher (1987) also showed that high day temperatures (>30°C) can induce heavier nut drop and that young nuts were sensitive to increases in temperature during endosperm development. Despite significant evidence in literature supporting the possibility of increased nut abscission if external stresses coincide with the nut sizing and pre-mature nut drop phenological stage, similar findings of increased nut abscission (reduced final set) were not made over the course of this study (Figure 4.40 and Figure 4.41).

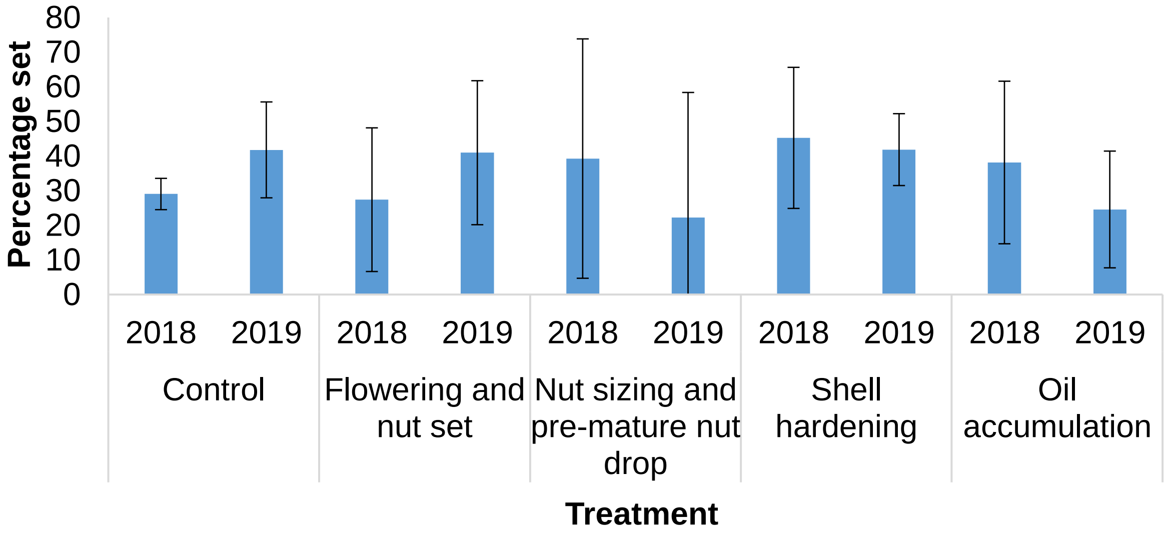


Figure 4.40: Average percentage final nut set over nine measurement replicates per treatment for the 2018/19 and 2019/20 seasons

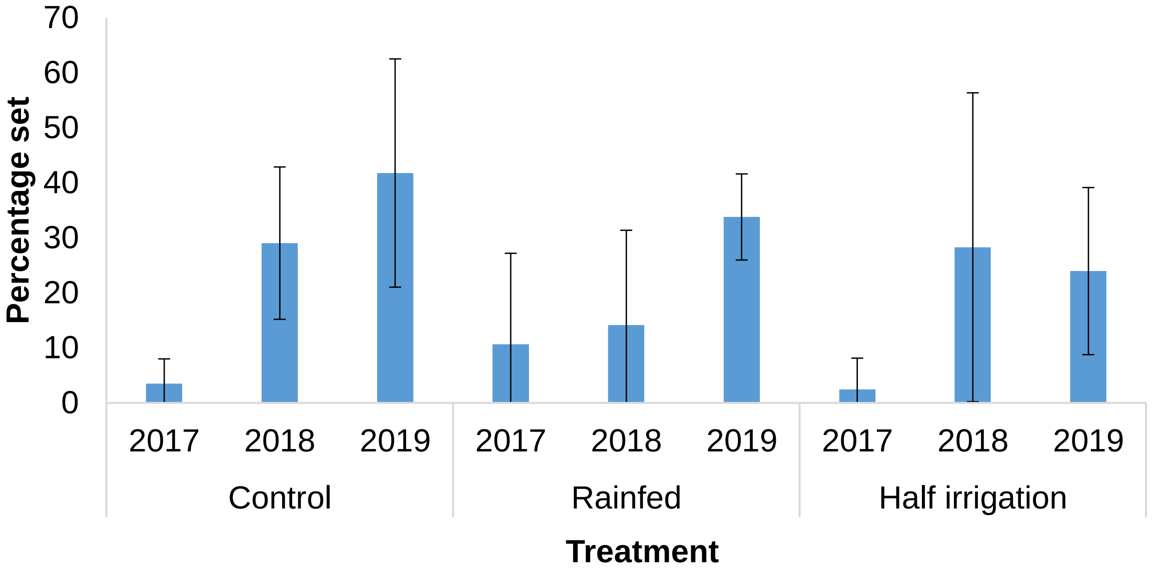


Figure 4.41: Average percentage final nut set over nine measurement replicates per treatment for the 2017/18, 2018/19 and 2019/20 seasons

In addition, the lack in measured difference in final nut set between the various treatments can potentially be attributed to limitations that arose in the methodology used during the current trial. A single macadamia tree produces >10000 inflorescence, each containing approximately 200-300 flowers which are born on hardened wood in all parts of the canopy (Carr, 2013). Although between 5-10% of these flowers set fruit (Carr, 2013), only 0.3% may reach maturity (Nagao, 2011). Hence, by selecting a single branch or multiple racemes within the canopy, it may still provide a non-representative data set of the percentage final nut set (% Final set = ((Initial set – Nut drop)/ Initial set)) x 100) as a crop load adjustment could have been made in a different part of the canopy. Initial nut set per raceme is further affected by possible pest and disease incidence and the potential lack of cross pollination (Carr, 2013). In some instances, entire racemes were lost due strong winds or mechanical damage by farm equipment. It is therefore recommended that whole tree nut abscission for each of the respective treatments should be measured, as this will provide the best possible indication of the effect of water deficits on nut abscission and reduce the substantial standard deviation observed in Figure 4.40 and Figure 4.41.

Both rainfed and half irrigation treatments resulted in significantly ($p \leq 0.05$) higher yields (nut in husk and wet in shell yield) than the fully irrigated trees when considering cumulative yield over both the 2017/18 and 2018/19 seasons, and yield for each season individually (Figure 4.42). Trochoulias and Johns (1992) similarly reported an inconsistent response of macadamia to irrigation in high rainfall areas, with improved yields in irrigated trees in only 5 years of the 8 season study period. Trees used in the study by Trochoulias and Johns (1992) were, however, widely spaced (11 m x 11 m) which could have resulted in trees having a much larger root volume, as well as a larger soil water reservoir to buffer against the development of water stress. Yield differences between half irrigation and control trees could be possibly linked to limitation of nutrient losses as a result of leaching in control trees due to higher irrigation volumes. Control trees were, however, irrigated according to a capacitance probe, the industry norm, which raises concerns with the current industry irrigation recommendations. Similar to trees stressed during different phenological stages, trees receiving half the normal irrigation may have experienced improved root growing conditions and/or lower disease incidence which may have improved the tree yield response. Nevertheless, rainfed trees further showed a 7 kg WIS increase and a 2% increase in total kernel recovered (TKR) (Figure 4.43) in the 2018/19 season when compared to the 2017/18, suggesting no knock-on effect of water deficits in the 2017/18 season on macadamia yield and quality in the second season of measurements. Figure 4.43 further shows no significant difference (*p* > 0.05) in the TKR percentage between the rainfed, half irrigation and control treatments over a two season period, while the percentage discolouration was significantly (*p* ≤ 0.05) higher during the 2017/18 season. Consequently, the percentage first grade kernel was significantly (*p* ≤ 0.05) higher during the 2018/19 season than during the 2017/18 season.

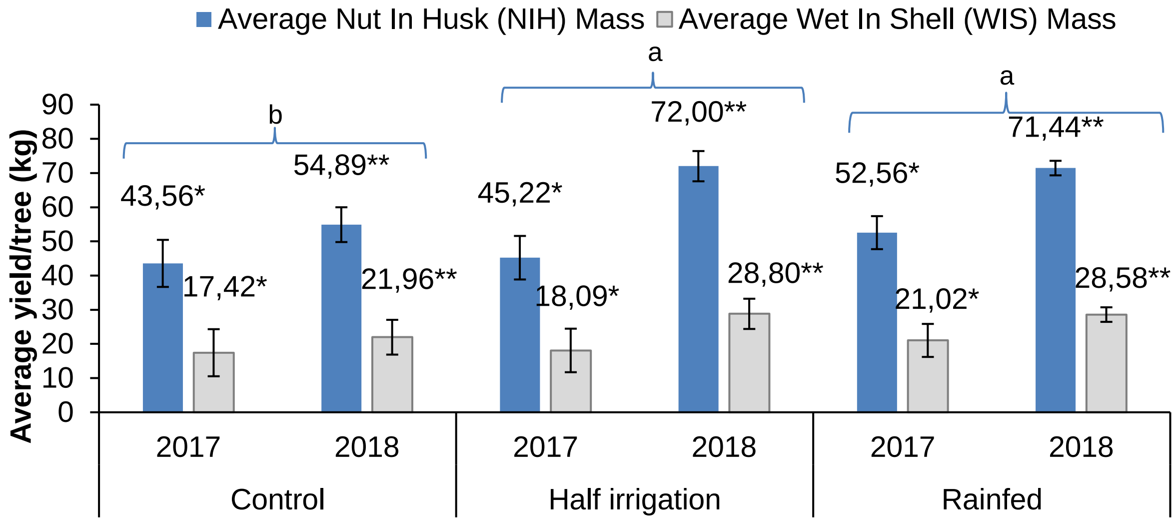


Figure 4.42: Average harvested mass (kg) of nut in husk per tree over nine measurement replicates per treatment for the 2017/18 and 2018/19 seasons. Sample means across both seasons with different letters indicate significant differences (p ≤ 0.05) between treatments. Sample means with a different number of * indicate significant differences (p ≤ 0.05) between seasons. NIH:WIS = 60:40

Two way ANOVA, however, shows no significant difference (*p* > 0.05) between both treatment and year over a two year period, showing no seasonal effect on different treatment outcomes.

Although annual environmental conditions weren't significantly different, seasonal conditions such as temperature and VPD during more sensitive phenological stages, such as anthesis, could possibly have had an over-riding effect on the increase in yield over the two seasons (Smit et al., 2020, Stephenson et al., 2003, Stephenson et al., 1989).

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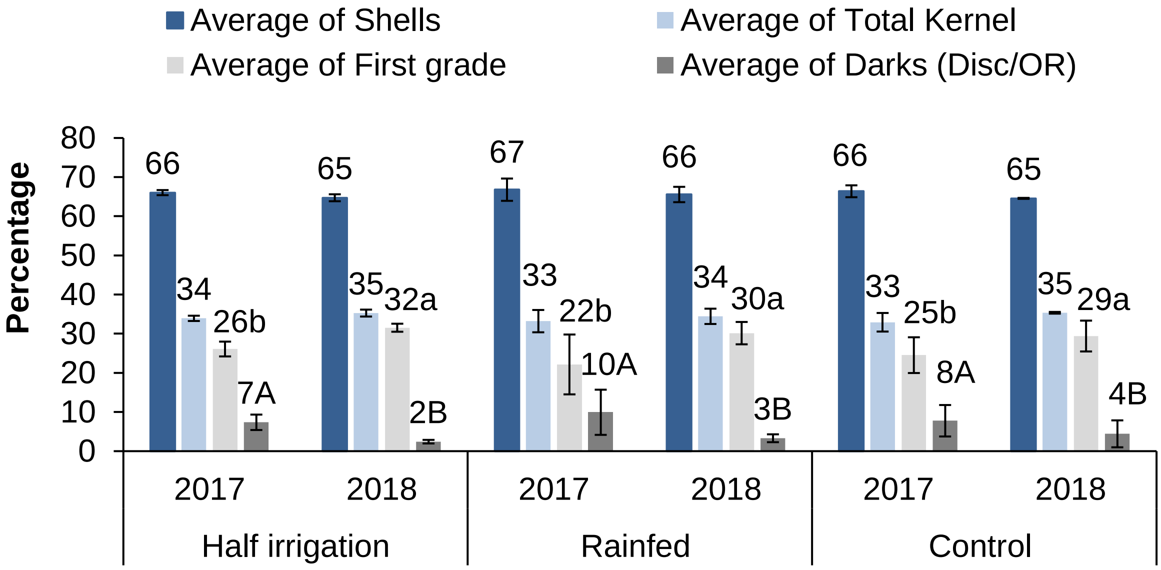

Figure 4.43: Average quality parameters over nine measurement replicates per treatment for the 2017/18 and 2018/19 seasons. A 2000g sample was used for each treatment. First grade sample means with different letters indicate significant differences ($p \leq 0.05$) between seasons. Darks sample means with a different number of * indicate significant differences ($p \leq 0.05$) between seasons.

In contrast to the effect of water stress during different phenological stages on yield, a significant difference ($p \leq 0.05$) in quality was observed between the seven experimental treatments in the 2018/2019 season (Figure 4.44). Trees stressed during flowering and nut set, as well as trees stressed during shell hardening had a significantly ($p \leq 0.05$) higher shell percentage and therefore significantly ($p \leq 0.05$) lower TKR percentage, when compared to the control. Water stress during flowering and nut set and shell hardening stages had 3.35% and 1.42% lower TKR than the treatment control. This was unexpected as water stress during flowering is not expected to have an influence on nut quality. The reduction in TKR observed could possibly be attributed to a lag in recovery in physiological functioning after the onset of water stress, leading to a possible deficit in carbohydrate availability during the nut sizing and premature nut drop phenological stage. Stephenson et al. (1989) showed that the macadamia flowering period coincides with the spring vegetative flush, tapping large amounts of stored carbohydrate reserves. A reduction in cumulative diurnal photosynthesis at this time could lead to a deficit in carbohydrate reserves during the nut sizing stage as a result of the onset of water stress in flowering and nut set. This is supported by findings by Stephenson et al. (2003) who demonstrated that floral development and premature nut drop are the most sensitive phenological stages to water deficits in terms of yield (both kernel and NIS). Yield improvements through irrigation in areas where relative dry periods coincide with the flowering and early nut sizing stages have also been reported (Carr, 2013). Stephenson et al. (2003), however, noted an increase in TKR for trees subjected to water deficits during the premature nut drop stage, attributing the increase in TKR to a fruit 'thinning' effect which allows for the partitioning of carbohydrate to the remaining nuts.

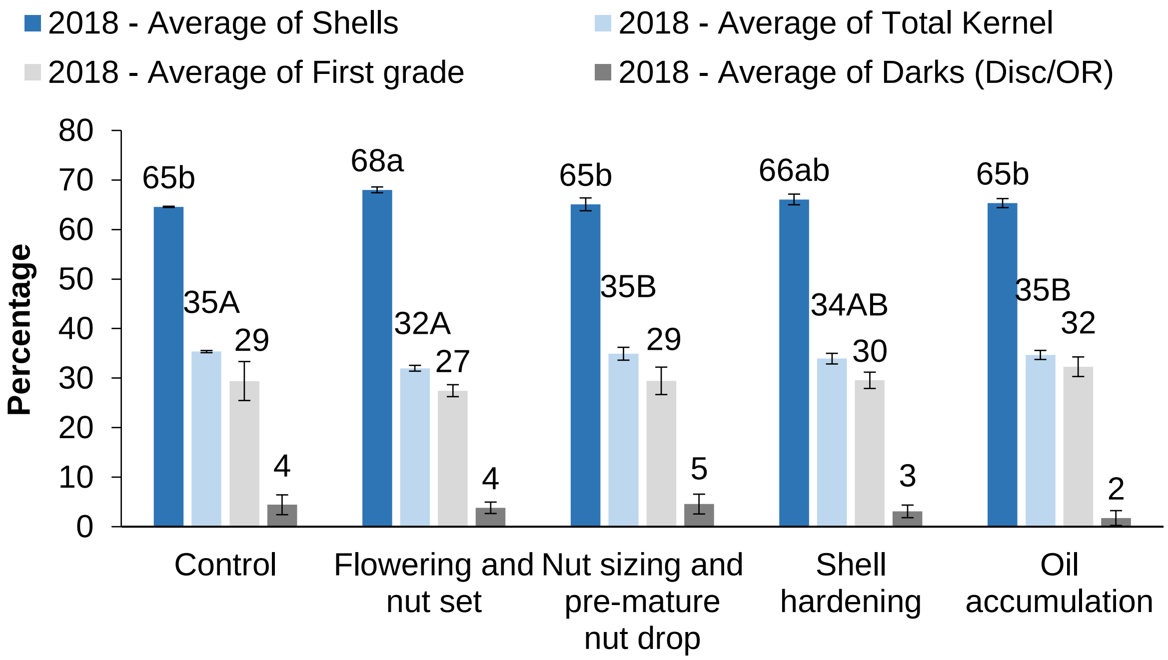

Figure 4.44: Average quality parameters over nine measurement replicates per treatment for the 2018/19 season. A 2000g sample were used for each treatment. Sample means with different letters indicate significant differences ($p \leq 0.05$) between treatments

Even though Stephenson et al. (2003) did not distinguish between the shell hardening and oil accumulation phenological stages, the authors reported that water stress during nut maturation/oil accumulation stage (December-January) was highly detrimental to yield and quality. A study by Awada et al. (1967) also reported sufficient soil water to be essential for nut maturation. Hence, although similar phenological stages were identified with this study, the contrast in the degree of sensitivity of yield and quality to water stress during the two different phenological stages can possibly be attributed to the higher level of stress achieved in the lysimeter study by Stephenson et al. (2003). Furthermore, rainfall and other relevant environmental factors, such as VPD_{air} (Table 4.14), were very favourable during the oil accumulation stage in this study (VPD_{air}<0.8 kPa and rainfall>260 mm), significantly reducing the probability of inducing sufficient stress during this stage to cause an impact on yield and quality.

The study by Stephenson et al. (2003) further reported water stress during floral initiation to have no effect on yield or nut number and also no difference in the flowering intensity between irrigated and stressed trees. Similar findings were made for trees exposed to water deficits during the floral initiation period (rainfed treatments), with no observed difference in flowering intensity, yield or quality.

4.3.5 THE EFFECT OF PLANT AND SOIL WATER DEFICITS ON MACADAMIA PHYSIOLOGICAL FUNCTIONING

There is limited literature available on macadamia physiological responses to water deficits, with most available literature assessing A_{max}, g_s, $\Psi_{L,}$ Ψ_{pd} and soil water deficits independently. This information is critical for understanding thresholds for stress in macadamia that could have an impact on yield and for scheduling irrigation to maximise water use efficiency.

In order to try and understand the response of macadamias to water stress, various levels of water deficits were imposed in an intermediate macadamia orchard in order to try and identify a Ψ_{pd} threshold at which g_s and A_{max} are significantly reduced. Trees undergoing a 30 day stress period without irrigation were exposed to a 62.35 mm water deficit, where a water deficit was calculated as the difference between ET_o and rainfall. Importantly, no rainfall was recorded during his period. In addition, trees undergoing a 25, 20 and 15 day period without irrigation were subjected to a 50.67, 38.72 and 18.16 mm water deficit over each respective period. Throughout the trial weather conditions remained fairly cool, with moderate VPD (<1 kPa). The combination of a well-drained soil and the withholding of irrigation in the intermediate orchard resulted in a reduction in the average minimum Ψ_{pd} from -0.1 MPa for control trees to an average minimum of -0.48 MPa for trees receiving no water over a 30 day period (Figure 4.45). A reduction in Ψ_{pd} was correlated with the duration of the different water deficit treatments, with trees exposed to a 25, 20 and 15 day water deficit having an average minimum Ψ_{pd} of -0.26 MPa, -0.13 MPa and -0.12 MPa respectively (Figure 4.45).

Table 4.16: Weather data summary over the 30 day trial period in the intermediate orchard. Daily average values were used for air temperature (T_{air}), total incident solar radiation (R_s), air vapour pressure deficit (VPD_{air}) and total reference evapotranspiration (ET_o)

Treatment	Date	Time (days)	T_{air} (°C) (Av ± Std)	R_s (MJ m^{-2} day^{-1}) (Av ± Std)	VPD_{air} (kPa) (Av ± Std)	ET_o (mm) (Av ± Std)	ET_o (mm) (Total)
Control	25 May-24 Jun	31	12.9 ± 2.2	9.7 ± 2.1	0.83 ± 0.32	2.0 ± 0.6	62.4
15 day water deficit	9-24 Jun	16	11.9 ± 2.1	9.1 ± 2.7	0.75 ± 0.33	1.9 ± 0.6	18.2
20 day water deficit	4-24 Jun	21	12.2 ± 1.9	9.3 ± 2.5	0.74 ± 0.31	1.8 ± 0.5	38.7
25 day water deficit	30 May-24 Jun	26	12.8 ± 2.1	9.5 ± 2.3	0.76 ± 0.28	1.9 ± 0.5	50.7
30 day water deficit	25 May-24 Jun	31	13.0 ± 2.2	9.7 ± 2.1	0.83 ± 0.32	2.0 ± 0.6	62.4

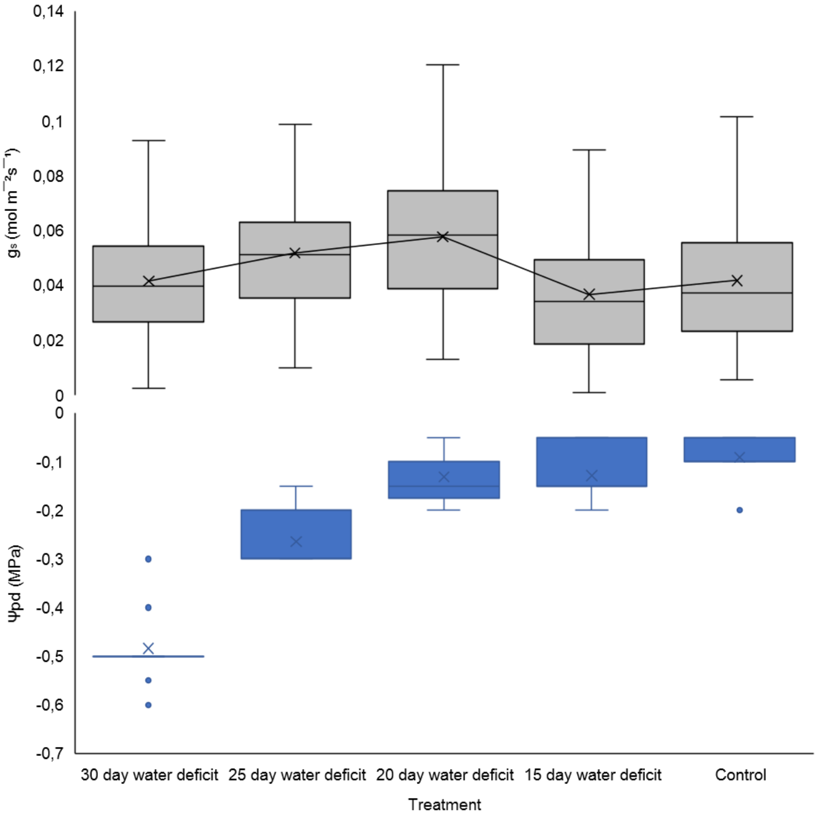

Figure 4.45: Stomatal conductance (g_s) (mol $m^{-2}s^{-1}$) at different pre-dawn water potentials (Ψ_{pd}) (-MPa) for four water deficit treatments and a well-watered control. Stomatal conductance data points were obtained over an eight-hour measurement period during three measuring campaigns (22 June-24 June 2020). Pre-dawn water potentials were recorded prior to sun-rise during each of measuring campaigns.

A linear reduction in g_s with more negative Ψ_{pd} levels was, however, not observed in the intermediate orchard, with g_s remaining relatively constant for Ψ_{pd} readings between -0.05 and -0.5 MPa. Stomatal conductance was the same for trees subjected to a 30 day water deficit (0.41 mol $m^{-2}s^{-1}$) and for control trees (0.41 mol $m^{-2}s^{-1}$) (Figure 4.45). Stomatal conductance values in this trial were substantially lower than the average diurnal g_s values reported in a lysimeter study by Stephenson et al. (2003). Stephenson et al. (2003) reported mean maximum g_s values of approximately 0.28 mol $m^{-2}s^{-1}$ and 0.25 mol $m^{-2}s^{-1}$ for stressed and unstressed trees during a five hour measurement campaign. Maximum g_s values recorded in the intermediate orchard was approximately 0.13 mol $m^{-2}s^{-1}$. Maximum g_s was, however, similar to the levels reported by Lloyd et al. (1991) (g_s ±0.15 mol $m^{-2}s^{-1}$) for five year old, unirrigated macadamia trees after a 30 day rainless period (Ψ_{pd} ± -0.15 MPa). These authors first noted a reduction in g_s, relative to irrigated trees (g_s ±0.20 mol $m^{-2}s^{-1}$), after approximately 30 days without water. This was unexpected, as Lloyd et al. (1991) noted that at the stage when a reduction in g_s was first observed, soil water would have already been depleted by more than 125 mm ($K_c = 0.6$) which is substantially more than what was previously reported to affect the physiological functioning of peach (75 mm) (Chalmers et al., 2012) and citrus (60 mm) (Buss, 1988). The low g_s values in this study were most likely a result of prevailing weather conditions, such as air temperature and relative humidity, which were below the optimum required for optimal physiological functioning. Both the study by Lloyd et al. (1991) and by Stephenson et al. (2003) were carried out in spring (September-October), which coincided with much warmer temperatures, higher VPD_{air}, solar radiation and ET_o values than what was experienced during the measurement campaigns in this study (Table 4.17). Seasonal effects on leaf gas exchange have been previously noted by Machado et al. (2002) who recorded lower leaf gas exchange rates in citrus trees during winter than in summer.

The lack of a response of g_s to water deficit treatments is also reflected in the response of A_{max} to these treatments (Figure 4.46). Although g_s and A_{max} were highly correlated (R^2 0.87-0.92) over all treatments, there was no substantial difference recorded in the response of A_{max} to g_s between the different water deficit treatments and well irrigated trees (Figure 4.46). This suggests that both A_{max} and g_s were unaffected by the level of stress achieved in the orchard over a 30 day period and that during this trial macadamia gas exchange parameters are more affected by changes in atmospheric, such as VPD_{air}, than soil conditions. It can thus be tentatively proposed that Ψ_{pd} above -0.5 MPa do not result in stressful conditions that lead to changes in g_s or A_{max}.

Table 4.17: Mean weather variables, including air temperature (T_{air}), maximum temperature (T_{max}), vapour pressure deficit (VPD_{air}), solar radiation (R_s) and daily total reference evapotranspiration (ET_o) during each of the 10 leaf gas exchange measurement campaigns. Measurements performed during the 2018/19 season were conducted in the mature orchard while measurements in 2020 were performed in the intermediate orchard

Date	Year	T_{air} (°C)	T_{max} (°C)	R_s (MJ m^{-2} day^{-1})	VPD_{air} (kPa)	ET_o (mm)
1 June	2018	17.7	27.7	15.8	1.45	3.11
2 June	2018	14.1	23.5	15.8	1.05	2.68
1 October	2018	18.5	31.6	24.8	1.91	5.14
2 October	2018	23.3	35.1	25.3	2.75	6.11
30 January	2019	21.8	28.0	18.5	0.62	3.46
31 January	2019	21.7	28.8	20.4	0.66	3.82
22 June	2020	12.4	20.1	10.2	0.63	1.76
23 June	2020	12.7	23.2	9.4	1.01	2.14
24 June	2020	11.6	20.6	10.1	0.62	1.69
9 July	2020	13.9	22.4	10.3	0.54	1.71

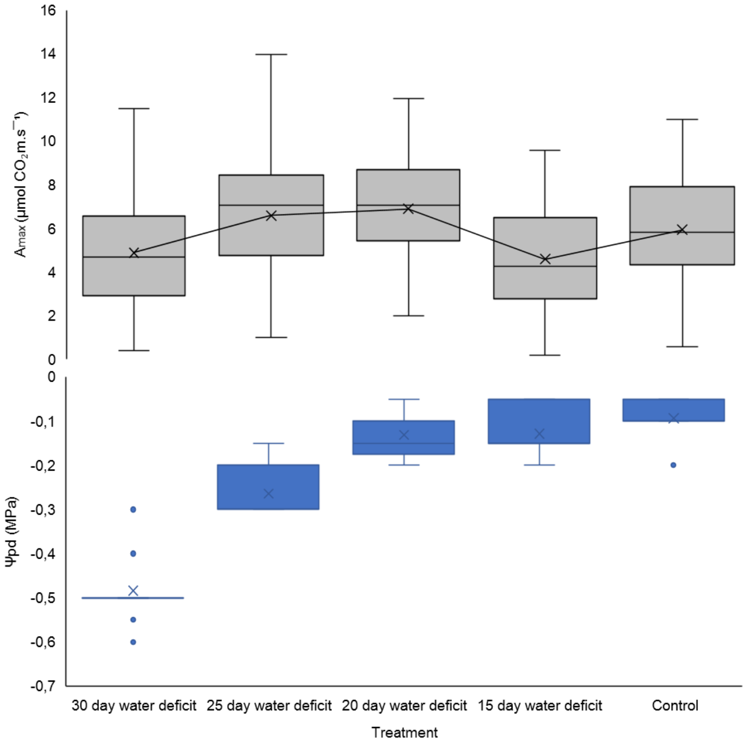

Figure 4.46: Maximum net photosynthetic assimilation rate (A_{max}) at different pre-dawn water potentials (Ψ_{pd}) (-MPa) for four water deficit treatments and a well-watered control. Maximum net photosynthetic assimilation rate data points were obtained over an eight-hour measurement period during three measuring campaigns (22 June-24 June 2020). Pre-dawn water potentials were recorded prior to sun-rise during each of measuring campaigns.

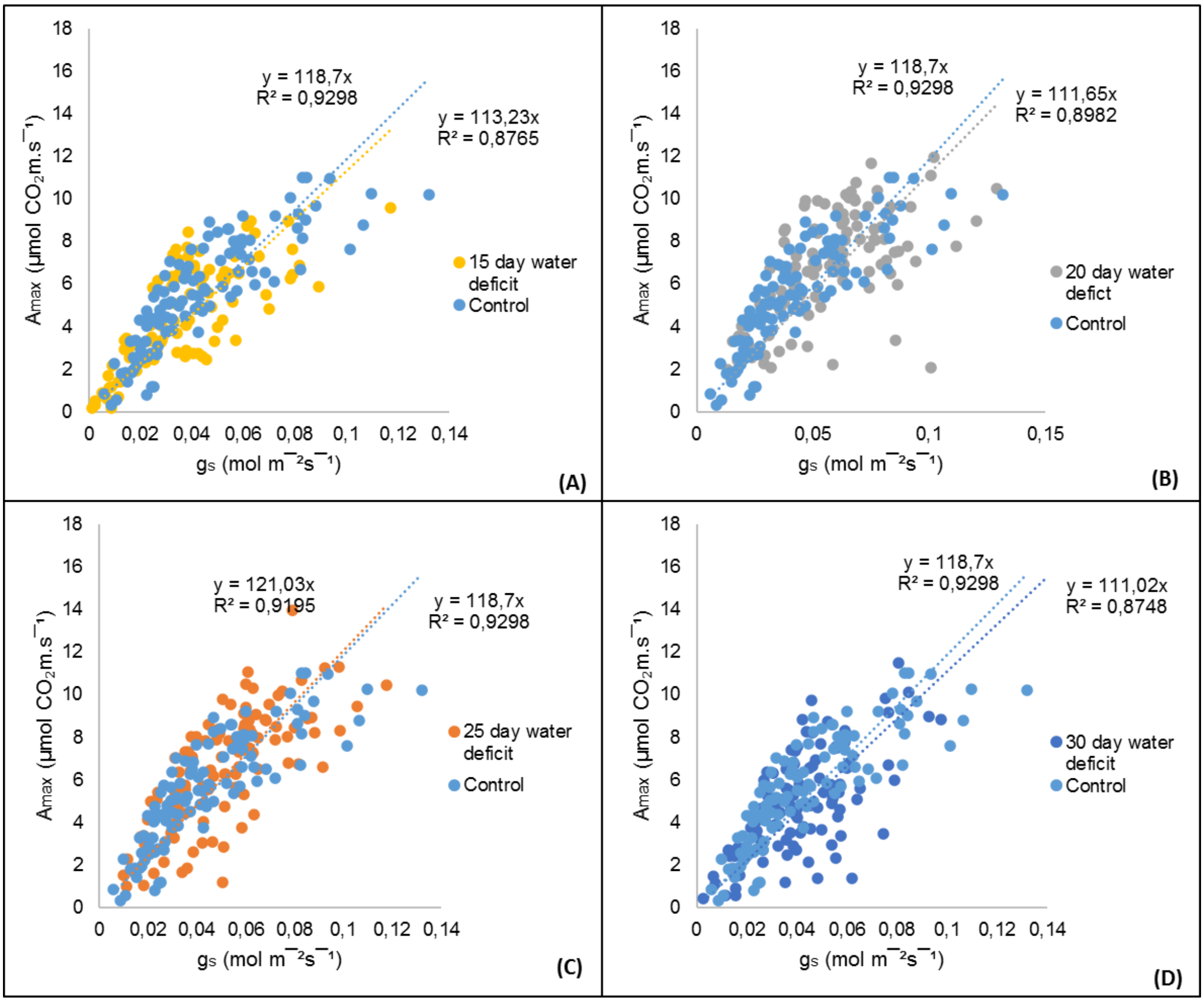

Figure 4.47 The relationship between the maximum net photosynthetic assimilation rate (A_{max}) and stomatal conductance (g_{s}) (mol m^{-2}s^{-1}) of four water deficit treatments and a well-watered control. Data points were obtained over an eight-hour measurement period during three measuring campaigns (22 June-24 June 2020).

Stephenson et al. (2003) showed the g_{s} of stressed trees to be similar to that of unstressed trees, until peak VPD$_{\mathrm{air}}$ levels (1.6 kPa) have been reached. The authors found that g_{s} of stressed trees declined and remained low after the midday depression (caused by peak VPD$_{\mathrm{air}}$), whereas unstressed trees recovered. Stephenson et al. (2003) attributed the lower gas exchange values after midday to a root signal induced reduction in $g_{\mathrm{s},}$ caused by low root zone water potentials. During the current study, g_{s} of stressed and control trees showed a similar response to changing levels (<3 kPa) of VPD$_{\mathrm{leaf}}$ (assuming that T$_{\mathrm{leaf}}$ = T$_{\mathrm{air}}$) (Figure 4.48). Stomatal conductance of stressed trees was, however, substantially reduced, relative to the control, at VPD$_{\mathrm{leaf}}$ levels >3 kPa. Hence, suggesting a similar repose to what is observed by Stephenson et al. (2003), with a substantial reduction in g_{s} of stressed trees, once a threshold VPD level is reached. The findings by Stephenson et al. (2003) combined with those observed over the course of this study may aid in our understanding on why water deficit condition imposed during the flower initiation have limited effect of the yield and quality of macadamias. Flower initiation typically coincide with winter periods (May-July) in the southern hemisphere, which is characterised by lower atmospheric temperatures, low solar radiation and low $\mathrm{VPD}_{\mathrm{air}}$. Under these conditions, threshold VPD levels will seldom be exceeded and as a result gas exchange of trees experiencing a mild water deficit will not be impacted.

Stephenson et al. (2003) further showed that photosynthesis and g_s were highly but negatively correlated with VPD. Similar observations were, however, not made in the intermediate orchard, as observed form Figure 4.48 and Figure 4.49. Since $A_{\max}$ is a function of g_s, the correlation between $A_{\max}$, water deficits and VPD is most likely related to the sensitivity of g_s to these factors. Hence, the effect of VPD on macadamia gas exchange may influence the interpretation of tree physiological responses to water deficits under field conditions.

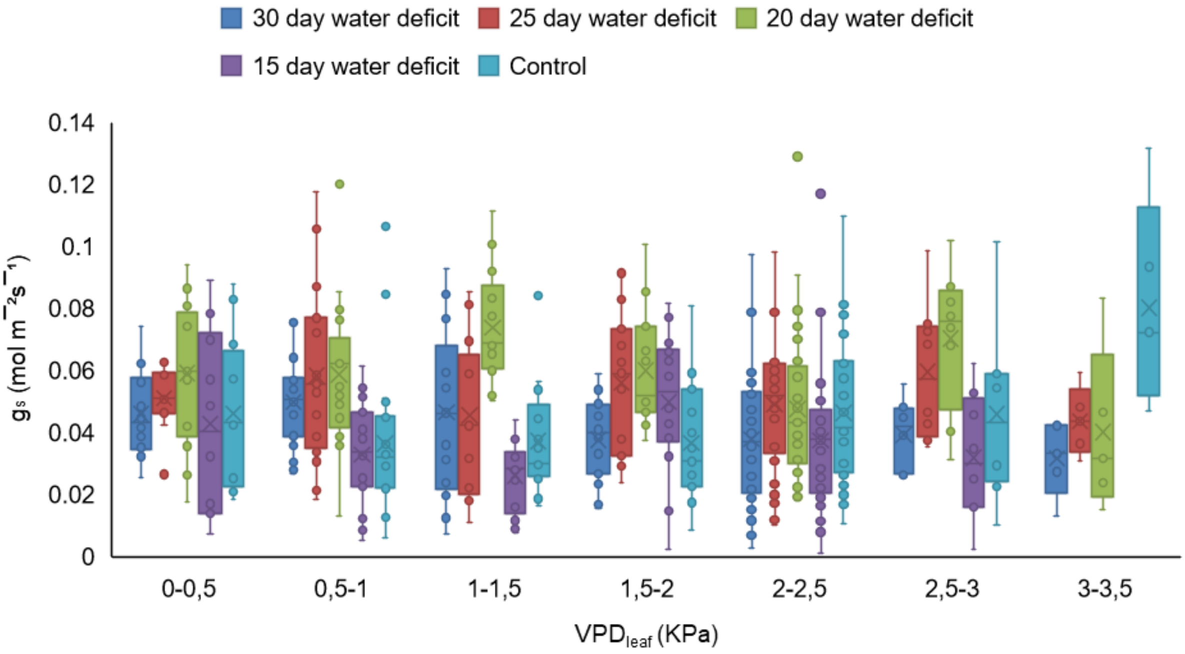

Figure 4.48: Stomatal conductance (g_s) (mol m^{-2}s^{-1}) at different leaf vapour pressure deficits ($\mathrm{VPD}_{\mathrm{leaf}}$) (kPa) for four water deficit treatments and a well-watered control. Data points were obtained over an eight-hour measurement period during three measuring campaigns (22 June-24 June 2020)

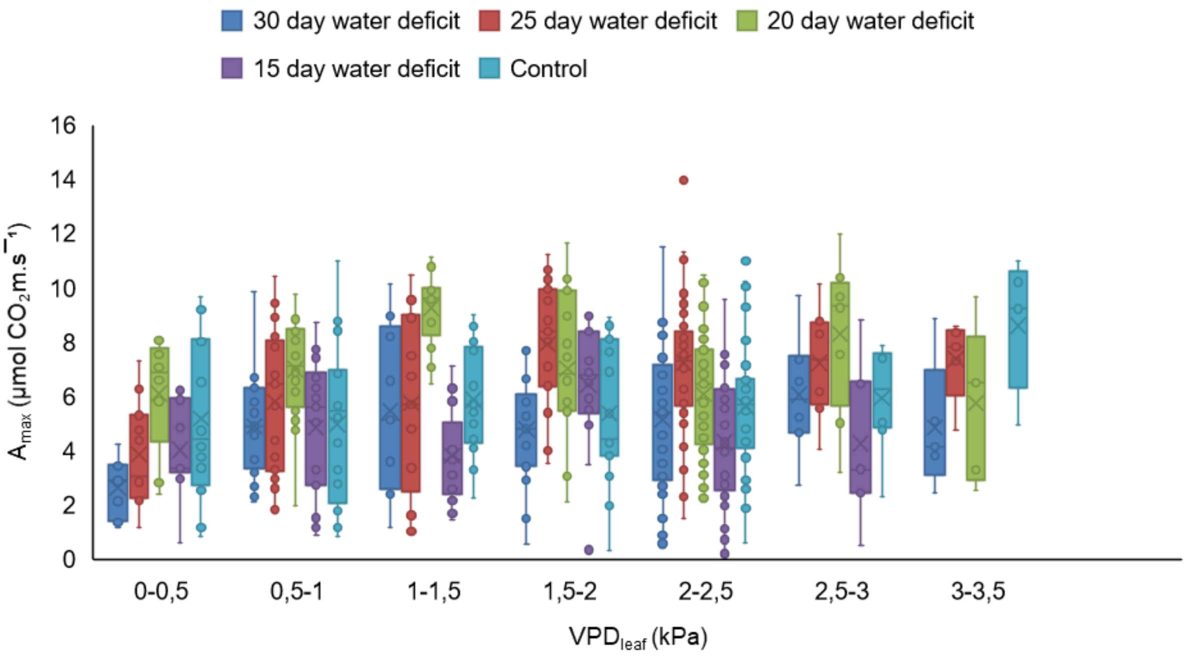

Figure 4.49: Maximum net photosynthetic assimilation rate (A_{max}) at different leaf vapour pressure deficits (VPD$_{leaf}$) (kPa) for four water deficit treatments and a well-watered control. Data points were obtained over an eight-hour measurement period during three measuring campaigns (22 June-24 June 2020)

When assessing the response of macadamia gas exchange to different Ψ_{pd} levels for a range of atmospheric variables, including VPD (Table 4.17), g_s and A_{max} was shown to be highly but negatively correlated with different water deficit levels (Figure 4.50 and Figure 4.51). Measurements conducted in both mature and intermediate orchards showed a substantial reduction in average g_s (R^2 0.76) and A_{max} (R^2 0.79) with every unit change in Ψ_{pd}. A considerable difference in average g_s was observed between well-watered trees (Ψ_{pd} -0.05 MPa) and trees subjected to water deficits with a 26%, 30% and 74% reduction in average g_s observed for trees at a Ψ_{pd} of -0.4 MPa, -0.7 MPa and -1.2 MPa respectively (Figure 4.50). The response of g_s to water deficits was also reflected in A_{max} (Figure 4.51). Lloyd et al. (1991) showed g_s of unirrigated macadamia trees to be 30% lower than that of the irrigated trees after a two month rainless period, when measured in spring. Although much lower Ψ_{pd} (<-0.6 MPa) were recorded in the mature orchard than what was reported by Lloyd et al. (1991) (± -0.22 MPa), minimum values of both g_s and Ψ_{pd}, in both studies were recorded during spring (October) which coincided with relative high ET$_o$ and VPD$_{air}$ levels (Table 4.17). Hence, significant stomatal down regulation to atmospheric evaporative demand and soil water deficits was observed, as these conditions were more likely to lead to an imbalance between atmospheric evaporative demand and the ability of the plant to supply the leaves with water (Campbell and Turner, 1990).

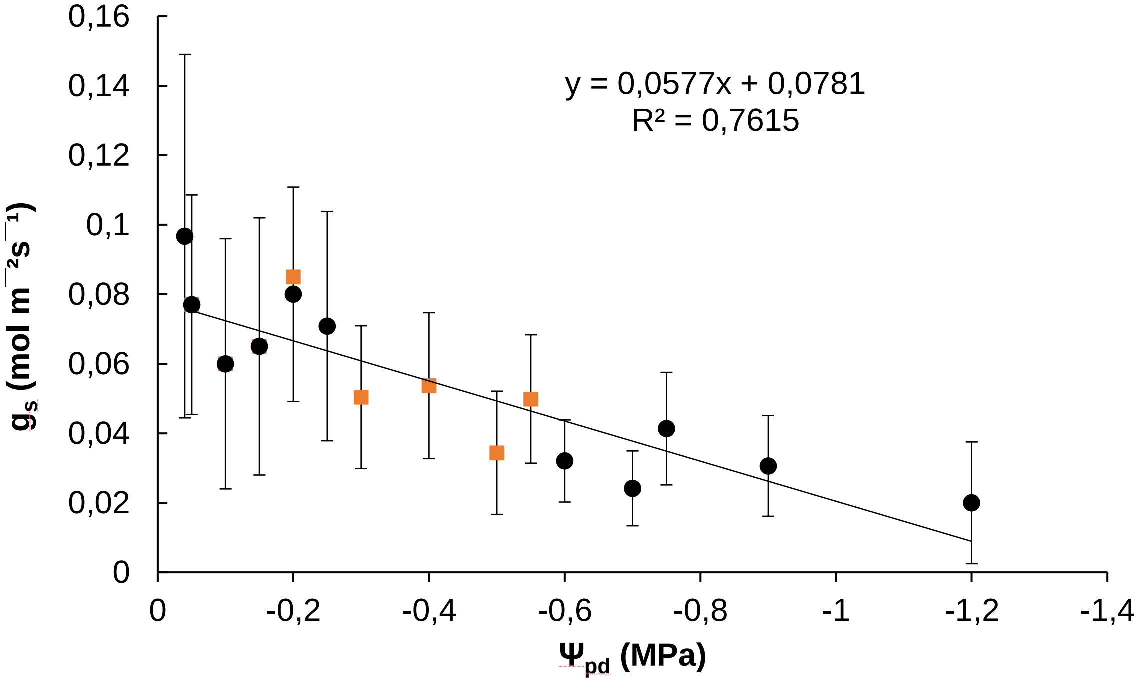

Figure 4.50: Mean stomatal conductance (g_s) (mol $m^{-2}s^{-1}$) at different pre-dawn water potential levels (Ψ_{pd}) (-MPa). Gas exchange data presented was collected over an eight-hour measurement period during 10 different measurement campaigns. Orange data points were obtained during the intermediate orchard measuring campaign while black data points were obtained during the mature orchard measurement campaigns

The down regulation in A_{max} in response to water deficits (Figure 4.51) can be related to the reduction g_s for trees subjected to water deficits. A reduction in g_s leads to a decrease in transpiration and therefore a decrease in CO_2 entering the leaf mesophyll (gas exchange), ultimately resulting in a lower CO_2 assimilation rate and an increase in leaf temperature (Ribeiro and Machado, 2007). It thus seems that from the data collected in this trial, macadamia trees start experiencing water stress when Ψ_{pd} <-0.6 MPa. In most instances is this trial these values were only achieved after water was withheld for a period of a month and under drier conditions reflected in higher ET_o and VPD.

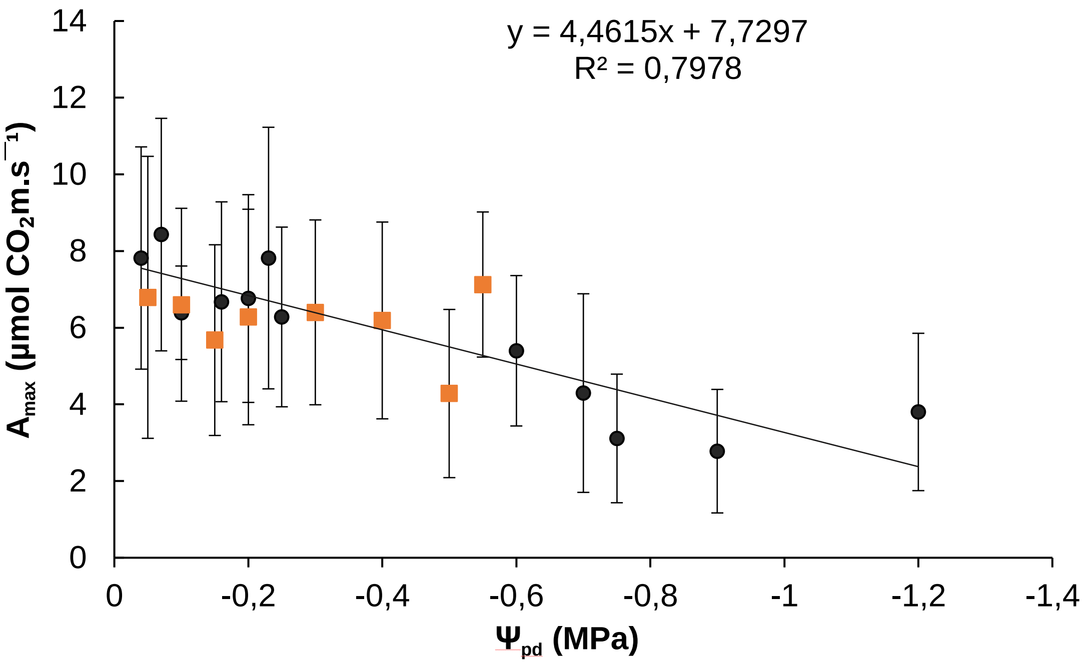

Figure 4.51: Mean maximum net photosynthetic assimilation rate (A_{max}) at different pre-dawn water potential levels (Ψ_{pd}) (-MPa). Gas exchange data presented was collected over an eight-hour measurement period during 10 different measurement campaigns. Orange data points represent data obtained during a measurement campaign in the intermediate orchard, while black data points represent data obtained during measurement campaigns in the mature orchard

4.3.6 MIDDAY STEM (Ψ_{STEM}) AND LEAF WATER POTENTIAL (Ψ_L) AS INDICATORS OF MACADAMIA WATER STRESS

Plant tissue water potential at any time depends on both the bulk soil water content and the hydraulic conductivity of the plant, as well as the resistance to water flow between the bulk soil and plant tissue (Jones, 2004). The scheduling of irrigation, based on plant water status, requires some reference or threshold value for when irrigation is required, which is related to the development of stress which impacts plant performance. Whilst, Ψ_{pd} is widely regarded as one of the best measures of developing water stress, measurements of Ψ_{stem} and Ψ_{leaf} have been investigated as they may be more practical for commercial use (Jones, 2004). Diurnal $\Psi_{leaf,}$ however, imitates the effect of multiple, often fluctuating variables at a single leaf level such as, local leaf water demand (VPD, leaf intercepted radiation), soil water availability, internal plant hydraulic conductivity and stomatal regulation (Chone et al., 2001, Naor and Cohen, 2003). Hence, potentially making Ψ_{leaf} an unsuitable indicator of water deficit conditions in isohydric plants (Jones, 2004). Since, bagged Ψ_{stem} aren't as subject to environmental fluctuations as Ψ_{leaf}, these measurements are more preferred as they have shown to be more stable and more closely related to soil water status than Ψ_{leaf} (Correia et al., 1995, McCutchan and Shackel, 1992). Results from this study suggests Ψ_{pd} measurements in macadamia are strongly correlated (r^2 0.79) with bagged midday Ψ_{stem} measurements (Figure 4.52). This relationship should, however, be determined in a range of growing regions which differ substantially in climate, as it may differ between humid and more arid regions.

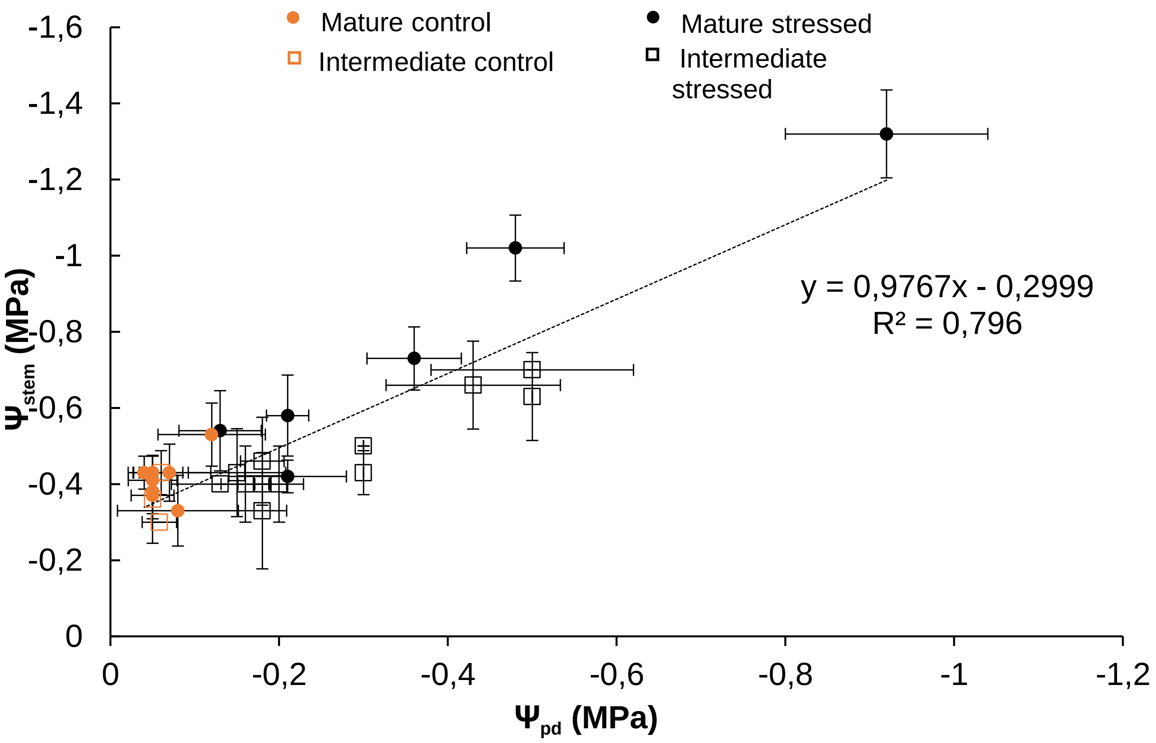

Figure 4.52: The relationship between predawn (Ψ_{pd}) (-MPa) and bagged midday Ψ_{stem} (MPa) measurements (Mean ± std). Data points represents data obtained during both the mature and intermediate orchards measurement campaigns. Non-filled data points represent measurements made under stressed conditions while filled data points represent measurements made under well-watered conditions

4.3.7 CONCLUSIONS

Results from this study suggest that macadamias are less sensitive to water stress than most other horticultural crops. This is based on the findings that withholding water during key phenological stages had no impact on yield for one season of measurements relative to the control, where irrigation was scheduled by the grower according to soil water measurements. In addition, irrigating half the volume of the grower scheduled control or relying solely on rainfall had no impact on yield over two seasons. A second season of yield measurements quantifying the impact of stress at different phenological stages was unfortunately lost due to the COVID-19 lockdown and these results could have proven invaluable in reaching a more definite conclusion regarding how water stress impacts yield and quality of macadamia orchards. Importantly, what the study has illustrated is that despite withholding irrigation for fairly long periods of time, key indicators of plant stress, did not suggest that the trees were often stressed, when compared to the well-watered control. In the current study, this was complicated by the fact that there was large variation between replicates, which was probably indicative of variations in spatial water availability, which could have resulted in some trees having access to more water than other trees. Nevertheless, tentative results from this study suggest that both predawn leaf water potential and midday stem water potential can be used as indicators of water stress in macadamia orchards, with predawn <-0.6 MPa probably indicating the onset of stress that could impact yield. Importantly, this trial has also demonstrated that the “traditional” ways of scheduling irrigation with capacitance probes may not be appropriate for macadamia orchards, as a slight yield penalty was noted in the grower control when compared to the half irrigation and rainfed treatments. This suggests possible overirrigation, which had a negative impact on yield. When using the half irrigation as the “control” and comparing to the yield from when water stress was implemented at different phenological stages, yield from the half irrigation treatment was significantly higher than these treatments. This reiterates the importance of choosing the right control and ensuring that this treatment is irrigated optimally. It also challenges the perception of what is the best way to manage irrigation in macadamia orchards. Mild stress was achieved in some trees during the flowering and fruit set stage, when conditions are fairly dry, due to increasing temperatures in spring but as yet no rainfall. This may be a critical time for irrigation in macadamia orchards. However, the impact of VPD on stomatal conductance needs to be considered at this time and relying solely on ET_o to schedule irrigation may result in over-irrigation.

This study has provided a good foundation for future research, but there are still many issues which are unresolved. Due to the limited amount of stress measured in the current trial, it will be very important to continue this work in a location where it is easier to implement stress. For this a more uniform orchard needs to be chosen with a deep, well-drained soil. This should hopefully allow the determination of more accurate predawn and midday stem potential thresholds for stress in macadamia and allow for improvements in irrigation scheduling that ensure optimal utilisation of a scare and finite resource. It will also allow a more in depth analysis of which are the most sensitive phenological stages to water stress in terms of yield and quality.

5 GENERAL DISCUSSION AND CONCLUSIONS

Despite the rapid expansion of irrigated macadamia production, information regarding water use of macadamia orchards is lacking, together with the knowledge of how yield and quality of macadamia orchards are impacted by water stress. In order to provide producers with water use guidelines which are applicable to a range of environments, this study examined the mechanisms and driving variables of macadamia water use to select and parameterize water use models. Not only has this study demonstrated that macadamias have substantial stomatal and non-stomatal limitations to net CO_2 assimilation, but it has also shown that the crop is predominantly isohydric in nature, a trait which has a significant effect on the transpiration (E_c) of macadamias. This study used measurements of leaf gas exchange and E_c, to successfully select, parameterize, and validate a range of E_c models in two field-grown macadamia orchards differing canopy sizes. Finally, the impact of withholding irrigation at different phenological stages on yield and quality of macadamias was determined.

Fairly low net CO_2 assimilation (A) rates were obtained for macadamias in this study, especially compared to other subtropical evergreen crops, such as citrus and olive. These low A values were explained by both stomatal and non-stomatal limitations to A. Non-stomatal limitations in macadamias, which include previously demonstrated low mesophyll conductance (g_m) and light limitations within the internal leaf space, were attributed to the sclerophyllous nature of macadamia leaves. Stomatal limitations to A accounted for approximately one third of the total limitation to carbon assimilation in macadamias. Understanding stomatal behaviour, and more specifically stomatal conductance (g_s), was therefore essential to understanding the relationship between carbon gain and water loss through transpiration. Macadamia g_s is carefully controlled in response to increasing leaf vapour pressure deficit (VPD_{leaf}), with a decline in g_s being observed when VPD_{leaf} exceeded 2.50 kPa. Strict stomatal control was accompanied with nearly constant midday leaf water potentials, which is typical of an isohydric water management strategy. Isohydric behaviour is often linked to an underlying hydraulic limitation, which necessitates strict leaf level control of g_s in an attempt to avoid hydraulic failure as a result of xylem embolism. An examination of hydraulic conductance within macadamias has showed that although whole tree hydraulic conductance is comparable with other tree crops, there is a significant hydraulic limitation within the stem to leaf interface. This hydraulic limitation most likely leads to decreases in relative water content within the leaf space, directly resulting in decreased g_s under conditions of high VPD_{leaf}.

The distinct stomatal behaviour shared between predominantly isohydric tree crops, creates an interesting scenario when examining whole tree E_c. It raises the question that if macadamias are predominantly isohydric, and display strict leaf level control of g_s under conditions of high VPD_{leaf}, would E_c respond in a similar fashion? This study suggests that this is exactly what happens in macadamias. Under conditions of non-limiting soil water, macadamia E_c increased linearly with air vapour pressure deficit (VPD_{air}) and reference evapotranspiration (ET_o) at low atmospheric evaporative demands ($VPD_{air} < 0.8$ kPa and ET_o <0.13 mm day^{-1}), but at higher atmospheric evaporative demands the rate of increase in macadamia E_c decreased, suggesting that macadamia E_c is a water supply controlled system. Supply controlled E_c implies that the rate of water supply to the leaves cannot always match the rate of water loss from the leaf as dictated by atmospheric evaporative demand.

Differences in the magnitude of E_c were, however, observed between the three orchards examined. The distinguishing factor between the orchards was canopy size, with trees in the mature bearing (MB) orchard being approximately double the size of trees within the intermediate bearing (IB) orchard. Larger trees in the MB orchard transpired approximately 60% more than trees in the IB orchard exposed to the same set of weather conditions, confirming that E_c is significantly influenced by canopy size. A similar relationship was found between the IB orchard and the NB orchard, where E_c and canopy size were 13 times lower than in the IB orchard.

Table 5.1: Summary of tree water use of the macadamia orchards in the Schagen Valley, outside of Nelspruit (ND-not determined)

	Mature orchard		**Intermediate orchard**		**Non-bearing orchard**	
	L	**mm**	**L**	**mm**	**L**	**mm**
Annual E_c[*]	10 496	328	5 792	181	352	11
Max. E_c per day	47	1.47	40	1.26	1	0.08
Avg. E_c per day	29	0.90	17	0.52	2.5	0.03
Canopy cover	0.90		0.56		0.16	
WUE_T (kg m^{-3})[#]	1.97	1.92	ND		ND	
WUP_T (R m^{-3})[#]	117.75	118.11	ND		ND	

[*] average of two seasons of measurements for the mature and intermediate orchards

[#] calculated using transpiration volumes, WUE was calculated using in-shell mass

An examination of transpiration crop coefficients (K_t), which were used to study the variation of E_c in relation to ET_o, showed that there was a large degree of variation in seasonal K_t, which could largely be attributed to variations in canopy size. Although macadamia E_c is greatly influenced by canopy size, this study has shown that significant increases in E_c, and subsequently K_t, occurred during certain phenological periods, without any substantial increases in canopy size or ET_o. A summary of monthly K_t values for the orchards in this study is provided in Table 5.2.

Table 5.2: Summary of monthly transpiration crop coefficients (K_t) for the macadamia orchards in Nelspruit

Month	Mature	Intermediate	Non-bearing
August	0.20	0.12	0.010
September	0.25	0.12	0.007
October	0.22	0.11	0.011
November	0.23	0.12	0.012
December	0.26	0.14	0.009
January	0.27	0.17	0.012
February	0.25	0.17	0.010
March	0.27	0.18	0.010
April	0.23	0.20	0.009
May	0.18	0.16	0.009
June	0.18	0.16	0.010
July	0.16	0.14	0.011

This study has demonstrated that macadamia E_c is under strict control of g_c, which was confirmed by the high degree of coupling ($\Omega = 0.08$) in orchards, which was as a result of low measured g_c (0.3-0.7 mm s^{-1}) in relation to g_a (37-75 mm s^{-1}). The high degree of coupling in macadamias resulted in the successful parametrisation and validation of a Jarvis-Steward type g_c model when used in conjunction with the Penman-Monteith equation. This model was, however, parameter intensive and required reasonable estimates of both g_c and g_a, which can be difficult to obtain. Nevertheless, the study has demonstrated that although g_c could be estimated using the Jarvis-Steward approach, multiple adjustments of the maximum canopy conductance ($g_{c\ max}$) model parameter were required to account for changes in leaf area index (LAI) over a season, as a result of tree growth and pruning. The distinct relationship between g_c and E_c, as a result of the high degree of coupling, created an opportunity to estimate E_c directly using a simplified and less parameter intensive modified Jarvis-Steward model. proposed by Whitley et al. (2009). Not only did the model provide good estimates of E_c on both a daily and weekly basis, with comparable accuracy to the g_c model, it only required an adjustment for canopy size between orchards, using easily obtained measures of canopy dimensions including canopy width and breadth used in the calculation of the effective fraction of ground cover ($f_{c\ eff}$). This model could therefore be used in the macadamia orchards in this study varying in canopy size. However, it is unclear if this empirical model would provide accurate estimates of E_c in different orchards in different climactic regions, especially those consisting of cultivars different to the one used in this study, seeing that $E_{c\ max}$ might differ substantially between cultivars.

Regardless of the observed success of mechanistic models to estimate E_c, this study also attempted to evaluate the ability of the widely used and accepted empirical FAO-56 dual crop coefficient model to estimate macadamia E_c, given that most farmers are familiar with the crop coefficient approach. As expected the model provided poor estimates of both K_t and E_c on a daily basis, which was largely attributed to an overestimation of K_t and E_c at daily ET_o rates > 4.0 mm day^{-1}, and an underestimation of K_t and E_c when ET_o < 2.0 mm day^{-1}. These over and under estimations of K_t and E_c was largely due to the linear relationship between r_{leaf} and r_s and ET_o, which stems from the fact that the model is based on the premise that E_c is a demand limited process, whilst macadamia E_c is a supply-controlled system. The model, however, provided reasonable estimates of K_t and E_c on a monthly or seasonal basis, which is most likely due to the compensatory errors over the longer period of estimation. The FAO-56 dual crop coefficient model could therefore be used with a great degree of reliability by institutions that depend on crop coefficients to determine water allocations.

Regardless of the accuracy of both mechanistic models and the empirical FAO-56 dual crop coefficient model in estimating macadamia E_c, all these models showed discrepancies between measured and simulated E_c during especially April of each season, a period during which oil accumulation in nuts occur. The significant effect of crop phenology, in particular the presence of oil storing nuts, on crop physiology and subsequently g_s, g_c and E_c during the month of April, was not accounted for by any of the models evaluated in this study. This observation not only reiterates the significant effect of phenology and physiology on macadamia E_c observed in this study, but highlights another potential shortcoming of both mechanistic and empirical models evaluated. Although these models have been widely used, they fail to account for the physiological changes in g_s, g_c and subsequently E_c brought about by phenology. In this study, the failure to account for these changes led to an underestimation of E_c during the oil accumulation period, which could potentially lead to reduced fruit quality as a result of soil water stress, if these models where used for irrigation scheduling.

Even though the models evaluated in this study had certain shortcomings, this is the first study that has successfully parameterized and validated these models in macadamias. This has provided the macadamia industry with a strategic water and irrigation management tool in the form of the FAO-56 dual crop coefficient model, and an irrigation scheduling tool in the form of g_c and E_c models. Caution should, however, be used before these models are fully implemented, largely due to the fact that the model parameters derived in this study have not been tested in different orchards and growing environments. Furthermore, it should be emphasized that the models evaluated in this study only provided estimates of E_c and estimates of soil evaporation would be required for the determination of the irrigation requirements of the crop.

Results from the water stress study are not conclusive, largely due to the loss of harvest in the third season. However, based on ecophysiological measurements over the course of the study it would appear that macadamias are less sensitive to water stress than most other horticultural crops. In addition, withholding water during key phenological stages had no impact on yield for one season of measurements relative to the control, where irrigation was scheduled by the grower according to soil water measurements. Irrigating half the volume of the grower scheduled control or relying solely on rainfall also had no impact on yield over two seasons. The implication of the results from the rainfed and half irrigation treatments suggests that the “traditional” ways of scheduling irrigation with capacitance probes may not be appropriate for all macadamia orchards, as a slight yield penalty was noted in the grower control when compared to the half irrigation and rainfed treatments. This suggests possible overirrigation, which had a negative impact on yield. When using the half irrigation as the “control” and comparing to the yield from when water stress was implemented at different phenological stages, yield from the half irrigation treatment was significantly higher than these treatments. This reiterates the importance of choosing the right control and ensuring that this treatment is irrigated optimally. It also challenges the perception of what is the best way to manage irrigation in macadamia orchards.

Tentative results from this study suggest that both predawn leaf water potential and midday stem water potential can be used as indicators of water stress in macadamia orchards, with predawn <-0.6 MPa probably indicating the onset of stress that could impact yield. Mild stress was achieved in some trees during the flowering and fruit set stage, when conditions are fairly dry, due to increasing temperatures in spring but as yet no rainfall. This may be a critical time for irrigation in macadamia orchards. However, the impact of VPD on stomatal conductance needs to be considered at this time and relying solely on ET_o to schedule irrigation may result in over-irrigation.

6 RECOMMENDATIONS

This study has focussed on the seasonal water use dynamics of macadamia orchards, and included a range of leaf gas exchange measurements, which were insightful from both a horticultural and ecological perspective. These measurements were, however, limited to one cultivar (HAES 695) which is a hybrid cross of *M. integrifolia* (Maiden & Betche) and *M. tetraphylla* (L.A.S. Johnson), and is the dominant cultivar planted in South Africa. This cultivar is, however, not as popular in other parts of the world, with most cultivars being descendants of *M. integrifolia*, a species which has evolved in a distinctly different environment to that of *M. tetraphylla*. It would therefore be of great interest to researchers to determine possible difference in leaf gas exchange between the various cultivars. Of particular interest would be to examine if differences in the response of $A_{\max}$ and g_s to increases in $\mathrm{VPD}_{\mathrm{leaf}}$ exists between cultivars, and if these differences could help explain the cultivar performance in relation to growing environment.

Furthermore, the daily and seasonal total E_c reported in this study was unexpectedly low considering the size of trees used in this study. It would therefore be of great value to the macadamia industry to obtain additional measurements of E_c in a range of different orchards, consisting of different cultivars, to aid macadamia growers in increasing irrigation and water use efficiency. It is further proposed that additional measurements of E_c in macadamias is necessary to validate parameters generated in mechanistic models developed in this study. Of particular interest would be to determine if differences exist in both $g_{c\ \max}$ and $E_{c\ \max}$ between different cultivars, as these parameters could have a significant impact on model accuracy.

This water stress study has provided a good foundation for future research, but there are still many issues which are unresolved. Due to the limited amount of stress measured in the current trial, it will be very important to continue this work in a location where it is easier to implement stress. For this a more uniform orchard needs to be chosen with a deep, well-drained soil. This should hopefully allow the determination of more accurate predawn and midday stem potential thresholds for stress in macadamia and allow for improvements in irrigation scheduling that ensure optimal utilisation of a scarce and finite resource. It will also allow a more in-depth analysis of which are the most sensitive phenological stages to water stress in terms of yield and quality.

All the knowledge gained of water use characteristics and volumes and the response of the trees to water stress need to be translated into practical guidelines for scheduling irrigation in macadamia orchards. The question of how to apply irrigation water to optimise water use efficiency in orchards and avoid water stress which leads to yield and quality penalties needs to be answered.

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7 CAPACITY BUILDING

7.1 DEGREE PURPOSES

Dr Theunis Smit – PhD Horticultural Science (graduated September 2020)

Increased demand for sustainably produced, healthy, and nutritious food has seen certain segments of the world agricultural sector flourish in the past few decades. The macadamia nut industry in particular has expanded at a tremendous rate, with more than 10 000 hectares of trees being planted annually across a range of environments. The greatest portion of these expansions occur in semi-arid areas, which are characterized by highly variable rainfall patterns, and are as a result irrigated to minimize the risk of yield, quality and income losses, brought about by water stress. The recently commercialized nature of the crop, in combination with lack of water use research specific to macadamia, has created great uncertainty amongst producers. This study has therefore firstly aimed at gaining a fundamental understanding of leaf gas exchange and macadamia transpiration (E_c) in response to a range of environmental and physiological variables, in an attempt to identify the driving variables of transpiration. Secondly, the study aimed to identify crop water use models that best incorporate the driving variables of E_c, in order to transfer results obtained from this study, to a range of growing environments. Measurements of leaf gas exchange, hydraulic conductance, canopy dimensions, weather, and E_c were made over an approximate three year period, in a fully irrigated commercial mature bearing (MB) and intermediate bearing (IB) macadamia orchard in the Mpumalanga province of South Africa. Leaf gas exchange measurements, included, but were not limited to net CO_2 assimilation rate (A) and stomatal conductance (g_s). Transpiration measurements were obtained using sap flow measurements using the heat ratio method of the heat pulse velocity technique. Macadamia A was found to be slightly lower than that of other evergreen subtropical crops, which is largely attributed to substantial stomatal and non-stomatal limitations to A. Non-stomatal limitations to A were linked to an internal light limitation resulting from the sclerophyllous nature of leaves. Stomatal limitations stem from the predominantly isohydric nature of macadamias, where g_s is carefully controlled in order to maintain midday leaf water potential within certain safety margins. Isohydric behaviour suggested an underlying hydraulic limitation, which was found to exist within the stem to leaf interface of macadamias. Responses of g_s to leaf vapour pressure deficit (VPD_{leaf}) showed that g_s declined as VPD_{leaf} exceeded 2.5 kPa. The response of g_s to VPD_{leaf}, however, varied substantially throughout the season, being significantly higher during fruiting periods compared to non-fruiting periods, implying isohydrodynamic behaviour and emphasizing the influence of phenology on leaf gas exchange. Similar results were found on both fruiting and non-fruiting branches implying that an upregulation of g_s at leaf level would most likely lead to an upregulation at the canopy level, which would lead to increased E_c. During fruiting periods, macadamia E_c was ~20% higher compared to non-fruiting periods, with no significant difference in weather variables or canopy size, which could act as confounding factors. Increased E_c during fruiting periods was associated with a greater response of E_c to air vapour pressure deficit (VPD_{air}) in the 0.0-3.0 kPa range, which was similar to the observed increases of g_s in response to $VPD_{leaf} > 1.5$ kPa. An examination of transpiration crop coefficients (K_t), confirmed that increased E_c during fruiting periods stem from a physiological upregulation of g_s and subsequently canopy conductance (g_a). Besides physiological and phenological variables influencing macadamia E_c, physical attributes (i.e. canopy size) and weather variables remained the key driving variables of E_c. Macadamia E_c increased in a linear fashion when $VPD_{air} < 0.8$ kPa, solar radiation (R_s) <0.3 MJ m^{-2} hr^{-1} and reference evapotranspiration (ET_o) <0.13 mm day^{-1}, but failed to increase at the same rate when these limits were exceeded. The reduction in the rate of E_c in response to increases in environmental evaporative demand under non-limiting soil water conditions, indicates that E_c in macadamias is a supply-controlled system. Supply controlled E_c was confirmed upon examination of maximum daily recorded E_c ($E_{c\ max}$) in response to increases in the aforementioned weather variables, with daily $E_{c\ max}$ failing to increase at VPD_{air} >1.5 kPa, R_s > 15 MJ m^{-2} day^{-1} and ET_o > 3.5 mm day^{-1}. The response of E_c and $E_{c\ max}$ to these weather variables did not vary between the two orchards, the magnitude of both E_c and $E_{c\ max}$, however, differed between orchards, being highest in the MB orchard. Higher E_c in the MB orchard was largely attributed to a ~60% larger canopy, with E_c in the MB orchard being ~60% more than E_c in the IB orchard. Transpiration measured in this study, however, remains site specific, and identification and validation of crop water use models were therefore needed to extrapolate data to a broader range of growing environments. The study therefore evaluated three models including the widely used FAO-56 dual crop coefficient, a mechanistic canopy conductance (g_c) model in conjunction with the Penman-Monteith equation, and a simplified mechanistic canopy transpiration model. The study showed, that a poor estimation of daily K_t and subsequently E_c was obtained using the FAO-56 dual crop coefficient model, which was largely attributed to overestimation of K_t and therefore E_c when daily reference evapotranspiration (ET_o) rates exceeded 4.0 mm day^{-1}, and an underestimation of K_t and E_c when ET_o < 2.0 mm day^{-1}. The model, however, provided reasonable estimates of K_t and E_c on a monthly or seasonal basis, with only slight discrepancies observed between measured and simulated K_t and E_c from January to April in each season, which was attributed to physiological upregulation of E_c in the presence of fruit. The mechanistic g_c estimations in conjunction with the Penman-Monteith equation, provided more accurate estimates of daily E_c in both the MB and IB orchards, compared to the empirical FAO-56 dual crop coefficient model, but was particularly sensitive to seasonal changes in leaf area index (LAI), with adjustments of maximum canopy conductance ($g_{c\ max}$) being required to achieve accurate estimates of E_c. An adjustment for variations in LAI, however, failed to provide increased estimates of E_c during the January to April period reaffirming the phenological and physiological influence of fruit on g_c and E_c during this period. Measurements of macadamia g_c in this study was rather low (0.3-0.7 mm s^{-1}) in relation to g_a (37-75 mm s^{-1}), confirming that macadamias are well coupled to the atmosphere. The high degree of coupling in macadamias implies that changes in g_c would lead to direct changes in E_c, which contributed to the success of the use of a simplified mechanistic E_c model. This model provided reasonable estimates of daily E_c without multiple adjustments for canopy size being needed within each of the orchards. The mechanistic E_c model, similar to the other models tested, however, failed to provide reasonable estimates of E_c during the January to April period. The results from this study have shown that macadamias are predominantly isohydric in nature, a trait which ultimately dictates leaf gas exchange and E_c in this recently domesticated subtropical crop. Strict stomatal control in response to increased atmospheric evaporative demand, is also evident in the supply controlled nature of macadamia E_c, which has added to the success of mechanistic models in accurately estimating macadamia E_c. Although the study has reaffirmed that E_c is largely driven by environmental demand and canopy size, it demonstrated that physiological and phenological factors can have a significant effect on leaf level gas exchange and subsequently E_c of macadamias.

Mr King Dlamini (MSc): (busy with dissertation preparation)

"Optimising irrigation scheduling and fertilizer management in evergreen subtropical crops using simple irrigation scheduling tools" Mr Dlamini registered for his MSc in February 2017 and was funded by additional Water RDI Roadmap Human Capital Development Funds. Mr Dlamini assisted two PhD students with their projects by monitoring soil water status and nutrients using fairly simple monitoring tools, which included the chameleon sensor and wetting front detectors. His project linked well to the avocado stress measurements and macadamia water use measurements to assess if these simple tools could be useful for growers in future.

"The chameleon soil water sensor and wetting front detectors are simple tools that have been introduced to farmers by the Virtual Irrigation Academy to help improve crop yields and quality through the improved management of irrigation water, soil nutrients and salt. These tools were introduced to Avocado and Macadamia farmers as part of an avocado stress trial and as a learning tool for a macadamia farmer to test their application on a large scale. The main objective was to determine whether chameleon water sensors and wetting front detectors

(WFDs) can be a useful tool for monitoring soil water and salinity in avocado and macadamia orchards. The use of these tools on the avocado stress trial was to establish the response of avocado trees to induced water stress during different phenological stages and the impact on salt and nutrients in soil. The avocado trial was set up on an orchard with high clay content that had high water retention and there were no apparent signs of stress on the trees measured. This supported evidence from the sensors that suggested the soil was mostly wet. Salt and nitrates in the avocado site increased in the soil during periods when fertiliser was applied, but with plant uptake and water application the salts and nitrates were leached out. The macadamia farm had sensors placed on blocks on the farm with different soil types and position in the landscape. The water content measured by the sensors were different from block to block which was often a function of the soil type. A stress trial on the farm was used to measure at what water content stress was induced in macadamia trees, which proved to be when the soil had a dry profile at all three depths to 60cm. Stress was induced by long periods of hot dry winds. The soil nitrates and salt were also elevated when fertiliser was applied but again, uptake and leaching reduced the salt and nitrate concentration."

Mr Armand Smit (busy with dissertation preparation)
"The impact of water stress at different phenological stages on macadamia yield and quality"
Mr Smit registered for an MSc in 2018 and was responsible for assessing the impact of water stress at different phenological stages on macadamia yield and quality. He has completed all his field work.

"“Irrigated agriculture is currently the single largest consumer of water on the planet, accounting for a near 22% of total freshwater consumption and two-thirds allocated towards human consumption. Efficient water use strategies are therefore fundamental. Current macadamia irrigation quantities are, however, based on the physiology, phenology and morphology of older horticultural crops which can be less tolerant to water stress and deficit irrigation. The effect of water stress at different phenological stages on the yield and quality of macadamias were assessed over a three season period. Seven water stress treatments were imposed on 63 randomly selected, mature bearing macadamia trees (cv. HAES 695, 'Beaumont', *M. tetraphylla x M. integrifolia*, grafted) and respective yield, quality and physiological responses were compared to a well-watered control. Mild water stress was imposed at flowering and nut set, nut sizing and premature nut drop, shell hardening and oil accumulation. Additional treatments included a rainfed, half irrigation and control treartment. Tree based measurements such as stomatal conductance (g_s), light saturated net photosynthetic assimilation rate (A_{max}), pre-dawn leaf (Ψ_{pd}) and midday stem (Ψ_x) water potential were used in conjuction with soil water potential meauseremnets to establish different macadamia water stress thresholds under orchard conditions. Results from this study suggest that macadamias are less sensitive to water stress than most other horticultural crops. Withholding water during key phenological stages had no impact on yield for one season of measurements relative to the control. Irrigating half the volume of the control or relying solely on rainfall also had no impact on yield over two seasons. Stress during flowering and nut set and shell hardening phenological stages were detrimental to macadamia quality, significantly reducing the perecentage total kernel recovery relative to the control. Severe stress at any phenological stage will likely have a negative impact on both yield and quality, however, in deep soil and under normal rainfall conditions, reaching such level of stress would be unlikely. Tentative results suggest that both Ψ_{pd} and Ψ_x can be used as indicators of water stress in macadamia orchards, with Ψ_{pd} <0.6 MPa probably indicating the onset of stress that could impact both yield and quality."

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 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

Scientific publications

Smit, T. G., Taylor, N. J., & Midgley, S. J. 2020. The seasonal regulation of gas exchange and water relations of field grown macadamia. *Scientia Horticulturae*, *267*, 109346.

Taylor, N. J., Smit, T. G., Midgley, S. J. E., & Annandale, J. G. 2020. Stomatal regulation of transpiration and photosynthesis in macadamias. In *XXX International Horticultural Congress IHC2018: International Symposium on Cultivars, Rootstocks and Management Systems of 1281* (pp. 463-470).

Popular articles

TG Smit, NJ Taylor, JG Annandale (2018) Water use dynamics of macadamia orchards South African Macadamia Growers; Association Yearbook 24: 28-33

Do we have enough water for all our macs? Article in The Macadamia following interviews with T Smit and A Smit. The Macadamia Winter 2018 issue (https://themacadamia.co.za/2018/10/23/do-we-have-enough-water-for-all-our-macs/)

Macadamia irrigation in the spotlight. Article by Lindi Botha in the Lowvelder following a presentation by T Smit seminar on sustainable water use at the University of Mpumalanga in Mbombela. (https://lowvelder.co.za/445085/macadamia-irrigation-spotlight/)

Waterverbruiknavorsing van makadamias. TG Smit, NJ Taylor, AH Smit, JG Annandale and SJE Midgley. Spilpunt Magazine January/February 2019 issue.

Latest research: Macadamias need less water than you think! Article in Farmers Weekly by Lindi Botha following interviews with T Smit and A Smit. (https://www.farmersweekly.co.za/crops/fruit-nuts/latest-research-macadamias-need-less-water-than-you-think/)

Research shows SA Mac orchards are over-irrigated Macadamia Autumn 2020 – Lindi Botha published without our knowledge (no project members spoke to the journalist) and plagiarised an article from the SAMAC website.

Presentations at local and international conferences

TG Smit, NJ Taylor, JG Annandale, SJE Midgley. Water use and water use dynamics of macadamia orchards Combined Congress, 14-18 January 2018 at Ratanga Junction in Cape Town (Mr Smit won the award for the best PhD presentation and overall best student presentation for the Southern African Society for Horticultural Science (SASHS))

NJ Taylor, TG Smit, SJE Midgley, JG Annandale. Stomatal regulation of transpiration and photosynthesis in macadamias. 30th International Horticultural Congress 2018 in Istanbul, Turkey from 12-16 August 2018

NJ Taylor, TG Smit, SJE Midgley, JG Annandale. Stomatal regulation of transpiration and photosynthesis in macadamias. Combined Congress in Bloemfontein in January 2019.

Presentations at research symposia and study groups

Information regarding the project (Project K5/2552//4) was shared with growers from a Mayo Macs study group on 12 May 2017 at the Mayo Mac offices in the Schagen Valley, just outside Nelspruit.

TG Smit. Presentation of results and site visit for macadamia growers from the North and South coast of KwaZulu-Natal, whilst on a visit to Nelspruit in May 2017.

TG Smit, K Dlamini, NJ Taylor, JG Annandale, CS Everson, AD Clulow, MJ Savage and SJE Midgley. Macadamia water relations. SAMAC Research Symposium. 6 September 2017. (Mr Smit won the award for the best presentation at the symposium).

TG Smit. Information on water management of macadamias sessions were held in Empangeni, Umhlali, Hibberdene and Oribi on 18 and 19 October 2017.

TG Smit, NJ Taylor, JG Annandale, and SJE Midgley. Water Use of Macadamia Orchards. SAMAC Research Symposium. 9 November 2018, White River.

TG Smit, NJ Taylor, JG Annandale, and SJE Midgley. Water Use of Macadamia Orchards. Australian Macadamia Societies bi-annual industry conference held on the Gold Coast, Brisbane from 13-15 November 2018

NJ Taylor, T Smit, A Smit, SJE Midgley, A Clulow and JG Annandale. Sustainable water use for the future. SAMAC Live webinars 1 September 2020.

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.

10 APPENDIX

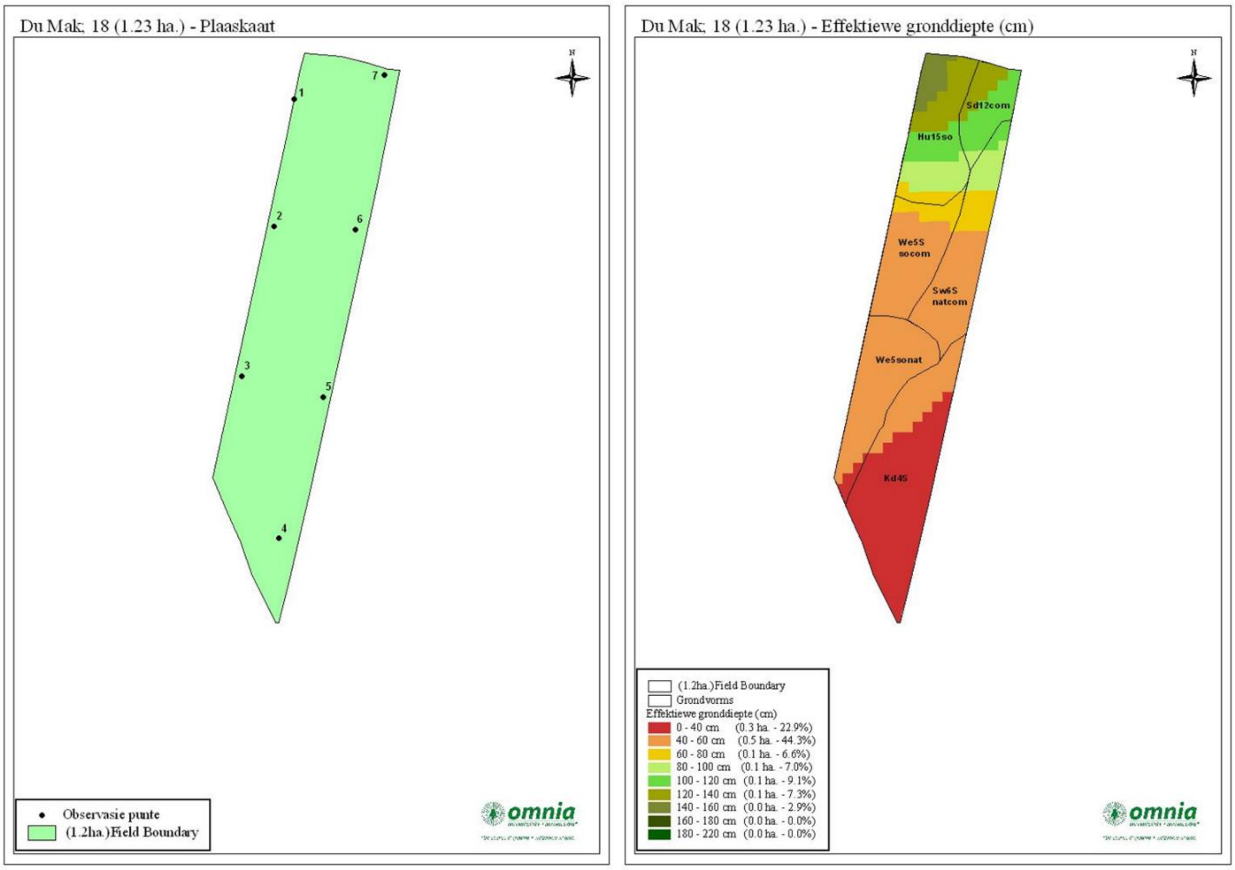

Figure 1 (Left) Farm map showing where samples were taken. (Right) Effective soil depth

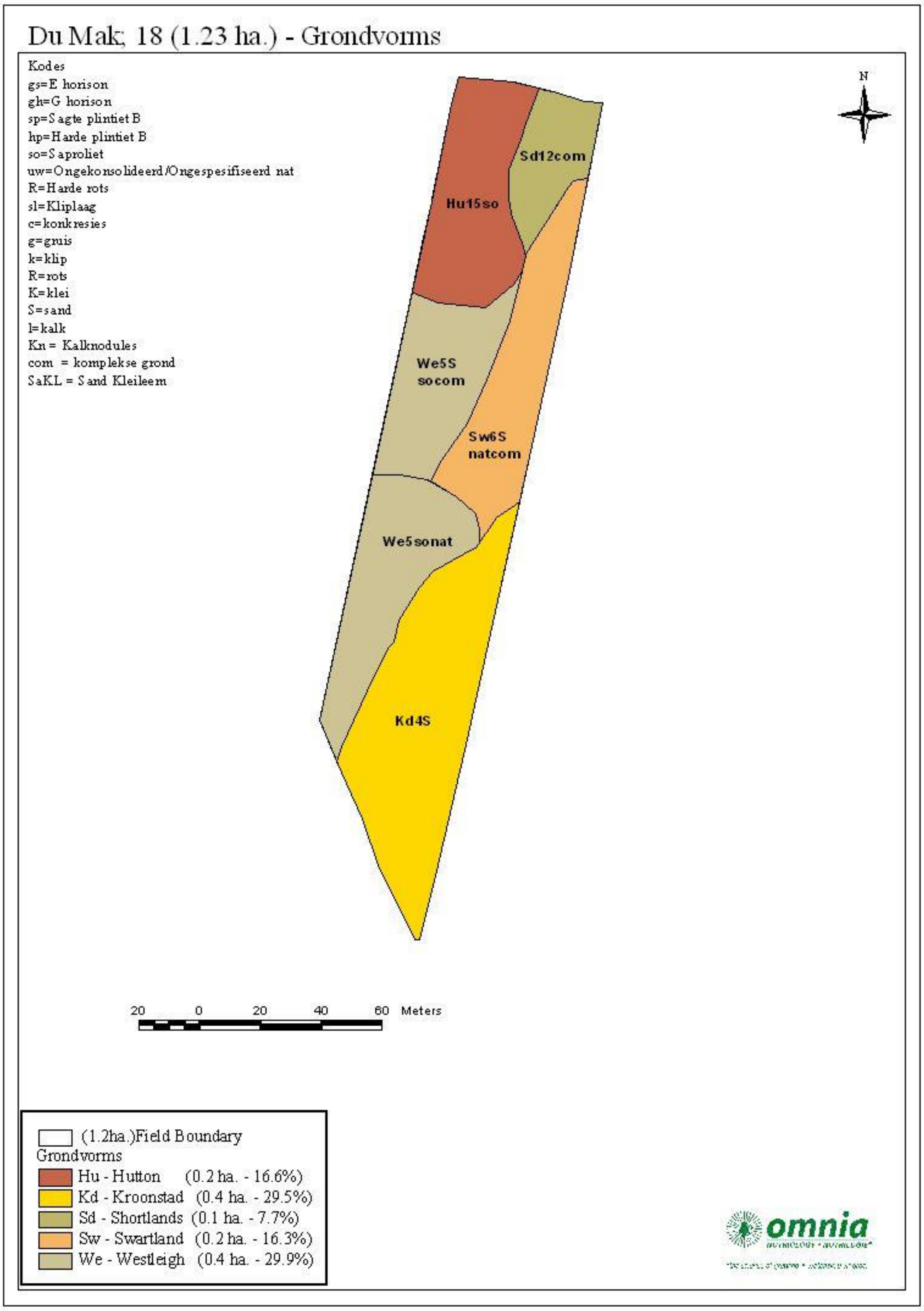

Figure 2 Soil forms throughout the orchard

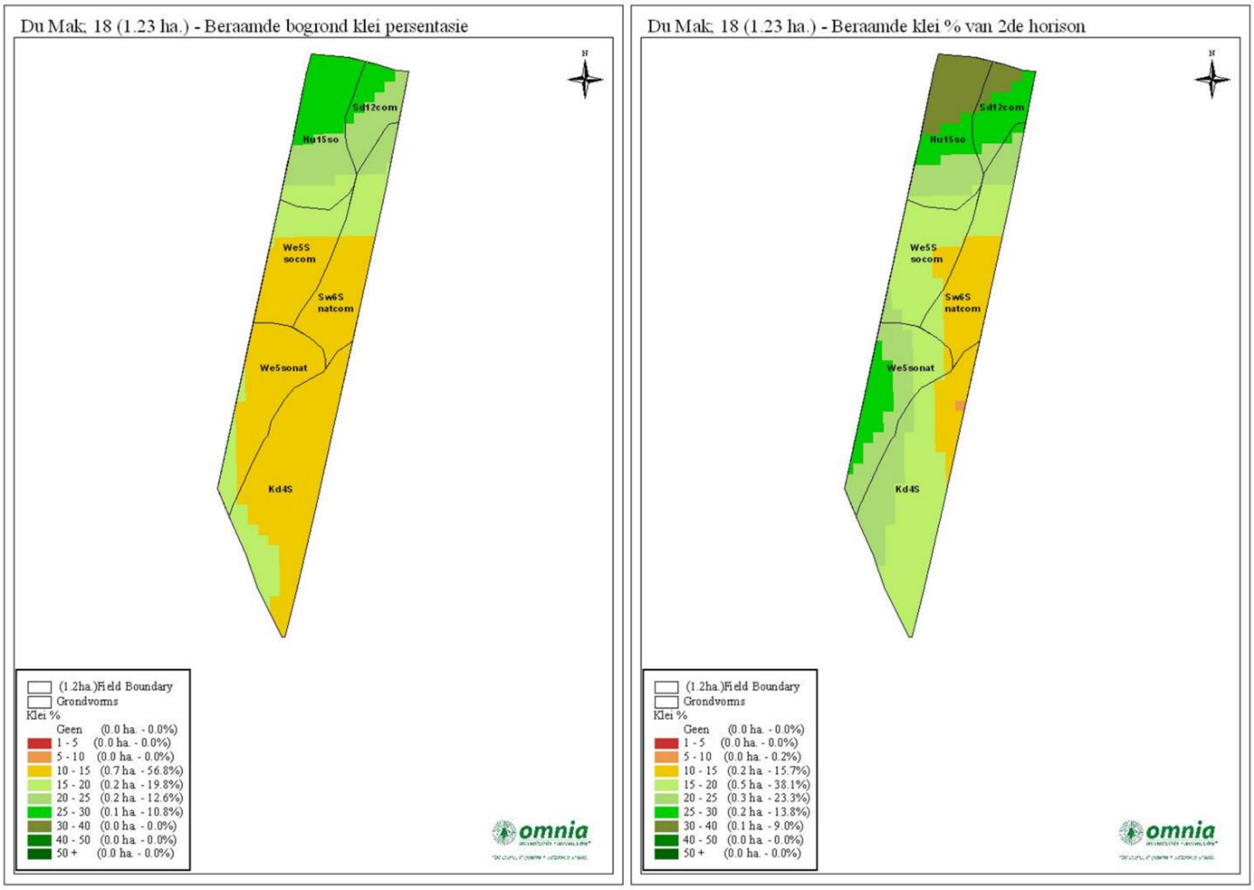

Figure 3 (Left) Estimated clay percentage in the topsoil. (Right) Estimated clay percentage in the 2nd horizon

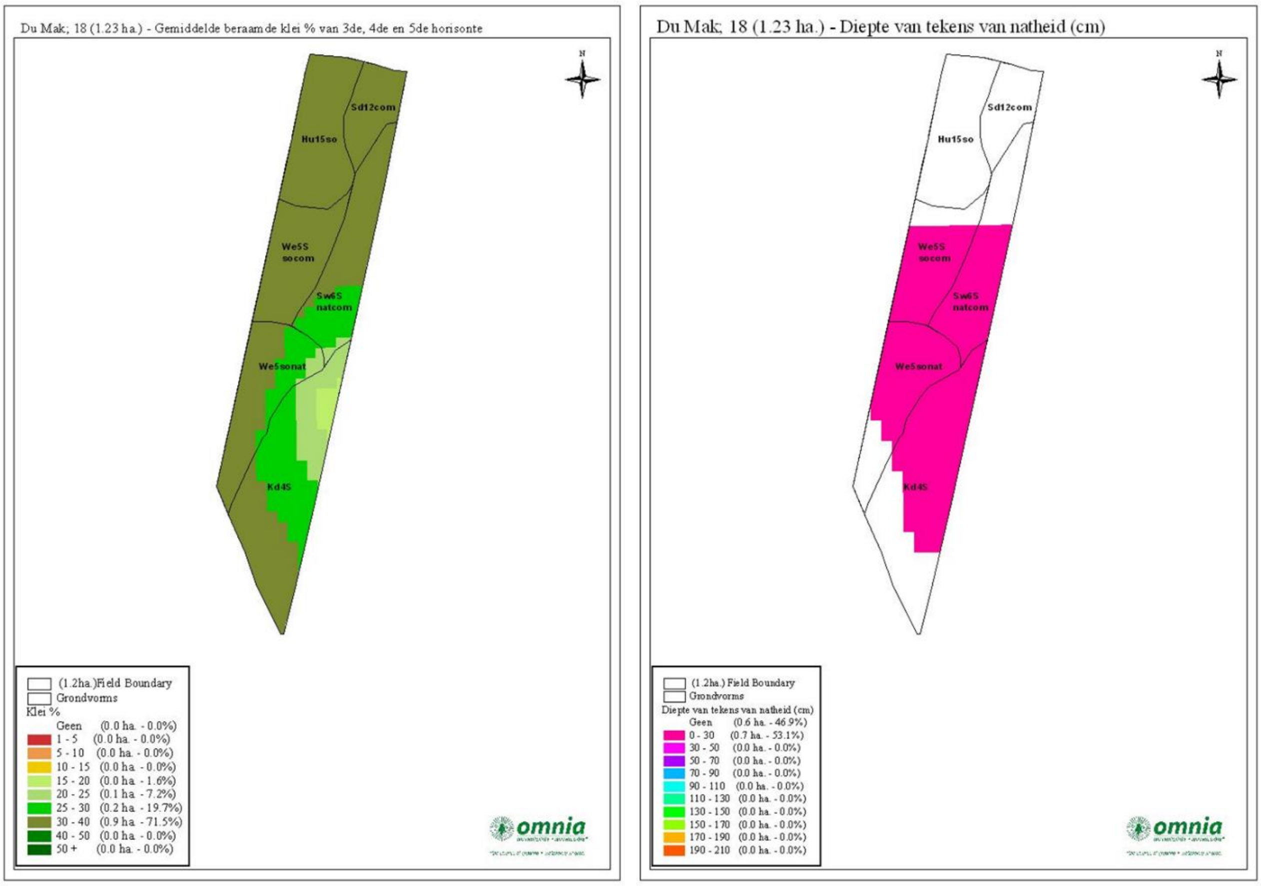

Figure 4 (Left) Estimated clay content in the 3rd, 4th and 5th horizons. (Right) Depth at which signs of wetness were noted.

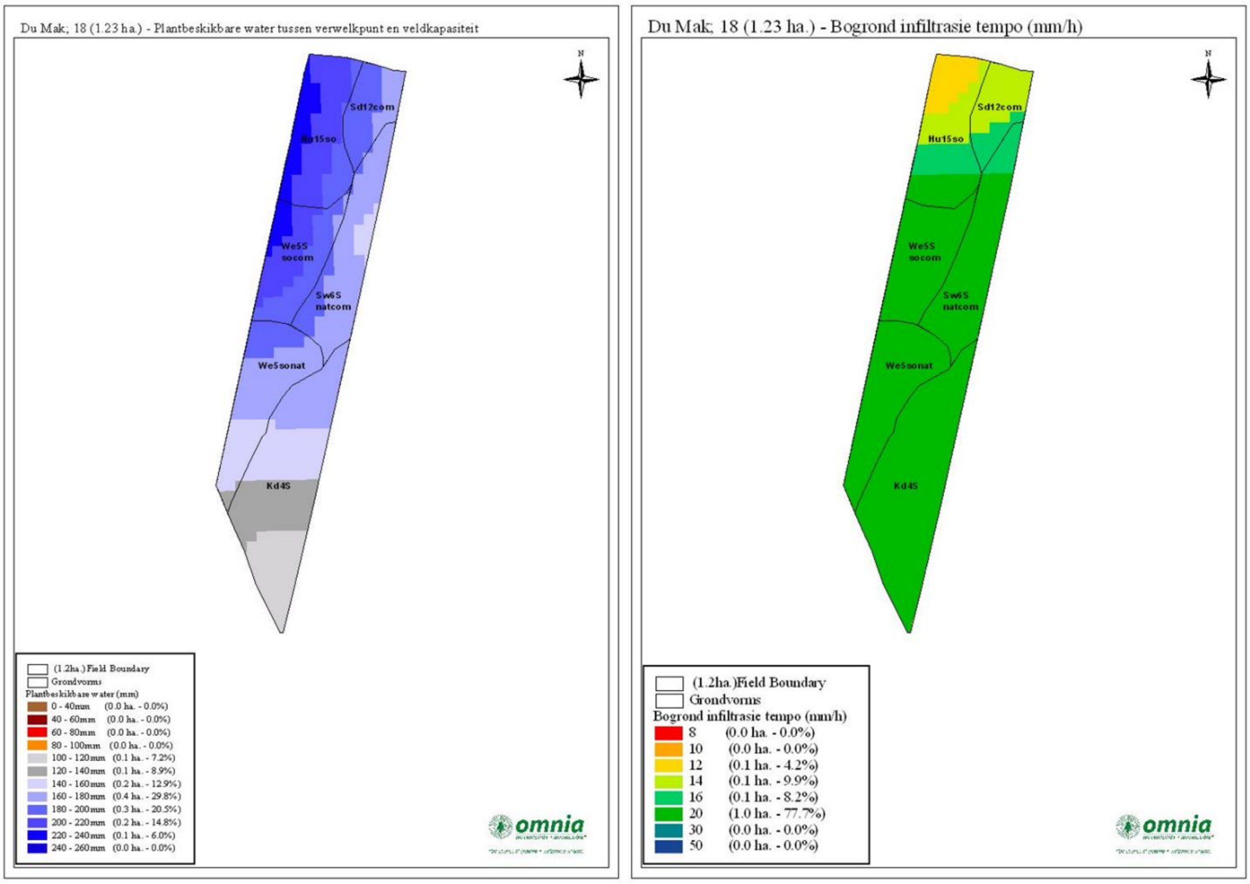

Figure 5 (Left) Plant available water between permanent wilting point and field capacity. (Right) Top soil infiltration rate.