COUPLED EFFECTS OF IRRIGATION MANAGEMENT AND WATER SALINITY ON DATE PALM CULTIVARS IN THE HYPER-ARID ENVIRONMENT OF THE UNITED ARAB EMIRATES

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Palmerston North, New Zealand

Ahmed Hassan

Al Muaini

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ABSTRACT

Dates, and the farming of date palms (*Phoenix dactylifera* L.), are culturally, aesthetically and economically important in the United Arab Emirates. In this hyper-arid region, dates require irrigation, as rainfall is virtually non-existent. Groundwater is relied upon as the source of this irrigation water. Yet, the groundwater reserves in the Emirates are expected to run-out in about 55 years. Furthermore they are becoming more saline. In the Emirate of Abu Dhabi, Law 5 has been passed and that will limit the amount of water that can be withdrawn for agriculture, or any other purposes. Thus there are imperatives to minimise the amount of water being used for the irrigation of date palms, and to limit the amount of salt leaching from the rootzone of the date palms. These critical issues provide the underpinning reasons for the research described in this thesis. Environment Agency – Abu Dhabi (EAD) has invested in two research projects to determine the minimum amount of irrigation water, as a function of salinity that needs to be applied to date palms to ensure economic returns from date production. These two projects underpin my doctoral research. Using the Compensation Heat Pulse Method (CHPM) of monitoring sapflow has enabled quantification of palm-tree water use, ET_c. This was carried out on three cultivars of differing salt tolerances: the salt-tolerant 'Lulu, the moderately tolerant 'Khalas', and the salt-intolerant 'Shahlah'. Two salinities of groundwater were considered: 5 dS m^{-1} and 15 dS m^{-1}. The sustainable daily rate of irrigation was considered to be 1.5 ET_c, which accounts for a 25% factor-of-safety, and a 25% salt-leaching fraction. This represents considerable savings over current practices. As well, both proximal and remote sensing were used to extrapolate these findings onto commercial date farms. Finally, an assessment of the green, blue and grey water footprints of date production was made. The grey-water footprint from salt leaching was found to be the largest. A benefit-cost assessment was made of the option of using desalinated water to augment and dilute the brackish groundwater used for irrigation. To dilute 15 dS m^{-1} groundwater to 5 dS m^{-1} irrigation water was shown to have a benefit-cost ratio of 1.4. However, the environmental impact of the reject brine will need to be considered.

ACKNOWLEDGEMENTS

During this year, the UAE aims to be the "global capital for tolerance". The President, His Highness Sheikh Khalifa bin Zayed Al Nahyan, declared 2019 as the 'Year of Tolerance'. Sheikh Khalifa said the UAE and tolerance go 'hand in hand'. He added that "the Year of Tolerance will be celebrated as a national effort towards further advancing a decades-long dream of creating a tolerant and cohesive society, open to peoples of varying cultures and religions from around the world." It is good that I have completed my PhD during this Year of Tolerance.

I would like to sincerely thank Her Excellency Razan Khalifa Al Mubarak, the Managing Director of Abu Dhabi Board Executive Committee for supporting me when I first embarked on my doctoral studies. My thanks also to Her Excellency Dr Shaikha Al Dhaheri, the Acting Secretary General of the Environment Agency - Abu Dhabi (EAD) for her continued support for my research and PhD degree. My thanks also extend to Dr Frederic Launay and Dr Simon Pearson, of EAD for their help and guidance.

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I also express my thanks to Professor Peter Kemp and Dr Brent Clothier, my research supervisors, for their patient guidance, enthusiastic encouragement and critiques of this research work. I am pleased to have worked closely with Dr Brent and I would also like to thank him for his advice and assistance in keeping my progress on schedule. I also thank his wife Penny and the rest of the Clothier family for their hospitality. I would like to thank Dr Abdullah Dakheel from the International Center for Biosaline Agriculture in Dubai, for valuable inputs and positive feedback on my research.

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I appreciate my family for supporting me in this doctoral project especially my Mom, my wife, and my children. I hope that they are proud of what I have achieved. At the outset, it was my father's desire, may Allah bless his soul, for me to complete a doctorate. I hope that through this PhD I have fulfilled his wish.

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LIST OF ABBREVIATIONS

AD	Abu Dhabi
AED	Arab Emirates dirham
CHPM	Compensation Heat Pulse Method
CWP	Consumed water productivity (kg kL^{-1})
Dhs	UAE dirhams
DST	Decision Support Tool
CDI	Capacative De-Ionisation
c_{nat}	The natural concentration of a pollutant in groundwater (mg L^{-1})
c_{ret}	The returned concentration of a pollutant (mg L^{-1})
EAD	Environment Agency Of Abu Dhabi
EC	Electrical Conductivity (dS m^{-1})
*ET*c	Crop Transpiration (mm d^{-1} or L hr^{-1})
*ET*o	Reference Evapotranspiration (mm d^{-1} or L hr^{-1})
FAO	Food and Agriculture Organization
FGC	Fractional ground cover (-)
GPA	Ground projected area (m^2)
GW	Groundwater
HD	Heat Dissipation
HFD	Heat Field Deformation method
HPV	Heat Pulse Velocity (m s^{-1})
ICBA	International Centre for Biosaline Agriculture
*K*c	Crop Factor = *ET*c / *ET*o (-)
L	Litre
LAI	Leaf Area Index (-)
LI	Light-Interception Fraction (-)
LT	Light-Transmission Fraction (-), LT=1-LI
NZ	New Zealand
PAR	Photosynthetically Active Radiation (μmol m^{-2} s^{-1})
PW	Productivity of water (kg L^{-1})
Rg	Net radiation (W m^{-2})
SF	Sap flux (L h^{-1})
SFD	Sap flux density (m s^{-1})
T	Transpiration (mm d^{-1} or L hr^{-1})
TDR	Time Domain Reflectometry
Tmax	Maximum Air Temperature (° C)
TSE	Treated Sewage Effluent
UAE	United Arab Emirates
UAEU	United Arab Emirates University
VPD	Vapour Pressure Deficit (kPa)

W	Windspeed (m s^{-1})
WF	Water footprint (L kg^{-1})
WFN	Water Footprint Network

FRONTISPIECE

Ahmed Al Muaini downloading data from the instrumented ‘Lulu’ date palms of the low salinity treatment (5 dS m^{-1}) at the International Center for Biosaline Agriculture (ICBA) near Dubai, United Arab Emirates.

CHAPTER 1

1 Introduction

1.1 Background

Very recently, one of the leading Emirati newspapers, **The National**, reported that"… Date palms are as synonymous with the Middle East as oil and sand. Inextricably woven into the historical narrative and cultural lexicon of the region – and even mentioned numerous times in the Quran – dates are renowned for their antioxidant properties and other health benefits. They added that "… in fact, [date palm] *Phoenix dactylifera* L. trees are among the earliest plants to have been cultivated by humankind. Locally, the Sheikh Mohammed Centre for Cultural Understanding reports that date palm seeds dating back to 5110 BC were identified on Delma Island in Abu Dhabi." (**The National**, March 10th 2019).

The 40 million date palms in the United Arab Emirates (UAE) are hugely important; culturally, environmentally, and aesthetically, as well as nutrition-wise and for heritage value.

The UAE is hyper-arid, with a reference evapotranspiration, ETo, of about 2500 mm y^{-1}, yet rainfall is usually less than 100 mm y^{-1}. So all of these date palms in the UAE need irrigation. The irrigation of date palms using groundwater consumers about one-third of total groundwater extractions.

So there are huge pressures on the groundwater resources of the UAE. The water resources management strategy for the Emirate of Abu Dhabi highlights these concerns (EAD, 2014). Indeed the photograph of the frontispiece makes the link between water and dates (Figure 1.1). That strategy begins with the fact that "…*Abu Dhabi realizes the importance of its water resources and promoting rational consumption of water for the welfare of future generations. The strategy aims to progress towards an efficient management and conservation of the three water sources; desalinated water, groundwater, and recycled water.*" Environment Agency – Abu Dhabi (EAD, 2014) notes that there is less than effectively 55 years remaining in the usable groundwater reserves. The 2010 baseline value for the consumption of groundwater by agriculture is 1,714 $Mm^3 y^{-1}$. The Strategy has set the 2030 target to be < 755 $Mm^3 y^{-1}$. Large improvements in the effectiveness of irrigation are therefore required.

It is this challenge that underpins the research described in this thesis: minimising the amount of groundwater used to irrigate date palms, minimising the salinization impact on groundwater by limiting the leaching of salts from the rootzone of dates, all whilst maintaining the socio-economic value of date production.

Figure 1.1. The photograph of the frontispiece of "The Water Resources Water Management Strategy for the Emirate of Abu Dhabi 2014-2018" (from EAD, 2014). This is a traditional irrigation system irrigating date palms.

1.2 EAD Date Projects

Given these challenges in relation to irrigation, and the specific concerns in relation to date-palm irrigation, and the importance of date production, in December 2013 EAD funded a short 6 month Pilot Project by Plant & Food Research Ltd (PFR) and Maven International on testing the feasibility of a suite of technologies with just one date variety, the salt-tolerant cultivar

'Lulu', at one salinity (Treatment S1 at 5 dS m^{-1}). This short project carried out at the International Center for Biosaline Research (ICBA) was a success (Al Yamani et al., 2018).

My employer, EAD, then financed a two-and-half year project extension that commenced in May 2015, which I led. This extended the 'Lulu' research at ICBA to include salinity Treatment S3 at 15 dS m^{-1}. Furthermore two cultivars of different salt tolerances were also added: the moderately salt tolerant 'Khalas', and the salt-intolerant 'Shahlah'. These varieties were studied across both the Treatments S1 and S3. This Date Extension Project was resourced by EAD at the level of AED 4.18 million, or NZ$ 1.32 million. The experiments were decommissioned in September 2017.

The contractual goals of this extension project funded by EAD were:

1 To investigate ways to improve irrigation management and optimise water usage. Experiments on three varieties of date palms will be set up to apply daily replacement volumes.

2 To investigate the impact of different levels of water salinity on tree water use, irrigation need and date production. Replicated measurements of the tree water use and the soil water balance will be set up for two salinity levels (5 dS m^{-1} and 15 dS m^{-1}).

3 To investigate how different varieties of date palm respond to altered irrigation volumes and salinity levels. Replicated experiments will be set up on the three most common varieties of date palms (i.e. 'Lulu', 'Khalas' and 'Shahlah').

4 To investigate the combined effect of irrigation management and water salinity on final crop yield and fruit quality. The trial site at ICBA has been operating for about 15 years.

5 The final deliverable from this project will be a date palm plantation management tool (i.e. customised software to assess the impacts of irrigation and salinity management).

6 Completion of Ahmed Al Muaini's PhD. Staff from EAD and ICBA will be closely involved with this project and supporting many of the deliverables. Ahmed Hassan Al

Muaini will also complete his PhD research whilst supporting this project. This involvement by Emirati staff will enable the development of key skills and knowledge including in measuring sap flow, light metering technologies and modelling.

My PhD research (Goal 6) related to Goals 1-4, and not Goal 6. However, in relation to fruit quality, this goal was not pursued as it was not possible to obtain sufficient fruit quality data from ICBA.

In addition, in 2018, EAD then resourced a subsequent project on the application of these scientific results to commercial date-palm farms, the so-called Commercial Dates Project. This was resourced at AED 82,022, or NZD 30,378. I was the EAD lead on this project. The goal of this project was to predict the water-use requirements of commercial date farms on the basis of proximally sensed measurements of the extent of the canopies of date palms on commercial farms in the Al Ain and Liwa regions of Abu Dhabi.

More details of my roles and responsibilities in these EAD projects are provided in Appendix B.

1.3 Research Objectives and Thesis Structure

From the goals of these EAD projects, objectives were set for my PhD research programme.

1.3.1 Thesis Objectives

The Objectives of my thesis mirror the goals of the two original EAD projects. They were to:

- Extend the knowledge gained in the 2014 Pilot Project.
- To investigate ways to improve irrigation management and optimise water usage.
- To investigate the impact of different levels of water salinity (5 dS m^{-1} and 15 dS m^{-1}) on tree water use, irrigation need and date production. .

- To investigate how different varieties of date palm respond to altered irrigation volumes and salinity levels. Three varieties of date palms of different salt tolerances would be considered: ‘Lulu’, ‘Khalas’ and ‘Shahlah’.
- To investigate the combined effect of irrigation management and water salinity on final crop yield and fruit quality with ICBA.

Later in 2018, with the augmented funding through the Commercial Dates project, an additional PhD Objective was added. This was to:

- To determine how by using proximal sensing it would be possible to predict the water use of date palms on commercial date farms.

Finally, through interactions with collaborators from Plant & Food Research and Maven Consultants, and discussions with my colleagues at EAD, it was decided to add yet another Objective to my doctoral research in relation to the water footprint of date production. This was to:

- Quantify the green, blue and grey water footprints of date production and assess the benefit-cost ratio of using desalinated water to enhance date production.

1.3.2 Thesis Structure

In the following Chapter 2, a general review of the literature is provided for this PhD research. This covers the issues and imperatives for dates in the desert, water and date production, date palms and salinity, plus techniques for measuring the water use of date palms. In subsequent chapters, a short literature review is provided in relation to the specific objectives of that Chapter.

In Chapter 3 the details of the compensation heat pulse method (CPHM) that was used to measure the water use of date palms are described, and there it is outlined how the CPHM devices were modified to account for the unique vascular system of the monocotyledonous date palm. The research described in Chapter 3 has been published in *Acta Horticulturae* as Al Muaini et al. 2018.

In Chapters 4 and 5 the application of the CPHM to monitor tree water use is described, and the impact of salinity is determined for three date cultivars of varying salt tolerance in a long-term experimental trial at the International Centre for Biosaline Agriculture (ICBA) near Dubai. As well, new time domain reflectometry (TDR) devices were used for detailed monitoring of soil water and salt dynamics in the rootzone of the date palms. The TDR rods needed to be shielded to enable use under these saline conditions. In Chapter 4, are given the results of water-use studies on the salt-tolerant cultivar ‘Lulu’ at two salinities of groundwater used for irrigation: Treatment S1 at 5 dS m^{-1}; and Treatment S3 at 15 dS m^{-1}. The research described in Chapter 4 has been published in the journal *Agricultural Water Management* (Al Muaini et al. 2019a). Subsequently the research was extended to include date cultivars of different salt tolerances: ‘Khalas’ a moderately salt-tolerant variety; and the salt intolerant ‘Shahlah’. The results of the research in Chapter 5 on the three date cultivars have been submitted to the journal *Agricultural Water Management* (Al Muaini et al. 2019b).

Chapter 6 then describes how these experimental results can be extended and applied to commercial date farms to predict sustainable rate of irrigation as a function of tree size and tree spacing. This research was conducted through the ‘Commercial Dates’ project the Environment Agency – Abu Dhabi funded at the conclusion of the ‘Date Extension’ project. The results from the research described in Chapter 6 has been submitted to the journal *Agricultural Water Management* (Al Muaini et al. 2019c).

Finally, in Chapter 7, the water footprints of date production are quantified and an economic assessment is made of the value of groundwater for irrigation, and the benefit-cost ratio is determined for the use of desalinated water to dilute the brackish groundwater that is used for irrigation. The research described in Chapter 7 has been submitted to the *Journal of Cleaner Production* (Al Muaini et al. 2019d).

The concluding Chapter 8 highlights the main findings of these studies, and provides suggestions for future research.

In Appendix A, is provided my short *curriculum vitae* and a list of my record-of-achievements in terms of publications. In Appendix B, I have presented a declaration of my role in these projects, and in Appendix C there are official forms detailing my percentage contribution within this larger EAD, Maven International, and Plant & Food Research project to the publications that form the basis of Chapters 3, 4, 5, 6 and 7.

1.4 References

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Al-Muaini, Ahmed, Steve Green, Abdullah Dakheel, Al-Hareth Abdullah, Wasel Abdelwahid Abou Dahr, Steve Dixon, Peter Kemp, and Brent Clothier. 2019a. Irrigation Management with Saline Groundwater of a Date Palm Cultivar in the Hyper-arid United Arab Emirates. *Agricultural Water Management* 211:123-131.

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The National, March 10, 2019. Your guide to UAE dates. https://www.thenational.ae/lifestyle/home/your-guide-to-uae-dates-the-al-ain-farm-to-know-the-varieties-and-how-to-grow-your-own-palms-1.835033

CHAPTER 2

2 Literature Review

2.1 Literature Review

In this Chapter, a review is provided of the literature relating to dates, and date production in general. In subsequent Chapters, a short literature review is provided in relation to the specific topic of that Chapter.

2.2 Dates and the Desert: Issues and Imperatives

The date palm (*Phoenix dactylifera* L.) is considered a symbol of life in the desert (Brouk and Fishman, 2016). The date palm tolerates high temperatures, drought and salinity (Zaid and Aria-Jimenez, 2002). It has been cultivated since ancient times and man has been benefitted since then. It is the only indigenous wild desert plant definitely domesticated in its native harsh environments (Zohary and Hopf, 2000). Poor water management through overuse of water scarce resource is seen as the major problem in UAE (UNDP, 2004).

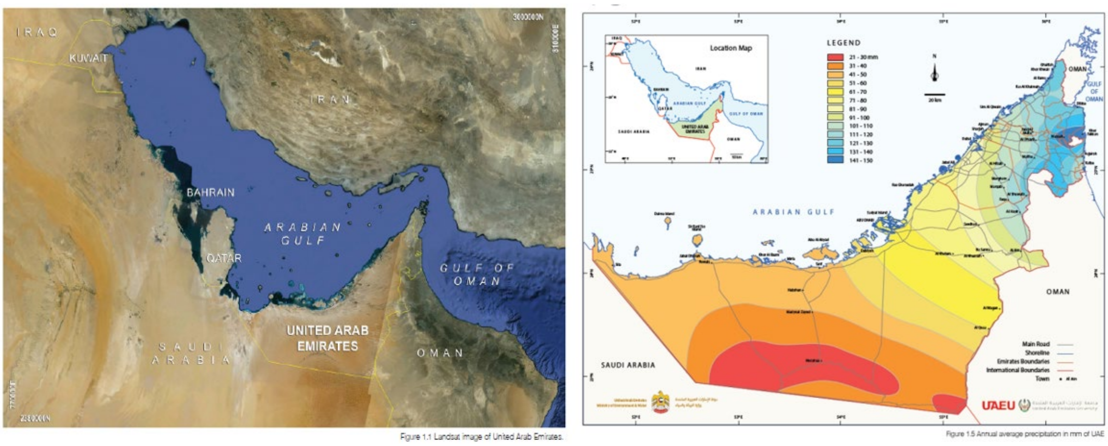
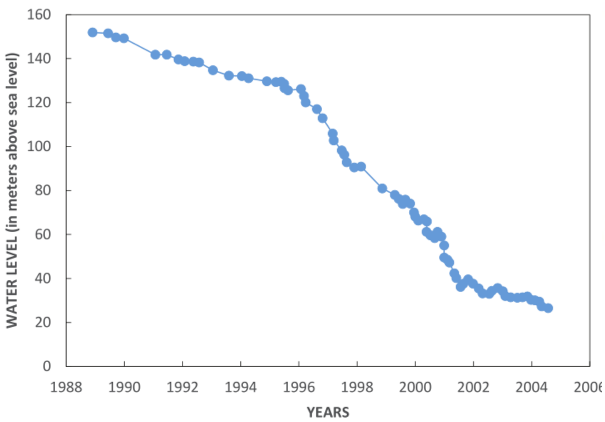


Figure 2.1. Left. A satellite image of the Arabian Gulf showing the location of the United Arab Emirates (UAE). Right. A map taken from the HydroAtlas published by the Ministry of Environment and Water (MOEW, 2014) of the spatial pattern of rainfall in the UAE. The blue zones are where rainfall exceeds 100 mm y^{-1}.

The United Arab Emirates (UAE) has a very dry climate with annual rainfall (*RF*) of less than 100 mm year^{-1}, very high summer temperatures and no perennial surface water resources. Figure 2.1 (left) presents a satellite image of the Arabian Gulf highlighting the desert nature of this region. Figure 2.1 (right) shows the spatial pattern of precipitation in the UAE as presented in the HydroAtlas published in 2014 by the Ministry of Environment and Water (MOEW, 2014). Only in the mountainous northwest bordering Oman is the annual precipitation over 100 mm/year. The annual reference evapotranspiration (*ET*o) can exceed 2500 mm y^{-1}. That *RF* / *ET*o is less than 5% means the UAE is classified as being hyper-arid.

As well, groundwater levels are falling rapidly due to the rate of pumping for agricultural irrigation greatly exceeding natural recharge from the scant rainfall. Groundwater is essentially a non-renewable resource and creating serious challenges in terms of its quantity and increasing salinity. Figure 2.2 (left) shows the recent decline in groundwater levels in the Al Ain area (MOEW, 2014). On the right in Figure 2.2 is shown rise in shallow groundwater salinity between 1969 and 2012. All aquifers are becoming more saline. The scale ranges from blue, where the rise in salinity is less than 1000 mg L^{-1}, to red where the increase exceeds 50,000 mg L^{-1}. The loss of groundwater quantity and quality is concerning, and environmental-protection legislation has recently been passed in Abu Dhabi.



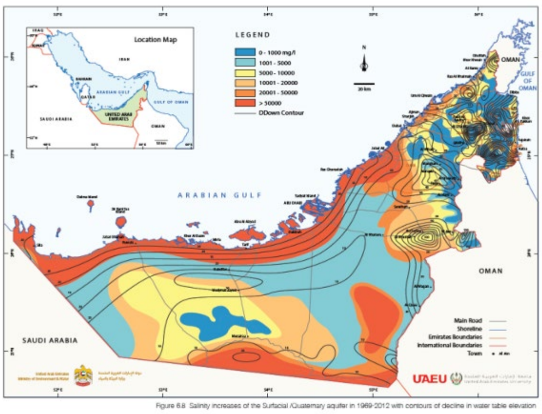


Figure 2.2. Left. The drop in groundwater level near Al Ain between 1988 and 2005. Right. The increase in the salinity of groundwater between 1969 and 2012 for the shallow aquifers of the United Arab Emirates (MOEW, 2014). The blue areas have undergone rises in salinity of under 1000 mg L^{-1}, whereas in the red areas salinity increases have been greater than 50,000 mg L^{-1}.

Yet, despite this loss of water security, groundwater is still being used extensively. The agriculture sector is the largest consumer of water in the UAE. The 2015 UAE State of the Environment Report indicates that the agriculture and landscape sectors, including forests, consumed 57 % of the annual UAE groundwater budget, followed by industrial, residential and other uses (Figure 2.3).

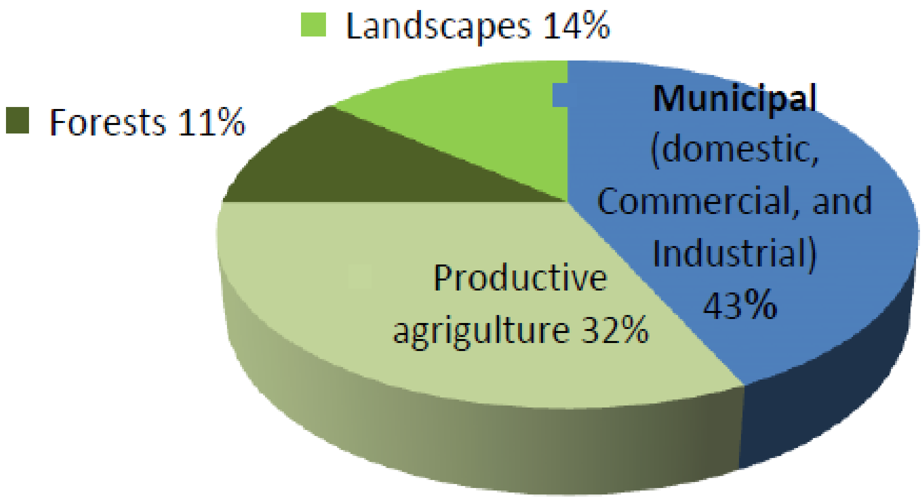


Figure 2.3. The breakdown of groundwater usage by sectors as presented in the 2015 UAE State of the Environment Report (MOEW, 2015).

Dates are an important crop, in the UAE and the MENA countries of the Middle East and North Africa. In the UAE, irrigation of date palms currently accounts for about one third of all groundwater use (MOEW, 2015). Anecdotal evidence suggests many farmers in the UAE apply excessive amounts of irrigation to their crops.

Arab countries possess 70% of the 120 million world's date palms and they produce 72% of the world's dates (Table 2.1). The UAE has the largest number of date palms for any single country in the world (AOAD, 2008). It has over 40 million date palm trees with a minimum of 200 cultivars, 68 of which have commercial importance (Jaradat and Zaid, 2004). And in the Emirates there are many non-productive date-palm trees used in amenity plantings and landscaping, as well as along road-side verges and median strips to prevent the blowing of sand onto infrastructures and roadways. The UAE is the world's 7^{th} largest date producer, accounting for 6% of the world's production (Table 2.1). Abboudi (2000) reported that the

UAE is 100% self-sufficient in date consumption. Historical records show that as a major crop in the UAE the date palm has sustained the desert way of life and Arab traditions.

Table 2.1. The sixteen leading date-producing countries in the world in 2017 (FAO, 2017).

Country	Date Production 2017 (Tonnes)
Egypt	1,590,414
Iran	1,185,165
Algeria	1,058,559
Saudi Arabia	754,761
Iraq	618,818
Pakistan	524,041
United Arab Emirates	475,286
Sudan	439,355
Oman	360,917
Tunisia	260,000
Libya	174,583
China	162,041
Morocco	129,562
Kuwait	87,391
Yemen	47,615
Israel	43,967
Global Production	8,328,055
From: http://www.fao.org/faostat/en/#data/QC	

2.3 Water and Date Production

Date palm production faces declining yields and market constraints. During the past 50 years, date palm groves have been subjected to loss and degradation due to the declining quantity and quality of the groundwater used to irrigate the palm trees, as well as through a loss of farmland to urban expansion, plus the impact of the red weevil of tree health and survival. Over the last decade, productivity of date palm trees has declined in traditional growing areas. Water shortages in summer are considered the main cause of the low productivity of date palms (Ghazouani, 2009). Also, in sandy soils, over-irrigation makes the groundwater table rise, leading to encroaching salt from groundwater rise, and loss of production through chronic waterlogging (Askri et al., 2010).

The allocation of marginal water resources, saline or treated effluent may facilitate future cultivation in the MENA region. Water quality has a significant effect on date palm growth and yield (Tripler et al. 2007, 2011). Therefore, water salinity should be addressed when considering date palm irrigation. The fate of solutes in soil is critical when irrigating with saline water, as poor irrigation leads to drought and salinity stresses which ultimately damage the crops (Shani and Dudley, 2001).

Therefore more precise information on crop water use is needed to help farmers improve their irrigation practices by better matching irrigation supply and water salinity to crop water demand and soil-water storage.

This formed the focus of my PhD project. The aim of my doctoral project, supported by my employer, Environment Agency – Abu Dhabi (EAD), was to understand better the water dynamics of crop water use and soil water storage, so as to develop sustainable irrigation practices. To enable this it was imperative to measure directly the transpiration from the date palm trees and it can now be determined through modern technologies such as sapflow measurement using sensors.

2.4 Water Use of Date Palms and Salinity

Water saving in water-scarce countries is possible if the crops are irrigated based on actual crop water demand and using modern irrigation methods. Direct information about the measurement of transpiration is scant. In previous studies indirect methods have been used to monitor date-palm water use (Alhammadi and Kurup, 2012). Water savings are possible through the introduction of new methods for assessing date palms actual water consumption (Tripler et al. 2007, 2011; Sperling et al. 2012, 2014). Thus, matching irrigation to actual water demand is of importance to determine better the needs for irrigation, and to modify those requirements according to the salinity of the water. These new water management techniques will save water, reduce nutrient losses, and decrease salt accumulation.

The date-palm canopy is a highly efficient photosynthetic system, annually producing upwards of 100 kg of fruit per tree in favourable circumstances (Berenstien, 2004). The palm trees can transpire over 150 m^3 of water per year (Tripler et al., 2007). Still, for their large canopy, palms have low photosynthesis and growth rates per unit leaf area (Smith, 1989).

The date canopy consists of approximately 90 fronds, each composed of about 150 leaflets along the leaf rachis, and covering around 160 m^2 (Berenstien, 2004).

Irrigation water salinity has a notable effect on crop physiology. Plant responses to salt stress compound the drought-stress responses (Munns, 2002). They cause reductions of photosynthesis and cell growth with possible permanent damage and in severe cases the death of plants. Salinity stresses are usually associated with growth inhibition and yield reduction (Tester, 2003; Tripler et al., 2011), due to the osmotic effect on water uptake, the reduced water conductivity of roots, disrupted ion homeostasis in cells, inhibited metabolism, damaged membranes, and the energy requirements to ensure protection against salt (Greenway and Munns, 1980; Frans et al., 1996; Tester, 2003; Tripler et al. 2007, 2011). Nevertheless, salt-tolerant cultivars can maintain water uptake and cell turgor by osmotic adjustments and stomatal regulation (Chaves et al., 2009). Stomatal closure due to increased irrigation salinity has been reported for numerous agricultural crops; including grapevines (Downton et al., 1990), maize, wheat (Lewis et al., 1989), cotton (Brugnoli and Björkman, 1992), pepper (Günes et al., 1996), and olives (Tattini et al., 1995).

Date palms are more adapted to salinity stress than most cultivated trees. Water and soil-water salinity are commonly expressed in electrical conductivity units – *EC* (dS m^{-1}). Dates seem to have a threshold of about 4 dS m^{-1}, with a reduction of 3.6% in yield per unit of EC of the saturated soil paste extract above the threshold value (Maas and Hoffman, 1990). But, date palm leaf elongation is suppressed when the irrigation salinity is over 4 dS m^{-1} (Tripler et al., 2011; Sperling et al. 2014), stem growth is inhibited by irrigation salinity above 9 dS m^{-1}, and yield is reduced by half at a salinity of 18 dS m^{-1} (Alrasbi et al., 2010). Reduced water loss is attributed to inhibited stomatal conductance of saline-irrigated palms during summer (Sperling et al. 2014), which leads to lower CO_2 assimilation rates, as well as reduced plant development, sugar accumulation, and fruit growth (Tripler et al., 2007; Alrasbi et al., 2010; Tripler et al., 2011; Alhammadi and Kurup, 2012).

Salinity is not commonly considered in irrigation recommendations, yet it was reported to be a cause of over-estimation of water demands due to salt-induced limitation of transpiration in bell peppers (Ben-Gal et al., 2008), sunflowers (Meiri et al., 1977), and palms (Tripler et al., 2011), as well as via model predictions (Letey et al., 1985). Sellami and Sifaoui, (2003) estimated hourly variations of potential transpiration and potential evaporation rates using an approximated diurnal cycle. The hourly rates were assumed to be zero before sunrise and after sunset. Beginning at sunrise, they were assumed to follow a sinusoidal form that peaked at 02:00 pm. The integration of truncated sinusoidal expressions gave the daily potential transpiration and potential evaporation rates (Liu et al., 2005). This model provided very good estimates of hourly sap flow compared to the thermal-dissipation measurements with a relatively small error value of 1.31 litre hr^{-1}. The model overestimated some values of maximum hourly sap flow density. Indeed, the measured transpiration rate was given with an error of about 10% under optimal conditions considered (Cabibel and Do, 1991).

There exist numerous methods for measuring evapotranspiration (*ET*c). For date palms, sap flow has been evaluated using the empirical Granier technique and presented as a function of global and net radiation values (Sellami and Sifaoui, 2003). Furthermore, Renninger et al. (2010) had calibrated the heat-dissipation method for Amazonian palms while investigating transpiration changes between the wet and dry seasons.

Madurapperuma et al. (2009) measured sapflow in small potted cocos palms (*Syagrus romanzoffiana*) using both the heat-ratio method (HRM) and the compensation heat pulse method (CHPM). They found the HRM method more accurate, because the small palms, due to their small size, had quite low sapflow velocities.

The notion of longer sensor probes to reach deeper into the stem of larger palms has been addressed in previous works. Lu et al. (2000) worked on matured orchard-grown mango trees with sensors as long as 20 cm. Sellami and Sifaoui (2003) used 60-mm-long probes for sap flow measurements by the Granier technique in palm trees grown in an oasis. Roupsard et al. (2006) used 120-mm-long probes for sap flow assessments in tropical coconut palms using the empirical Granier technique. Nevertheless, none of those sensors were long enough for conducting research on fully grown date palm trees, and nor did they use a mechanistic means of measuring sap flow. Furthermore, extra-strong probes are needed, that can be inserted in drilled holes that are parallel, or forced or even hammered into the tree are needed/ There can be no spaces between the probe and the conducting tissue for long-term sap flow measurements, and the probes need to be perfectly aligned.

Minimising water use is extremely important for the sustainability of date palm plantations. Despite adaptation to arid climates, date palms are extensively irrigated to obtain commercial yields. Irrigation can exceed 2,000 mm year^{-1} (Tripler et al., 2011). Nevertheless, palm tolerance to salinity (Maas and Hoffman, 1977) allows the application of marginal and less expensive water.

There is a need to understand better the role that salt plays in controlling the water use and growth of date palms, and the impact on the yield from modern cultivars.

2.5 Measuring Date Palm Water Use

There exist numerous methods for measuring evapotranspiration (*ET*c). For date palms, sap flow has been evaluated using the empirical Granier technique (Sellami and Sifaoui, 2003). They did however note that the position of the probes in the trunk posed problems, for it was not possible to assess the representativeness of the location of the single measurement location within the trunk. Renninger et al. (2010) calibrated this heat-dissipation method for Amazonian palms while investigating transpiration changes between the wet and dry seasons. Because of the highest flow within the date-palm trunk being in the centre, the heat dissipation method is not considered suitable as it only employs a measurement at a single depth.

Madurapperuma et al. (2009) measured sapflow in small potted cocos palms (*Syagrus romanzoffiana*) using both the heat-ratio method (HRM) and the compensation heat pulse method (CHPM). They found the HRM method more accurate, because the small palms, due to their small size, had quite low sapflow velocities. For larger trees, the velocity of sap flow would render the HRM technique problematic, as it is not capable of resolving high flows

The notion of longer sensor probes to reach deeper into the stem of larger trees has been addressed in previous works, and is important for date palms for the trunks are large, and the flow of sap in a monocotyledon is greatest near the centre. Lu et al. (2000) worked on matured orchard-grown mango trees with sensors as long as 200 mm. Sellami and Sifaoui (2003) used just 60-mm-long probes for sap flow measurements by the Granier technique in palm trees grown in an oasis. Roupsard et al. (2006) used 120-mm-long probes for sap flow assessments in tropical coconut palms using the empirical Granier technique. Nevertheless, none of those sensors were long enough for fully grown date palm trees, and nor did they use a mechanistic means of interpreting the measured sap velocities. The CPHM (Green and Clothier, 1998; Green et al. 2003, 2008) was used here, and this is considered well suited for use in monocotyledons. But extra-strong long probes are now needed, and ones that can be inserted into pre-drilled holes that are parallel. The probes need to be perfectly aligned, otherwise misalignment would introduce errors in the calculation of the sap velocity. Also, there can be no spaces between the probe and the conducting vascular tissues for long-term sap flow measurements. The *ET*c results from the CPHM are shown here to provide detailed understanding of water and salt dynamics of date palms, and it shown how this information can be used to develop sustainable irrigation management practices.

In the following Chapter 3 is described the means by which CPHM was used to monitor *ET*c in date palms, and the initial attempts to quantify the crop-factor *K*c.

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CHAPTER 3

3 Trunk sap flow in date palms growing in the United Arab Emirates

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Chapter 3 presents the details of the devices developed to enable the use of the Compensation Heat Pulse Method (CPHM) for measuring the water use, *ET*c (L d^{-1}), of the monocotyledonous data palm. Unlike dicotyledons, where the sapflow is greatest in the outer annuli of the most recent growth rings, for the date palm the sap velocities are greatest near the centre of the trunk, where water moves upwards through the tough, fibrous, vascular bundles. In order to measure the velocity deep within the trunk of the date palm, 140 mm long sensors and a heating needle were developed. In this Chapter the radial profile of the sap velocities are shown, and integration of these enable the daily pattern of *ET*c to be monitored every 30 minutes. The experiments were carried out on the cultivar 'Khalas', a moderately salt tolerant variety, irrigated with groundwater of salinity 5 dS m^{-1}. During mid-summer the tree used about 182 L d^{-1}, whereas in early spring this was just 62 L d^{-1}. The sap flow measurements of *ET*c were compared to the reference evapotranspiration, *ET*o, and the crop factor, *K*c (= *ET*c / *ET*o). The *K*c was found to be 0.38, well less than the FAO's prescribed value of 0.95 for date palms.

In Chapter 4 this work was extended to the salt-tolerant cultivar 'Lulu' with irrigation salinities of both 5 and 15 dS m^{-1}. Then in Chapter 5 results from three cultivars of varying salinity are presented at both levels of groundwater salinity.

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3.1 Abstract

Data are presented from a field experiment to determine the water use of mature date palms (cv. Khalas) which is a common local variety grown commercially in the United Arab Emirates (UAE). The experiments were conducted at the International Centre for Biosaline Agriculture (ICBA), near Dubai, beginning in 2014. Tree water use was measured directly using the compensation heat-pulse method (CHPM) with 140 mm long sensors placed into the tree trunks. Local weather data was used to calculate the daily potential evaporation rate (ETo), and derive an appropriate value for the crop factor, Kc, for this variety. Information from these field experiments will be used to parameterize a decision support tool for irrigation allocation being developed for the Environment Agency - Abu Dhabi (EAD) to improve the management of groundwater usage for date palms in the United Arab Emirates.

3.2 Introduction

Currently, date palms (*Phoenix dactylifera* L) use about one third of all groundwater that is allocated for crop irrigation in the United Arab Emirates. The Environment Agency Abu Dhabi (EAD) is working with Plant and Food Research (PFR) to refine their estimates of the water demands of date palms. We are using the compensation heat-pulse method (CHPM) to measure the trunk sap flow and thereby determine the actual crop water use.
The trunk of the date palm is typically composed of many tough, fibrous vascular bundles cemented together in a matrix of cellular tissue, which is mostly lignified near the outer section of the trunk. The outer 20-30 mm of trunk does not transport water while sap flow tends to be greatest towards the centre of the trunk (Zaid and Arias-Jimenez, 2002). This poses a challenge for the CHPM. We have had to use very long sensors (140 mm) placed in the trunks of relatively large diameter (350-400 mm) trunks.

This paper presents a selection of data from a three-year field study in mature 'Khalas' palms. We illustrate how sap flow is related to the prevailing microclimate. Information from our wider field experiments, including other palm varieties with different salinity levels for irrigation water, is being used to parameterize a decision support tool for irrigation allocation across the UAE.

3.3 Materials and Methods

3.3.1 Study area

Field experiments were carried out at the International Centre for Biosaline Agriculture (25.09° N; 55.39° E; 48 m a.s.l.) near Dubai. The site comprises 18 different varieties of date palm (Phoenix dactylifera L) which were planted in 2001 at a spacing of 8 m. The soil is described as a Typic Torriorthent sandy-skeletal hyperthermic soil with a sand content > 90% and a bulk density range of 1.5-1.6 kg L^{-1} (AD151; Abdelfattah, 2013).

The palms are irrigated daily using water with low, medium and high salinity (nominal electrical conductivities (*EC*) of 5.0, 10.0 and 15.0 dS m^{-1}). The saline irrigation water is applied automatically via two bubblers (8-10 L min^{-1}) that discharge water into a 2 m diameter basin. The schedule is set up to deliver one or two irrigation events each day, between the hours of 0900 and 1500. Irrigation volumes are measured with a Sensus 620 flow meter (Raleigh, USA).

3.3.2 Transpiration

Three sets of sap flow probes (model HP4TC, Tranzflo NZ Ltd, Palmerston North, New Zealand) were placed in the trunk of three neighbouring trees that had trunk diameters of between 0.35-0.40 m. Specially-designed sensors were made from 15-g stainless hypo-tube with thermocouples at depths of 50, 75, 100 and 125 mm. The probes were installed in the trunk at a height of approximately 1.0 m above the soil surface. The trunk was then wrapped in aluminum foil for thermal insulation.

The compensation heat-pulse method (Green et al., 2003) was used with a standard probe spacing of 5 mm upstream and 10 mm downstream from the heater probe. A Campbell data logger (model CR1000, Campbell Scientific, Logan, USA) was used to control the heater output and then measure the cross-over time (*t*z, s) following the application of a 4.0 s heat pulse. Sap flow (L h^{-1}) was calculated from *t*z values using the approach outlined by Green et al. (2003, 2009). These calculations included a correction for the effect of wounding. A wound diameter of 3.6 mm was assumed for the 2.0 mm diameter drill holes used. This is the same wound factor that we have previously used for kiwifruit which have a very porous sap wood with many large vessels surrounded by large interstitial spaces (Green et al, 1988). Sap flux density (*SFD*) was calculated from the wound-corrected heat-pulse velocity (*HPV*) and measured volumetric-fractions of wood and water within the sapwood. Trunk sap flow (*T*, L h^{-1}) was calculated by multiplying the depth-wise pattern of *SFD* by the relative area of conducting sapwood using the simple annulus approach suggested by Hatton et al. (1990).

Typical profiles of *SFD* showed the highest fluxes were found in the middle part of the trunk (Figure 3.1), confirming the need for very-long probes. Data were collected at 30 min intervals. The monitoring ran continuously for a period of three years.

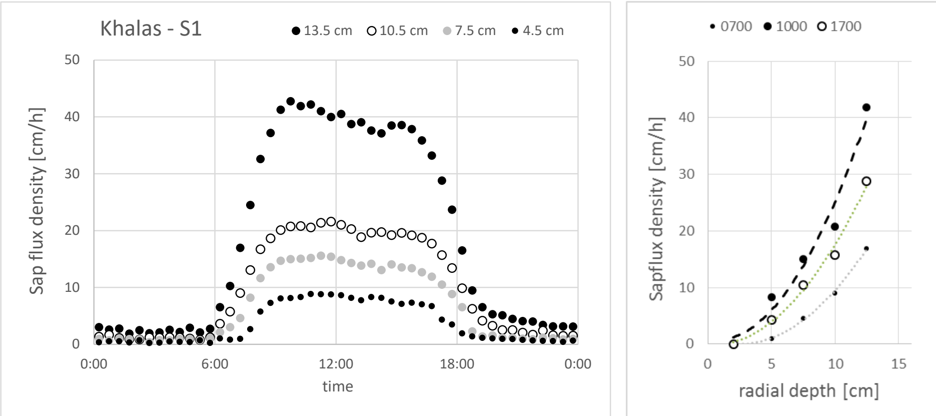

Figure 3.1. The left panel shows the diurnal pattern of sap flux density measured at four radial depths in the trunk of a mature date palm (cv. 'Khalas'). The right panel shows the corresponding profile of sap flux density

3.3.3 Light Interception

Light interception by the date palms was measured throughout the day, for a few days in early summer, using a linear light stick (Tranzflo NZ Ltd, Palmerston North, NZ) that consists of 20 quantum sensors that are sensitive to photosynthetically-active radiation (*PAR*). A reference value for the incoming *PAR* was first measured outside the date palm plot. Then the corresponding value of transmitted *PAR* light was measured on the ground. The latter was obtained from several scans (2 Hz) along a well-defined path comprising shadows from three or four rows of trees.

The canopy leaf area was also assessed using a series of digital images that were captured using a 2.1 MP digital camera (D-Link model 6010L) that is fitted with the fish-eye lens. This camera captures a hemispherical view and is placed under the canopy looking upwards to the sky (Figure 3.2). The camera is controlled via a laptop computer (Panasonic model CF-31 Toughbook). The D-link software enabled us to capture, label and save each image directly to the computer's hard-drive. Specialised software (Light Gap Analyser V2.0, Simon Frazer University, BC) was used to process the images in order to calculate a value for the leaf-area index (*LAI*, m^2 leaf area per m^2 ground area) of the date palm grove.

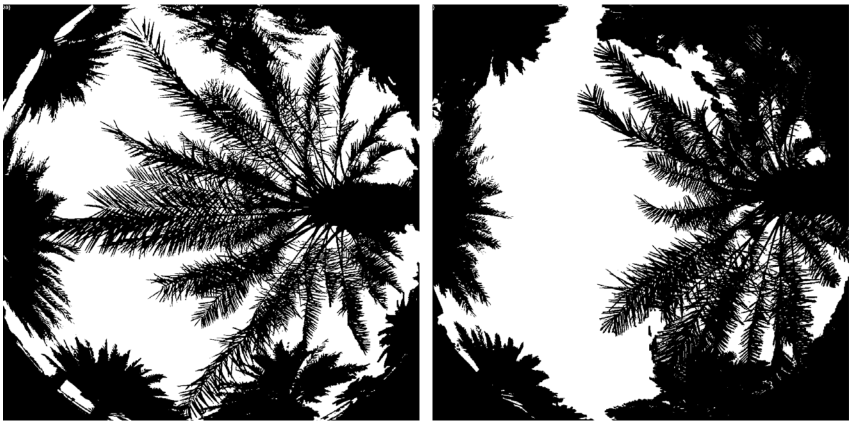

Figure 3.2. Images of mature 'Khalas' palm trees at ICBA taken with a digital fish-eye camera. The panel on the left shows palms irrigated using low salinity (5 dS m^{-1}) water. The panel on the right shows palms irrigated using high-salinity (15 dS m^{-1}) water.

3.3.4 Weather station and *ET*o estimates

A weather station located at ICBA measured solar radiation (LiCor 1200), air temperature and relative humidity (Vaisala HMP 45C), wind speed at 3 m (RM Young) and rainfall (TE525 MM-L, Texas Electronics) using a Campbell data logger (model CR1000). The weather data was used to estimate hourly and daily values of the reference evapotranspiration (*ET*o) using the standard crop-factor approach (FAO-56, Allen et al. 1998). The transpiration of the date palms is related to *ET*o through the dimensionless crop factor, *K*c:

$$ET_C = K_C . ET_O \qquad \text{Eq. [3.1]}$$

where ET_C is the crop water use and *K*c is found from the ratio of the measured daily sap flow to the corresponding daily evaporative demand. One of the aims of our research is to quantify the value of *K*c for the Khalas date palms. Here, and elsewhere, for consistency with FAO-56 (Allen et al. 1998) we refer to crop water-use, *ET*c, as that found from our measurements of transpiration using sap-flow monitoring. We recognize that *ET*c is actually only transpiration here, for in this hyper-arid environment there is essentially no soil-water evaporation, *E*. The desert sand is always dry, and given the high hydraulic conductivity of the desert sand in the irrigation basin, the surface there rapidly becomes dry as the irrigation water drains away rapidly under the influence of gravity. Thus we take *E* as zero, and transpiration if *ET*c.

3.4 Results and Discussion

Here we present a selection of data (February and July, 2017) from our three-year field study. Average climate data for these two months are summarized in Table 3.1. Corresponding values of daily irrigation volumes and daily tree water use are summarized in Table 3.2.

Table 3.1. The average daily climate recorded at ICBA. *R*g is global shortwave radiation, *T*max and *T*min are the maximum and minimum air temperatures, *VPD* is the vapour pressure deficit and *W* is the wind speed.

	*R*g, MJ m^{-2} d^{-1}	*T*max, °C	*T*min, °C	*VPD*, kPa	*W*, m s^{-1}
February					
Average	12.2	25.0	14.1	1.2	1.5
std dev	4.6	3.5	4.2	0.4	0.7
July					
Average	23.9	45.9	28.5	5.2	1.6
std dev	1.4	1.1	2.3	0.4	0.4

Table 3.2. A summary of daily irrigation volumes (*IR*) and the tree water use (*T*) of Khalas date palms at ICBA receiving the low-salinity irrigation water (5 dS m^{-1}). The tree spacing is 8 m and the effective ground area is *A*=64 m^2. The daily potential evaporation (*ET*o) is calculated using the FAO-56 Penman-Monteith model (Allen et al, 1998). The crop factor (*K*c) = *ETc*/*ET*o and the crop transpiration (*ET*c) = *T*/*A*.

	IR, L $tree^{-1}$ d^{-1}	*T*, L $tree^{-1}$ d^{-1}	*ET*C, mm d^{-1}	*ET*O, mm d^{-1}	*K*c
February					
Average	142	62	0.97	2.76	0.37
Std dev	75	16	0.25	0.57	0.12
July					
Average	252	182	2.85	7.50	0.38
Std dev	75	7	0.11	0.74	0.04

The diurnal pattern of trunk sap flow (*SF*, L h^{-1}) averaged for the three date palms is shown in Figures 3.3 & 3.4, along with corresponding daily totals (*T*, L d^{-1}). During mid-summer (July) the pattern of SF is very consistent since every day is essentially cloud-free with very air high temperatures and very low relative humidities (Figure 3.3 & Table 3.1). The diurnal pattern of *SF* in spring (February) is much lower and also less consistent on a day-to-day basis. There are more cloudy days, the air temperatures have decreased and there is a greater, albeit small, chance of some rainfall (Figure 3.4).

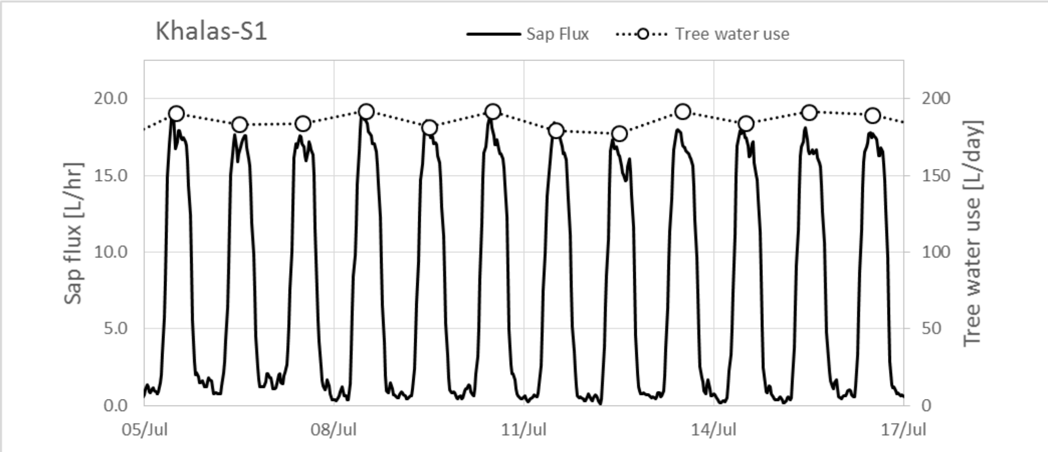

Figure 3.3. The solid line shows the diurnal pattern of transpiration from 'Khalas' date palms (n=3) being irrigated daily using low-salinity (S1=5 dS m^{-1}) water. Open symbols show the total daily water use. The average irrigation volume was 252 L d^{-1} applied during one or two irrigation events.

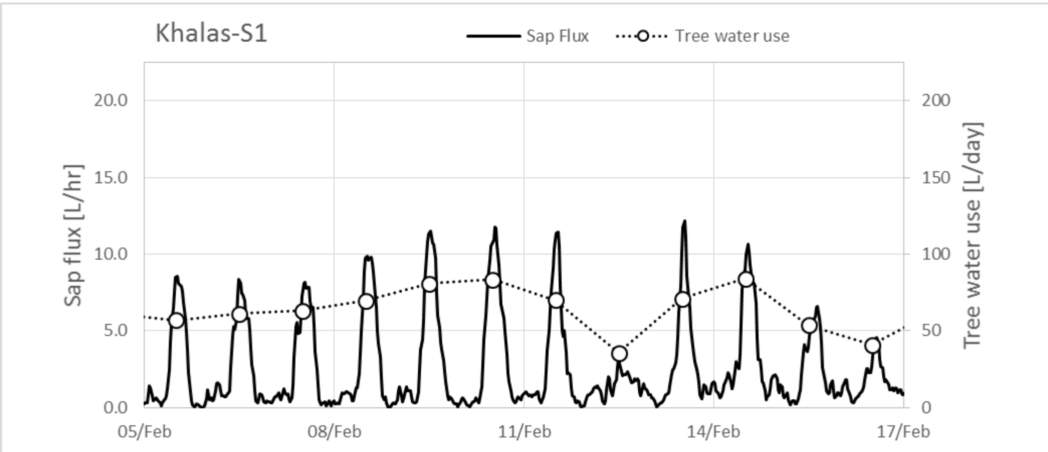

Figure 3.4. Same as Figure 3.3, during the month of February, 2017. The average irrigation volume was 142 L d^{-1} applied during one or two irrigation events. A small amount of rainfall (< 2 mm d^{-1}) was recorded on 12th and 16th of the month.

Tree water use during mid-summer averages out to be 182 (± 7) L d^{-1}, while during the spring it is lower being just 62 (±16) L d^{-1}. These values are similar to data reported for cv. Medjool by Sperling et al (2012) using a combination of heat-pulse and weighing lysimeters.

However, they are slightly higher than the values reported for cv. 'Lulu' by Al-Yamani et al (2017) during a pilot study undertaken at the same experimental site. This is expected as the total leaf area of the 'Khalas' palms is estimated to be 10-15% larger than the Lulu palms under the low salinity irrigation treatment (Dr Abdullah Dakheel, pers. comm.).

Values of tree water use have been rescaled to provide a measure of *ET*c simply by dividing *T* by the unit ground area (*A*=64 m^2 $tree^{-1}$). The values of *ET*c during mid-summer are 2.85 (± 0.11) mm d^{-1} (Table 3.2) for a monthly-averaged *ET*o value of 7.5 (± 0.74) mm d^{-1}. The corresponding values of *ET*c during spring are 0.97 (± 0.25) mm d^{-1} for monthly-averaged *ET*o of 2.76 (± 0.57) mm d^{-1}. As expected, the value of *ET*c increases linearly with *ET*o (the complete data set will be presented elsewhere). The slope of this relation gives a direct measure of the crop factor, *K*c (the summer value is 0.38 ± 0.04 and the spring value is 0.37 ± 0.12). The FAO value of Kc for date palms, purportedly under no salt stress, is reported to be 0.95, or approximately 2.5 times higher than observed for 'Khalas' in this experiment. Most all dates growing in the Middle East would, we consider, be under some degree of salt stress. The value of *K*c here of just 0.3 is for the low salinity treatment of 5 dS m^{-1}.The difference between this and FAO-56's value of 0.95 is best explained by differences in tree size (leaf area and age), planting density, cultivar type and management.

There are different ways to rapidly assess the crop water requirements for dates using the FAO-56 crop-factor approach, in particular through a better understanding of the impact of tree spacing, salinity, and date variety on the canopy leaf area of the trees which affects their rates of water use, and hence *K*c values. This includes the use of digital fish-eye images to determine the leaf area index and the use of ground-based light sensors to determine the percent light transmission (*LT*) through the leaf canopy. The transmission *LT* is 1-*LI* where *LI* is the light interception. For 'Khalas' under the low-salinity irrigation treatment, we estimate LAI = 0.41 ± 0.10 m^2 m^{-2} and *LT* = 31% (data not shown). We have obtained a wider-set of observations from this trial site, using a range of salinity-irrigation treatments in other varieties to quantify the impact of salinity on tree size, daily water use, and date production. That data will be used to explore how *Kc* is related to LAI and *LT* so we can more easily calculate the tree water demands using these two quick-assessment methods.

3.5 Conclusion

CHPM is a suitable method to quantify the total trunk sap flow in date palms. Mature palms of the 'Khalas' variety growing near Dubai are transpiring at a rate of 182 L d^{-1} during mid-summer and about 62 L d^{-1} during early spring, on average. Information from these field experiments are being used to parameterize a decision support tool for irrigation allocation, developed for Environment Agency - Abu Dhabi (EAD). Greater sustainable use of groundwater can be achieved by matching irrigation applications to crop water demands.

3.6 References

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CHAPTER 4

4 Irrigation Management with Saline Groundwater of a Date Palm Cultivar in the Hyper-arid United Arab Emirates

In Chapter 3, the utility of the Compensation Heat Pulse Method (CPHM) for measuring the water use, *ET*c (L d^{-1}), of the 'Khalas' date palm was demonstrated. Now in this Chapter 4, results are presented from the use of the CPHM to monitor, over 4 years, the *ET*c of the salt-tolerant cultivar 'Lulu' when irrigated with groundwater at either 5 dS m^{-1} (Treatment S1) or 15 dS m^{-1} (Treatment S3). The mid-summer *ET*c is up to 190 L d^{-1} for the S1 trees and 130 L d^{-1} for S3. A light stick was used to measure the light interception fraction by the trees, *LI*, and this was related to the crop factor, *K*c (= *ET*c / *ET*o), where *ET*o is the reference evapotranspiration and the units of the *ET*c are now in mm d^{-1}, considering the trees to be spaced at 8 x 8 m. The ratio of *K*c LI^{-1} was found to be 1-1.1. This enables *ET*c to be found from proximal sensing of *LI* and meteorological recording of *ET*o. The rate of sustainable irrigation is proposed to be at 1.5 *ET*c to allow for a 25% factor-of-safety and a 25% salt-leaching fraction. In the following Chapter 5, these results are extended to include the moderately salt-tolerant cultivar 'Khalas' and the salt-intolerant 'Shahlah'

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4.1 Abstract

The United Arab Emirates has a hyper-arid climate. Irrigation is essential for dates (Phoenix dactylifera L), an important crop economically and culturally. Groundwater is relied on, yet it is a non-renewable resource at the rate it is being used. Furthermore, as the water-table drops, it is becoming more saline. Law no. 5 has been passed in Abu Dhabi to regulate the use of groundwater and set allocation limits for agriculture. For assessing the allocation of irrigation water to date farms under Law 5, we carried out measurements of tree water-use by the compensation heat-pulse method, complemented by measurements of the changing soil-water dynamics using time domain reflectometry and bulk soil electrical conductivity. Over four years we measured the hourly pattern of Lulu date-palm water use, ETc, at two levels of irrigation-water salinity: Treatment S1 at 5 dS m^{-1}, and S3 at 15 dS m^{-1}. The mid-summer ETc for the S1 Lulu trees is up to 190 L d^{-1}, on average, whereas for the S3 trees ETc is lower at 130 L d^{-1} (68% of S1) because of the salt. Measurements of canopy radiation interception using a 'light stick' showed the S1 trees intercepted 26% of the incident radiation, whereas the S3 trees only intercepted 20% (ratio S3/S1 = 76%). The date yield of the S1 trees was 68 kg $tree^{-1}$, but was 46 kg $tree^{-1}$ for the S3 trees (ratio 68%). Current practice is to irrigate trees with 275 L d^{-1}, irrespective of salinity. Our recommendation for Law 5 is to tailor irrigation to the seasonal demand in the reference evapotranspiration of ETo, and allow for a 25% factor-of-safety and a 25% salt leaching fraction. For S1 date palms this would mean an annual average of 210 L d^{-1}, and for S3 just 137 L d^{-1}. This represents savings of 25–50% from current practice.

4.2 Introduction

The United Arab Emirates (UAE) has a hyper-arid climate with the reference evapotranspiration (ET_o) of Allen et al. (1998) exceeding 2000 mm y^{-1}, whilst having an average annual precipitation of around just 50 mm y^{-1}. There are very high summer temperatures, often exceeding 40 ºC, and there are virtually no surface water resources. Groundwater is relied upon for irrigation, yet the water-tables are falling rapidly, primarily due to pumping for agriculture, which greatly exceeds the natural recharge rates from the scant rainfall. Wada et al. (2012) reported that in the UAE groundwater abstraction is some 1.55 (±0.3) km^3 y^{-1}, and the groundwater resource is being depleted at a rate of 1.18 (±0.4) km^3 y^{-1}. They calculate that 64% of the gross irrigation water demand in the UAE is supplied by non-renewable groundwater extraction. The UAE State of the Environment Report in 2015 (MOEW, 2015) reported that groundwater levels had dropped at 10 m per decade until the mid-nineties, and by a further 70 m since then. The agricultural, forestry, and landscape sectors account for nearly 60% of the annual water demand of 4.2 km^3 across all of the UAE. This global demand is met by desalinated water (42%), treated sewage effluent (11%), or groundwater (44%).

Dates (*Phoenix dactylifera* L) are an important crop in the UAE, both economically and culturally. The UAE has the largest number of date palms for any single country in the world. It has over 40 million date palm trees, with a minimum of 200 cultivars, 68 of which have commercial importance (Jaradat and Zaid, 2004). The UAE is the world's 4th largest date producer, accounting for 12% of the world's production (Jaradat and Zaid, 2004). Irrigation of date palm currently accounts for about one third of all groundwater takes in the UAE (MOEW, 2015).

So there are serious challenges in terms of the quantity of groundwater left in the UAE. Furthermore, the MOEW (2015) report also pointed out emerging problems associated with the increasing salinity of the remaining groundwater stocks.

One of the key strategies for addressing Abu Dhabi's groundwater sustainability includes regulating for the responsible use of available groundwater. In 2017, Environment Agency – Abu Dhabi (EAD) announced the new Law No. 5 (2016), the Groundwater Organisation Law for the Abu Dhabi Emirate (https://www.ead.ae/Pages/Resources/environmental-laws.aspx). This law clearly states that groundwater resources in the Emirate of Abu Dhabi are owned by the Abu Dhabi Government. The main objective of this new law is to ensure proper management of groundwater resources in the Emirate. With the authorities and new responsibilities given to EAD, water users will no longer be able to use the groundwater on their property without an EAD licence. The licence will be granted under regulations contained in Law No. 5, and EAD will specify which wells should have flow meters, based on technical conditions that will be set. Furthermore groundwater extraction limits will be set according to the defined use for the water.

We have carried out 4 years of research on the water use of date palms that will enable the development of practical advice for improving the use of saline groundwater for irrigation on date farms. This can also help with the institutional and regulatory aspects of irrigation water management. We show here how our results are being used by EAD in the groundwater-take regulations that have been promulgated through Law 5 in Abu Dhabi.

4.2.1 Background

Our research on water use by the Lulu variety of date palm began with a pilot project in 2014 (EAD Contract 30409). In that 9-month long pilot-project we installed sapflow equipment in three Lulu date palms in the low-salinity irrigation treatment S1 with 5 dS m^{-1} water (Treatment S1). Also, time domain reflectometry (TDR) rods of varying length were inserted into the soil within the irrigation basins, and around it, to measure the changing soil water content. Preliminary results from this work, up until August 2014 at the end of the pilot project, were presented at the 2015 International Horticultural Congress (Al Yamani et al., 2017). Here we just present a brief update of this antecedent research as it provides the context for the results from the current project. The main results in this current paper are from the extension project (EAD Contract 31983) which formally began in 2015, although the data from the pilot project continued to be logged over the remaining months of 2014. For completeness, we present here the results for the full calendar year of 2014 for Lulu S1. In 2015, the extension project then expanded this work to extend the measurements on Lulu S1 over 3 more years, as well as to measure the palm water-use and soil-water and salt dynamics of Lulu under a high-salinity irrigation treatment S3 with 15 dS m^{-1} water.

4.2.2 Objectives

The outcome sought by this research carried out under Contracts 30409 and 31983 was to provide quantitative values for the allocation of irrigation water to date farms under Law 5, as a function of date variety and irrigation water salinity. To achieve this we carried out direct measurements of date palm water-use by the compensation heat-pulse method, complemented by measurements of the changing soil-water dynamics using TDR. Our objectives were:

- To measure, over several years, the daily pattern of Lulu date-palm water use, ET_c, under two levels of irrigation water salinity: 5 and 15 dS m^{-1}. These Lulu trees were on an 8 × 8 m spacing.
- To determine the crop factor, K_c, for these date palms so that palm-tree water use could be predicted from weather data using the reference evapotranspiration ET_o.
- To predict the daily irrigation requirements for Lulu date palms at these two levels of irrigation salinity for use in guiding the application of Law 5.
- To develop a 'light stick' device to enable proximal sensing of the percent light interception, as a surrogate measure of the canopy leaf-area of date palms, so as to predict the K_c for other date-palm varieties, different tree ages, other groundwater salinities, and other planting densities.

4.3 Materials and Methods

4.3.1 Study site

Our field experiments were carried out at the International Centre for Biosaline Agriculture (ICBA) (25.09° N; 55.39° E; 48 m a.s.l.) near Dubai. The date variety Lulu was selected from a long-term date experiment at ICBA involving 18 varieties that was started in 2001 and 2002. Lulu is one of the more salt-tolerant varieties of dates. Three levels of water salinity were applied: S1 = 5, S2 = 10 and S3 = 15 dS m^{-1}. Over several years, the hourly pattern of ETc was measured in treatments S1 and S3. No measurements were made on the S2 treatment. There were five Lulu trees in the S1 treatment, and five in the S3 treatment. The centre three trees of each treatment were instrumented, with the outer two acting as guard trees. Yield data were collected and we report here the results for 2017. The date palms flowered in March and the number of fruit bunches were thinned to between 4 and 9 per tree. The harvest of the dates took place during the first two weeks of August 2017.

The soil of the field site is a Typic Torriorthent sandy-skeletal hyperthermic soil (AD151; Abdelfattah, 2013) with a sand content of over 90% and a bulk density in the range of 1500 – 1600 kg m^{-3}.

A weather station located at ICBA measured solar radiation (LiCor 1200, LiCor Inc., Lincoln, Nebraska 68504-5000, USA), air temperature and relative humidity at 2 m (Vaisala HMP 45C, F1-00421 Helsinki, Finland), wind speed at 2 m (RM Young) and rainfall (TE525 MM-L, Texas Electronics, Dallas, Texas 75237) using a Campbell data logger (CR1000, Campbell Scientific, Logan, Utah 84321-1784, USA). The weather data are used to estimate hourly and daily values of the reference evapotranspiration (ETo) using the standard crop-factor approach (FAO-56; Allen et al. 1998). The transpiration of the date palms is related to ET_O (mm d^{-1}) through the dimensionless crop factor, K_C (Eq 4.1):

$$ET_C = K_C . ET_O \quad , \qquad \text{Eq. [4.1]}$$

where ET_C is the crop water use (mm d^{-1}) and K_C is determined from the ratio of the measured daily sapflow to the corresponding daily evaporative demand.

Changes in volumetric soil water content (θ, m^3 m^{-3}) were measured using TDR. The three waveguide rods were of 5 mm diameter and set 50 mm apart. The central rod from each set of waveguides was insulated using glue-lined heat-shrink tubing to minimise the effects of signal attenuation down the core rod by the saline water. There were nine waveguides around each of the three instrumented trees of both treatments. Inside the irrigation basin were installed four sets of waveguides of 1 m length and two of length 2 m. Two 1-m long waveguides were installed on the distal side of the berm of the irrigation basin. As well, one 1-m long set of waveguides was installed midway between two of the irrigation basins to act as reference for the un-irrigated soil. Each waveguide was connected via an RG58U coaxial cable to a multiplexer (Model SDMX-50, Campbell Scientific, USA). A data logger (Model CR1000, Campbell Scientific, USA) was used to communicate with the TDR instrument (model TDR-100, Campbell Scientific Instruments, USA). Because of the shielded central rod, we carried out a laboratory calibration to determine the impact of the insulation on the measured dielectric permittivity (Ferré et al., 1996), so that we could infer θ using the TDR algorithm of Baker and Allmaras (1990). The shielding also meant that these TDR signals could not be used to infer the soil's bulk electrical conductivity (EC_b).

So, in addition, six Campbell Scientific CS655 probes were installed at the depth of 150–270 mm in the irrigation basin which surrounds each of the instrumented trees in the Lulu S1 and S3 plots. Prior to installation the probes were calibrated in the laboratory using soil from the site. In the laboratory, the 120-mm twin rods of the CS655 probes were inserted into sand that had been pre-mixed with water at electrical conductivities (*EC*) of 0, 5, 10 and 15 dS m^{-1}. The sand was mixed to either a water content of 10% v v^{-1}, 20% v v^{-1} or 30% v v^{-1}. These data were then used to enable us to infer the soil solution *EC* from the bulk soil EC_b measured by the CS655 probes.

4.3.2 Irrigation design and operation

Irrigation to each tree is supplied via two bubblers with a design flow rate of 10 L min^{-1} discharging water into a 2-m diameter basin. Irrigation was applied automatically, via a SCADA system (Supervisory Control and Data Acquisition, Schneider Electric), in two aliquots daily at the times of 0800 and 1500. The salinity of the irrigation water was maintained at 5 dS m^{-1} for the S1 trees and 15 dS m^{-1} for the S3 treatment via a mixing system controlled also by the SCADA. The irrigation volumes delivered to the trees were measured with an in-line flow meter (Sensus 620, Raleigh, North Carolina, USA).

In conjunction with our complementary work on the irrigation of amenity forests with saline groundwater in the western desert of Abu Dhabi (Al Yamani et al., 2018), we considered that a sustainable schedule for irrigation of these date palms would be 1.5 ET_c. This would, we hypothesised, be sufficient by including a 25% factor-of-safety to account for reticulation inefficiencies and the natural variation in tree size, plus another 25% leaching fraction to fulfil the need to leach excess salts from the rootzone after the root uptake of fresh water following the previous irrigation. So within both the S1 and S3 treatments, we set up in 2016 and 2017, individual treatments on trees were used to assess salt dynamics and leaching in the rootzone. In both treatments there were three instrumented trees, plus two guard trees. The guard trees (#s 1 and 5) were irrigated at the existing rate of 275 L day^{-1} right throughout the year. The first tree in the treatments (#2) was irrigated at proposed sustainable rate of 1.3 ET_c, tree #3 at 1.5 ET_c, and tree #4 at 2.0 ET_c. These values were the weekly average numbers, and take into account that there is no irrigation on Fridays because of religious considerations. We maintained a constant surveillance of our sapflow measurements as they were being collected, just in case even the rate of 1.5 ET_c was too low, and might be affecting transpiration ET_c. We only report the 1.5 ETc results here.

4.3.3 Sapflow measurement

Being a monocotyledon, date palm does not have a cambium layer. Rather, the trunk is composed of tough, fibrous vascular bundles cemented together in a matrix of cellular tissue which is mostly lignified near the outer part of the trunk. The outer 30–40 mm of trunk is not involved in water transport and sap flow tends to be fastest near the centre of the trunk (Zaid and Arias-Jimenez, 2002). Long probes were used to measure the flow across the inner parts of the trunk. Sperling et al. (2012) used the heat dissipation method to monitor sapflow in date palms, and they found that they had to correct the Granier equation to account for the radially different pattern of sapflow in a monocotyledon. Madurapperuma et al. (2009) successfully used both the compensation heat-pulse (CPHM) and heat-ratio (HRM) methods to measure the transpiration of the small fronds (20–60 mm diameter) of potted, ornamental palm trees. Our 16-year old, production palm trees have trunks 10 times that size, and the higher sap flux densities (mm s^{-1}) would require use of the CPHM, rather than the HRM. So, we used the CHPM, with extra-long probes, so that we could indeed determine the radial pattern of flows, and account for this our calculation of tree water-use (Al Muaini et al., 2018).

A total of twelve sets of sapflow probes (Model HP4TC, Tranzflo NZ Ltd, Palmerston North, New Zealand) were used in this experiment to measure transpiration losses from the date palms. Four sets of probes were placed in three neighbouring trees of both treatments (S1 and S3) that had trunk diameters of 0.4–0.55 m. Specially-designed sensors, made from 15-g stainless hypo-tube with thermocouples at depths of 50, 75, 100 and 125 mm, were constructed for these experiments. The probes were installed in the trunk at a height of approximately 1.0 m. The trunk was then wrapped in aluminium foil for thermal insulation.

The CHPM (Green et al., 2003) was used, with a standard spacing of 5 mm upstream and 10 mm downstream from the heater probe. A Campbell data logger (Model CR1000, Campbell Scientific, Logan, Utah, USA) was used to measure the time taken to achieve thermal equilibrium between sensors located above and below the heater (t_Z, s) following the application of a 4.0-s heat pulse. Data were collected at 30-min intervals. Sapflow (L h^{-1}) was calculated from measurements of t_Z using the approach outlined by Green et al. (2003; 2008).

These calculations included a correction for the effect of wounding. Here we used a wound diameter of 2.8 mm for the 2.0-mm diameter drill holes. Sap flux density (mm s^{-1}) was then deduced from the wound-corrected heat-pulse velocity and measured volumetric fractions of wood and water within the sapwood. The fractions of wood (Fm) and water (Fl) in the sapwood were determined gravimetrically from core samples (Fm = 0.35 and Fl = 0.60). Transpiration, *ET*c, was determined by multiplying the sap flux density by the conducting wood area using the simple annulus approach suggested by Hatton et al. (1990).

Working with electronic equipment in a hyper-arid environment, with temperatures up to 50ºC, along with the occasional sandstorm, can present many technical issues. We encountered some intermittent issues associated with batteries and loggers on our Lulu experiments, and so some of our data records have gaps. Nonetheless we have been able to assemble high-quality datasets of biophysical results on tree-water use, soil water and salt dynamics, and the interactions between trees and their environment. This information is valuable for refining irrigation practices to conserve water.

4.3.4 Canopy radiation interception

Canopy radiation interception can be estimated from static, or mobile, arrays of quantum sensors using Beer's Law. We have developed a hand-held light stick that can be used in an understory transit to record the percentage of visible light being transmitted through the canopy. The percentage of light intercepted, as calculated from our light stick measurements, provides a surrogate measure of the canopy size and leaf density. The light stick (Tranzflo NZ Ltd, Palmerston North, NZ) is 1 m long with 20 equi-spaced quantum sensors that are sensitive to photosynthetically active radiation (*PAR*). A reference value for the incoming PAR was first measured outside the date palm plot. Then the corresponding value of transmitted PAR light was measured on the ground while traversing a fixed transect. The transmitted light value was obtained from the average of multiple scans of the sensors at 2 Hz whilst walking along a well-defined transit comprising multiple shadows from the trees along a row. Each transit lasted 30 s, and took in the shadow areas of 3-4 trees. Multiple transits of 4–5 sweeps, depending on sun angle, were used to cover the full shadow areas of the row of the 3-4 trees in each treatment.

4.4 Results and Discussion

4.4.1 Palm tree water-use: S1

The measured pattern of tree water-use, ET_c (L h^{-1}), in one of the Lulu S1 trees during a week in late summer of 2014, just after the end of the pilot project is shown in Figure 4.1. Also shown is the pattern in the reference evapotranspiration, ET_o (mm d^{-1}) as calculated from the weather station nearby (Allen et al., 1998). The respective ordinates have been scaled so as to achieve the closest overlap to reveal how the weather is driving tree water-use (Figure 4.1). In Figure 4.1 there can be seen some apparent transpiration at night. However, we have not included nocturnal values in the calculations, as the CHPM is not reliable for determination of the low flow rates that might occur at night.

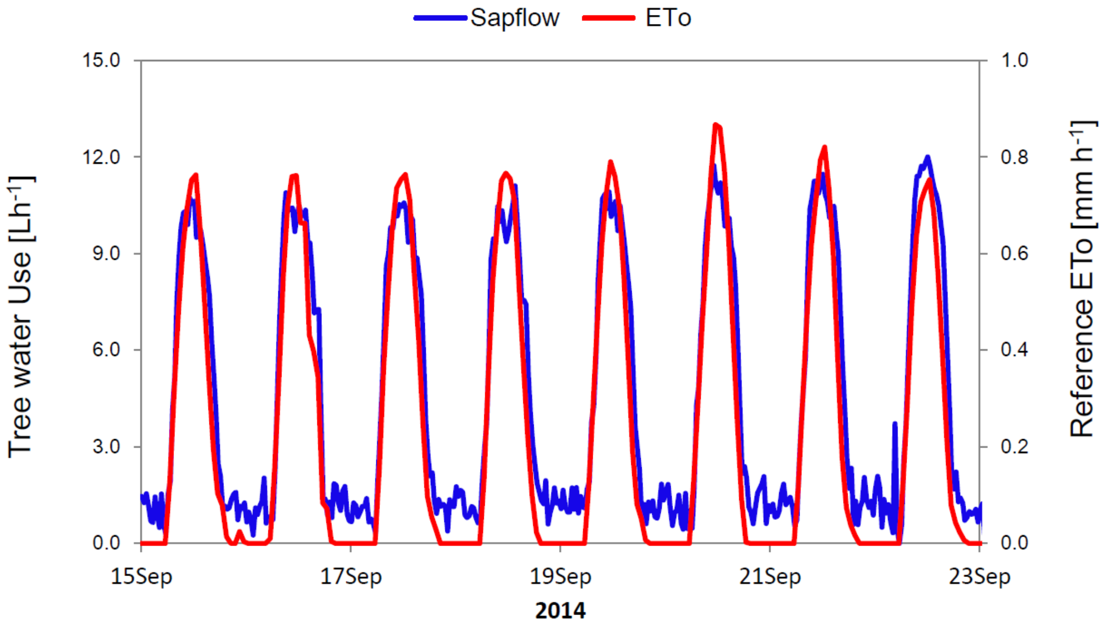


Figure 4.1. Late-summer diurnal traces of average volumetric sapflow (L h^{-1}) measured every 30 min by three sets of probes in the trunk of one of the date palm trees (cv. Lulu, Treatment S1) at the International Center for Biosaline Agriculture (ICBA) near Dubai, UAE, and the hourly reference evapotranspiration ET_o (mm h^{-1}) calculated using a local weather station. These data are for the beginning of the extension project in September 2014

The daily values in the ET_c (L d^{-1}) for all three trees and ET_o (mm d^{-1}) data for the whole of the calendar year of 2014 were regressed against each other, with the reference ET_o as the independent variable (Figure 4.2). The slope of the line of the regression, when divided by the area covered by each tree, 64 m^2, is the crop coefficient (Eq. 4.1), which here means that for these Lulu S1 trees, K_c =0.29.

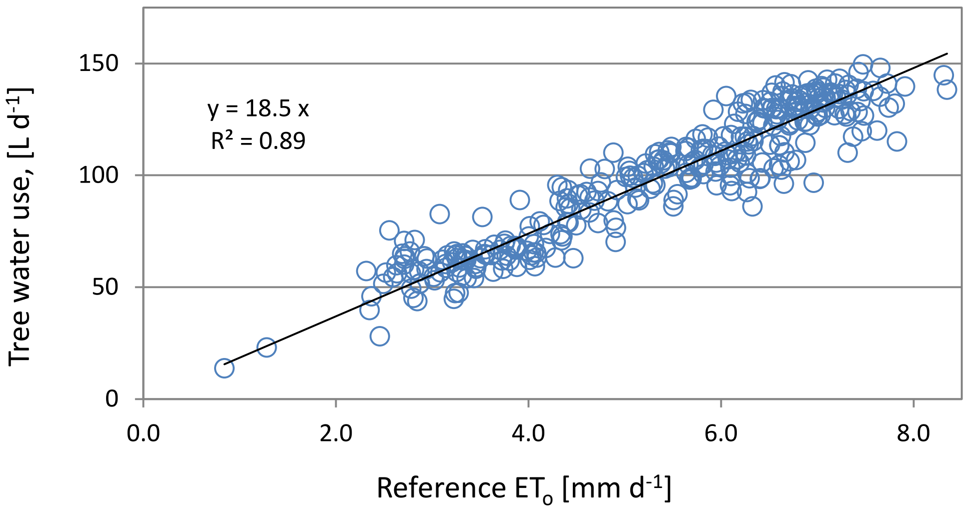


Figure 4. 2. A regression of the palm-tree water-use (ET_c, L d^{-1}) as determined by sap flow against the reference evapotranspiration (ET_o) as determined from the FAO-56 Penman-Monteith model. The slope of the regression (18.5), when divided by the area per tree (8x 8 m) crop gives a crop factor, K_c, of 0.29. These data are for the full year of 2014.

The Food and Agriculture Organisation's guidelines of FAO-56 (Allen et al., 1998) report that, in general, for dates it is considered that K_c should be 0.95. This difference is not surprising, because data cultivation around the world involves different varieties, different tree spacings, and can be irrigated with waters of differing salinities. Such a variation provides a salutary warning about using literature values universally for a given crop without taking into consideration variation in canopy characteristics and irrigation salinities. We discuss solutions to this challenge later in the paper.

We show in Figure 4.3 the full year's progression, throughout 2014, in the ET_c (L d^{-1}) predicted using the FAO-56 reference ET_o, with a K_c of 0.29 with the 8 × 8 m spacing. The sapflow-measured water use of the Lulu S1 trees is also shown. The impact of 3 separate days of rain, a rarity in the UAE, can be seen in February and March. Furthermore, some irregularities in the management of the irrigation system can also be seen in early August and early September. We will discuss the impact of the irrigation management system on tree water-use later on, as we encountered a similar problem in 2016, and there we obtained insight into how dependent these trees are on receiving the correct amount of water.

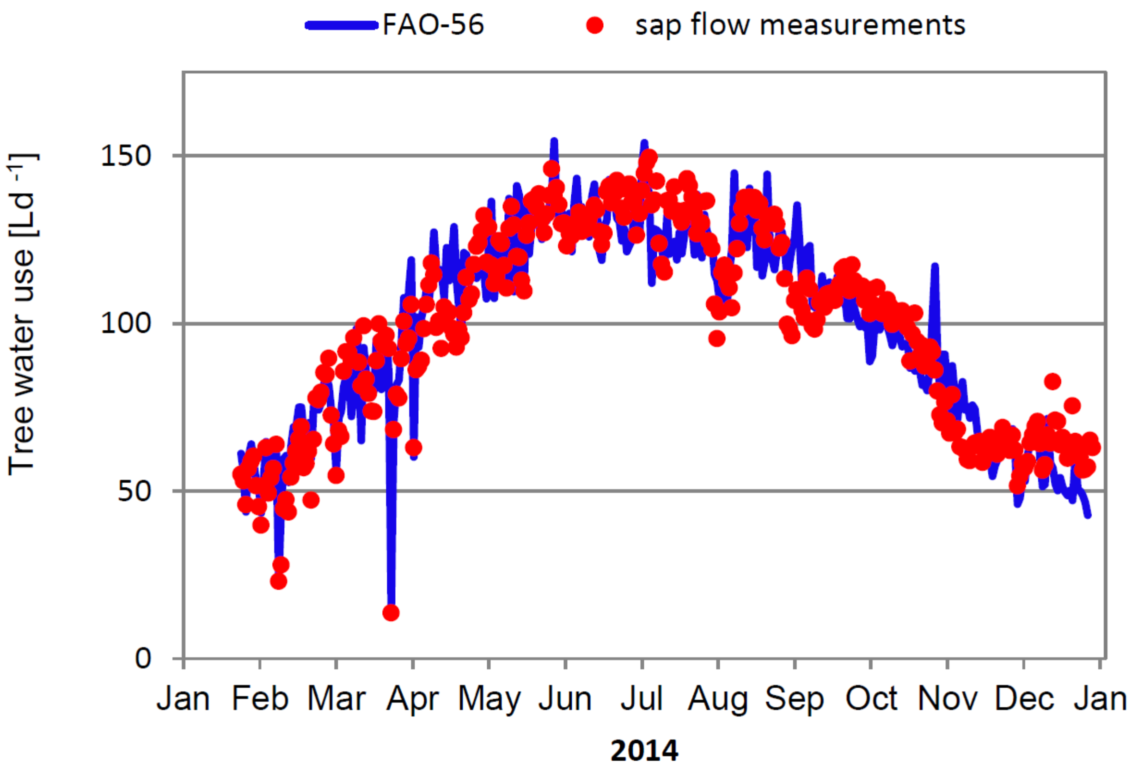


Figure 4.3. The average daily tree water-use (ET_c L d^{-1}) of three date palm trees (variety Lulu) at the International Center for Biosaline Agriculture (ICBA) near Dubai, UAE, as measured by the compensation heat-pulse method (red dots) over the full year 2014 for treatment S1 (5 dS m^{-1}). The model predictions are the calculation from the FAO-56 method using the daily reference evapotranspiration ET_o (mm d^{-1}) and the crop factor K_C of 0.29 from Figure 4.2. The dips in the measured ET_c during early August and early September were due to problems with the operation of the irrigation system. The new data extend to the full year of 2014 and early 2015, the preliminary part-season data of Al Yamani et al (2017).

From the seasonal traces in Figure 4.3, we can see that these (then) 13 year-old date palm trees were using up to a peak over 150 L d^{-1} in mid-summer, and with minima of about 50–60 L d^{-1} during winter. Throughout the year, all of these trees were, in general, receiving 275 L d^{-1} of irrigation, notwithstanding a few technical problems with the pre-SCADA irrigation controllers in August and September.

From the middle of 2015, a new SCADA-controlled irrigation system was installed. This system did not become fully operational until the middle of 2016, so we will not present the 2015 data here. We present, in Figure 4.4, the measured daily tree water-use values averaged for trees 2 and 3 for the latter part of 2016 and early 2017. We had problems with the heater probes and their circuitry for trees 1 and 4, so these data were not included in the daily water-use values of Figure 4.4. Also shown in Figure 4.4, for comparison, is the envelope curve of the maximum 1.25 ET_c for the Lulu S1 trees from Figure 4.3. The inter-year comparison is good. The measured weekly water use of the Lulu palms in 2016 lies within the safety factor we have allowed in our irrigation calculations notwithstanding the additional 25% leaching fraction we have allowed for salts.

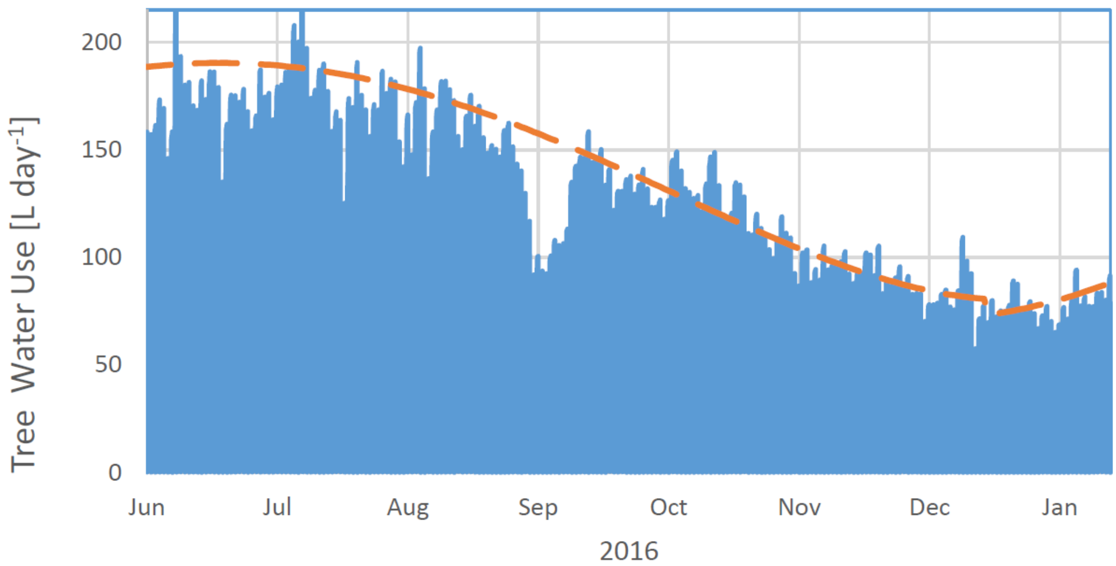


Figure 4.4. The average daily tree water-use (ET_c, L d^{-1}) of two date palm trees (Trees 2 and 3: variety Lulu) at the International Center for Biosaline Agriculture (ICBA) near Dubai, UAE, as measured by the compensation heat-pulse method (blue bars) over the year 2016 for treatment S1 (5 dS m^{-1}). The probes in Tree 4 had become inoperable. The red line is the envelope upper-bound of the sap-flow measurements of 1.25 ET_c made during 2014. The dip in the trees' water use in early September resulted from a failure with the irrigation system on Monday 12th and this was restored on Sunday 18th.

Figure 4.4 shows an obvious drop-off, and a subsequent recovery in the tree water-use during early September. We will explore this feature in greater detail by looking at how the water use of tree 3 relates to the changing pattern of soil-water content around the irrigation basin, as measured using TDR. Our exploration will reveal how date palms in this hyper-arid environment are critically dependent on good water management.

In Figure 4.5 we plot the diurnal pattern of tree 3's water-use, ET_c (L hr^{-1}) in relation to the daily trends in global radiation, Q (W m^{-2}). The results in Figure 4.5 relate to September in 2016, when the SCADA-controlled irrigation was better controlling the amount of irrigation

water applied. No direct comparison with the September results for 2015 (Figure 4.1) should be made, as the irrigation during 2015 was not well controlled, and there may well have been under-watering and water stress. Always, there are two standard irrigations (morning and afternoon) on Sunday 11th September. However, the irrigation system failed to work on Monday 12th. The twice-daily irrigations were not fully restored until Sunday 18th, although there were single irrigations on the 15th and 17th, and there was no irrigation on the 16th because it was a Friday. The tree water-uses on the first two days of failure, the 12th and 13th, were little affected by the lack of irrigation, as the tree would have been drawing water from the already wet soil of the basin, and the wetted soil around the periphery of the berm. However, sometime in mid-morning of the third day, the 14th, the tree water-use dropped precipitously. And this trend continued over the next few days, although it was somewhat stabilised by the half-irrigations on the 15th and 17th. However, even when full irrigation schedule was restored on the 18th, a rapid recovery in sapflow did not occur.
Rather, a full recovery back to pre-failure levels of tree water-use did not occur until around the 18th October which is more than one month after the original mishap occurred (Figure 4.5).

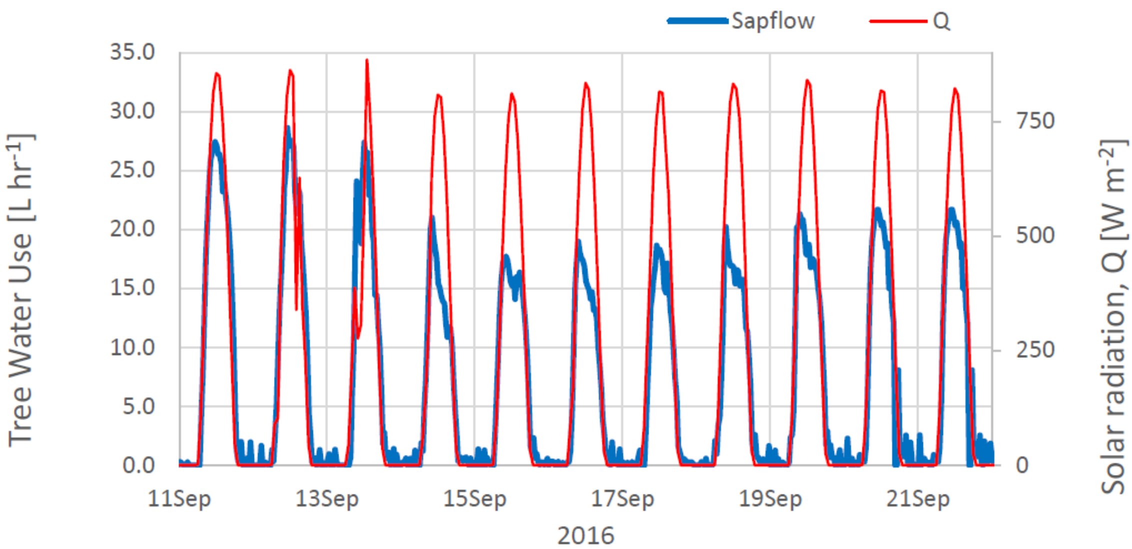


Figure 4.5. The pattern of tree water-use (ET_c, L d^{-1}) of date palm Tree 3 at the International Center for Biosaline Agriculture (ICBA) near Dubai, UAE, as measured by the compensation heat-pulse method (blue line) every 30 minutes over 11 days in mid-September 2016 for treatment S1 (5 dS m^{-1}). The irrigation system failed on Monday September 12th, and was not fully restored until Sunday 18th September. During this 6-day period, some 1000 L of scheduled irrigation was not applied.

Our TDR observations of the spatial pattern of soil-water dynamics in the top 1 m around the irrigation basin can explain this month-long lag in recovery, despite full irrigation being restored after just 6 days. This 'accidental' exploration also reveals insights into the rootzone dynamics that underpin regulated deficit irrigation (Fereres & Soriano, 2007), and partial rootzone drying (Dry and Loveys, 1998), both of which rely upon root signalling (Davies and Zhang, 1991).

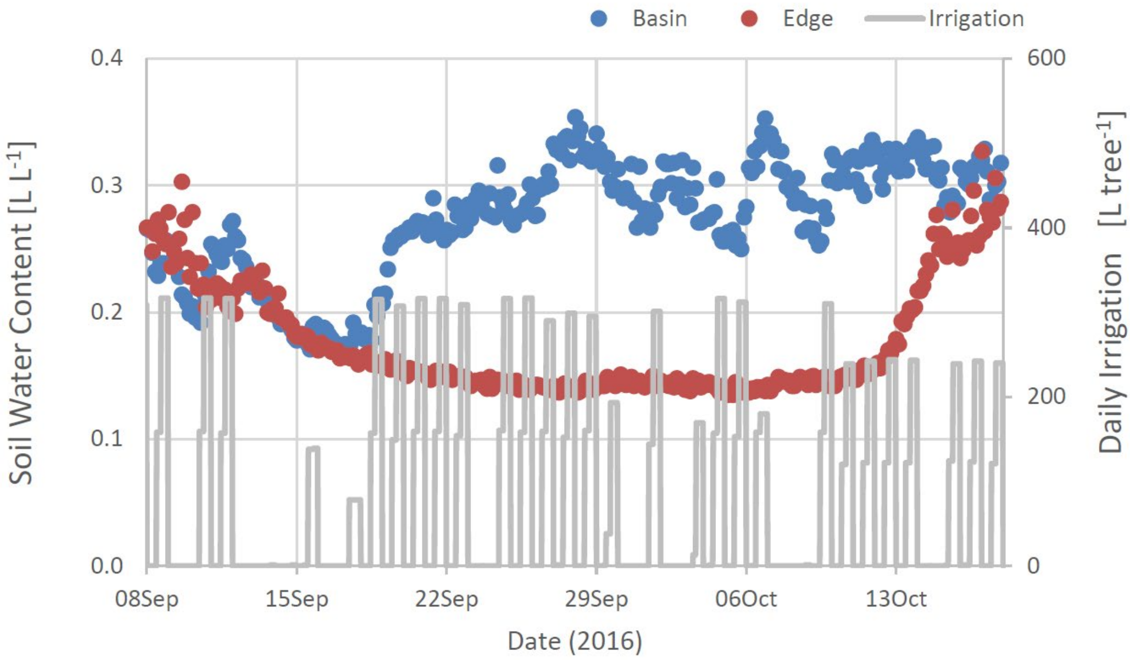


Figure 4.6. The volumetric soil-water content (left axis, L L^{-1}) measured by two, 1 m long Time Domain Reflectometer (TDR) rods around Lulu date palm Tree 3 in the S1 treatment (5 dS m^{-1}). One set of rods was located within the irrigation basin (blue dots), whereas the other was just on the distal side of the berm, 1.2 m from the tree trunk. Also shown is daily irrigation amounts (right axis, L) recoded by an in-line flow meter showing the twice-a-day irrigation aliquots, the absence of irrigation on Fridays, and the failure of the irrigation system between Monday, September 12th and Sunday 18th.

Prior to the failure of the irrigation system on Monday 12th September the soil water content in the top metre within the basin, and on the outer side of the berm dropped (Figure 4.6). This is normal after Fridays as there is never any irrigation for religious reasons. However the irrigations on the following Saturday and Sunday lifted soil water contents at both locations back to the previous Thursday's levels. Following the irrigation failure on Monday 12th, both soil-water contents dropped. The half-irrigations on the 15th and 17th only served to stabilise the basin water-content, whereas the distal-berm water-content continued to drop, presumably as the tree roots were drawing water from the periphery. The return to full irrigation on the 18th quickly returned the basin water content to its antecedent value of around 0.3 L L^{-1}. However the water content on the outside of the berm remained low, and so the roots there, and beyond, would have still been in quite dry soil. It took until the 16th October for the berm soil-water content to get back to 0.3 L L^{-1}. So the tree roots here, and beyond, would have spent a long time in dry soil conditions. The volumetric soil water content measured by the reference TDRs located at the midpoint between the trees remained at around 5-6% throughout the whole year, indicating an absence of roots and water uptake.

Long after the tree's central core of roots was restored to well-watered conditions, there would have been tree roots resident in dry soil for several weeks, during which time the soil-solution *EC* would have become elevated. It would seem that signalling from these drier and saltier roots resulted in the tree delaying its recovery back to the rates of water use that had prevailed prior to the irrigation failure (Figures 4.4 and 4.5). This unforeseen episode reveals that date palms in hyper-arid environments are crucially dependent on well-managed irrigation. This result also reveals how soil-water, salt dynamics and root signalling, can lead to alterations in soil-plant-atmosphere water relations. Good management of water and salt are imperatives for best irrigation practice, more especially so in hyper-arid and saline environments.

4.4.2 Palm tree water-use: S3

During parts of both 2015 and 2017 we managed to obtain good measurements of the tree water on trees 2 and 3 of the Lulu S3 treatment with 15 dS m^{-1} irrigation water. There were problems with irrigation management in early 2015, and issues with water damage to the electronics of the sap flow and data logging equipment in 2017. A composite graph of the reliable water-use data for the average of trees 2 and 3 in the S3 treatment is presented in Figure 4.7.

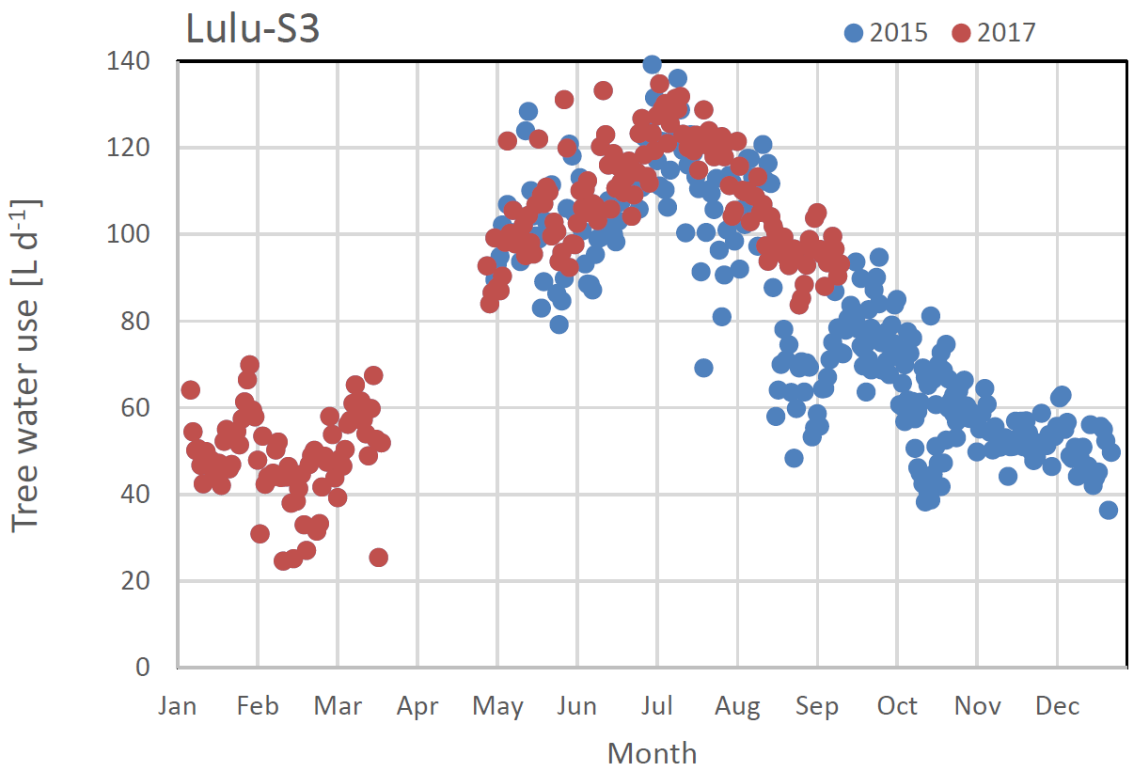


Figure 4.7. The average daily tree water-use (ET_c, L d^{-1}) of the date palm trees (Trees 2 and 3: variety Lulu) at the International Center for Biosaline Agriculture (ICBA) near Dubai, UAE, as measured by the compensation heat-pulse method over the year 2015 (blue dots) and 2017 (red dots) for treatment S3 (15 dS m^{-1}). The probes were reinstalled in May 2016. During 2015 there were problems with the heater controllers, and the irrigation was not reliable. These were remedied in early 2017. However the battery went flat in April 2017, and was replaced in May 2017.

Whereas the peak tree water-use in the S1 treatment was, in mid-summer, about 190 L d^{-1} (Figure 4.4), for the S3 treatment the peak water use was just 130 L d^{-1} (Figure 4.7), or some 68% of S1. Thus the crop coefficient for these S3 trees is $K_c = 0.20$. This difference highlights the impact that the higher salinity irrigation water has had on tree height and canopy size, as we detail later. The result quantifies how salinity affects the value of the appropriate crop coefficient for use in the FAO-56 calculation of crop irrigation requirements. We discuss later as to how this salinity effect may be more easily inferred, without the need for detailed measurements of sapflow.

4.4.3 Salt dynamics

To determine whether our proposed salt leaching fraction of 0.25 ET_c would be sufficient, we monitored the salt dynamics in both the S1 and S3 treatments using CS655 probes. We applied irrigation at a daily rate of 1.5 *ET*c to one of the trees in each treatment. The CS655 probes were calibrated in the laboratory and the results for the four soil solution *EC*s and the three levels of soil-water content are shown in Figure 4.8.

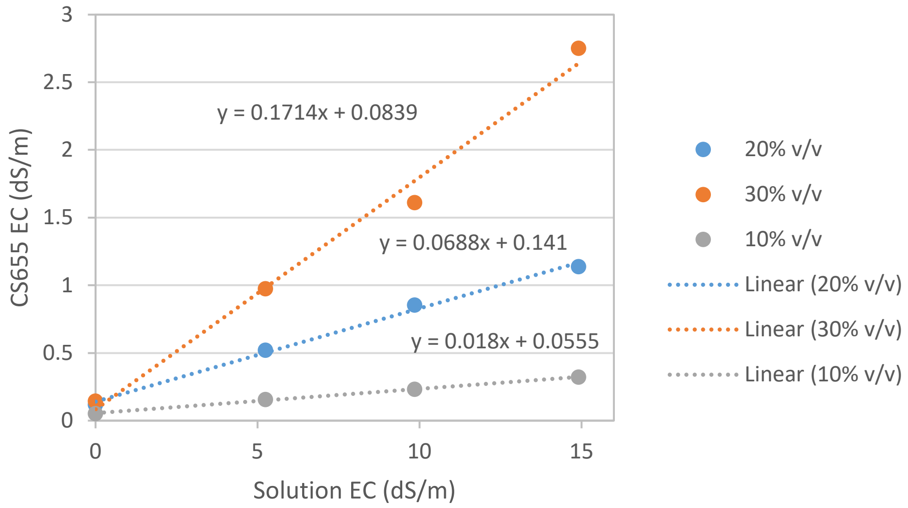
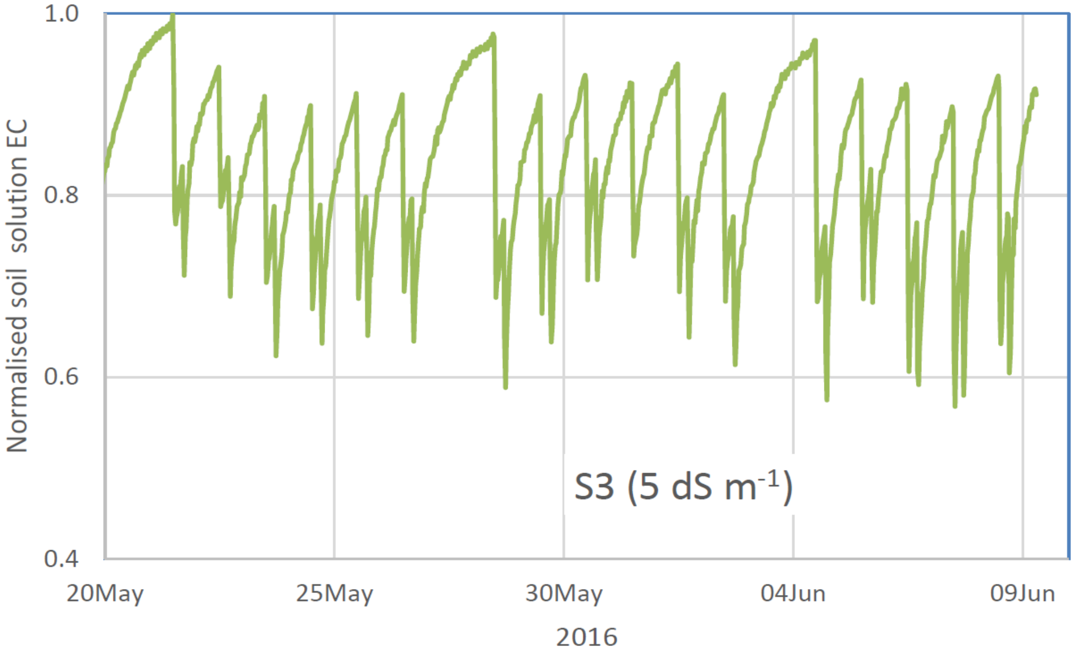


Figure 4.8. Laboratory calibration data for the Campbell CS655 time domain reflectometer (TDR) probes. Sand from the field site was mixed with 4 different saline solutions (0, 5, 10 and 15 dS m^{-1}) and 3 different volumetric water contents (θ = 0.1, 0.2 and 0.3 L L^{-1}). The calibration for determining the soil-solution electrical conductivity *EC* from the bulk-soil electrical conductivity EC_b was found by considering the *EC* to be linear with EC_b and parabolic with the soil water content θ.

For simplicity, so as to assess whether, or not, there was a build-up of salt under the irrigation regime of 1.5 ET_c, we considered a simple linear relation between solution *EC* and the CS655-measured bulk EC_b, combined with a parabolic relationship to account for changes in water content θ (Eq. 4.2),

$$EC = \frac{ECb + 0.829 - 2.964\,\theta - 6.953\,\theta^2}{0.087} \quad . \text{ Eq. 4.2}$$

Temperature effects were not taken into account. To enable easier comparison between the S1 and S3 treatments, the half-hourly *EC* measurements were normalised to the maximum *EC* recorded just prior to the first irrigation on Saturday 20th. This is the time when the pore-water *EC* was at its peak, since there were no irrigations on the Friday. The results for a 3-week window in late May are shown in Figure 4.9.



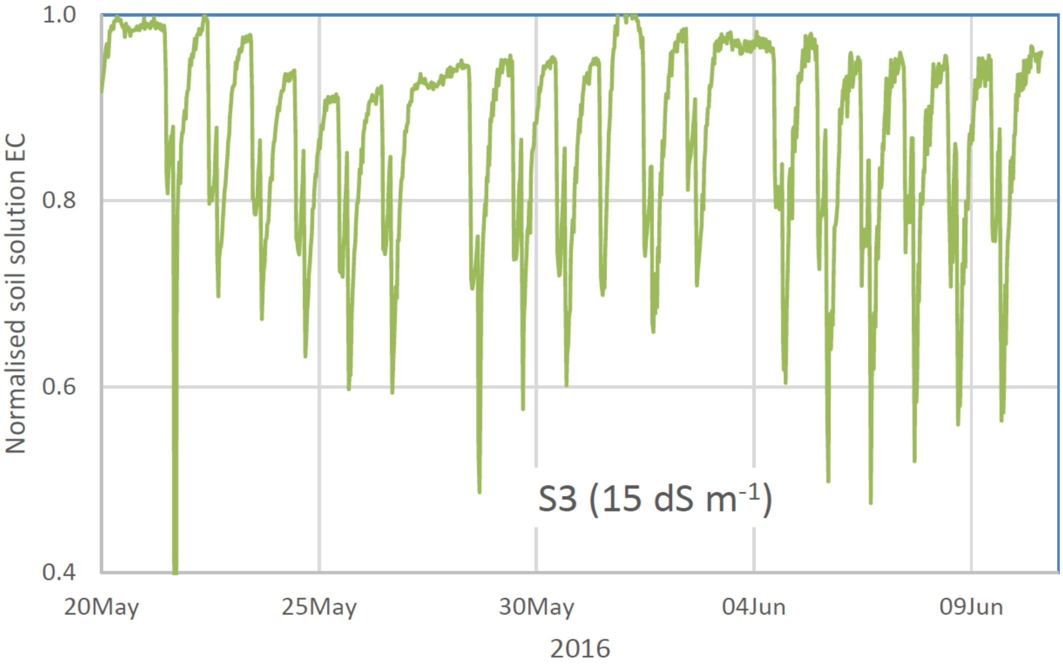


Figure 4.9. Top. The normalised, soil-solution electrical conductivity *EC* (EC/EC_{max}) predicted from the water content (θ) and bulk soil electrical conductivity EC_b for a tree in the S1 (5 dS m^{-1}) treatment (top), and in the S3 treatment (15 dS m^{-1}) (bottom). These data was for a period during mid-May in 2016. The irrigation regimes, *I*, for both trees, were on weekly average I = 1.5 ETc, to account for a 25% factor-of-safety, and a 25% leaching fraction. The EC_b and θ were measured using Campbell CS655 probes at a depth of 150-270 mm inside the respective irrigation basins. Two aliquots formed the daily irrigations, one early in the morning at, and the other in the early afternoon. There were no irrigations on Fridays.

As expected for both treatments, the drop in *EC* with the first morning irrigation is rapid, and then it rises again throughout the morning until the afternoon irrigation drops the *EC* to its lowest level. The weekly maximum value is always on the morning of Saturday. There appears to be no trend in salt build-up in either treatment during this early-summer period when the rates of crop water use are close to maximum. These observations confirm that our proposed use of irrigation at 1.5 ET_c, as being a sustainable rate of irrigation with regard to effective leaching salts following daily root-water uptake by the date palms prior to next irrigation. This short-term behaviour of salt leaching corroborates the annual finding with the drip irrigation of amenity forests in Abu Dhabi at the rate of 1.5 ET_c with saline groundwater of *EC* about 10 dS m^{-1} (Al Yamani et al., 2018).

4.4.4 Tree canopy characteristics

The visual differences between the S1 and S3 trees were patent. The characteristics of the 5 trees from both treatments are given in Table 4.1, and for completeness we also present there the results for the trees in treatment S2 where the irrigation water had an EC of 10 dS m^{-1}.

The dimensions of the trees and the yield of dates were measured during the first half of August 2017 across all 3 treatments: S1, S2, and S3. The S1 trees were harvested on 3rd August, S2 on the 10th August, and S3 on the 20th August.

The circumferences of the trees were not affected by the different salinities. However, the tree heights and the leaf areas were both strongly affected with the S1 trees at 3.5 m tall and 62.1 m^2 of leaf, the S2 at 3.0 m and 56.2 m^2 and the S3 trees at 2.6 m and 41.7 m^2. The ratio of the tree heights between S3 and S1 is 73%, and the corresponding ratio of leaf areas is 67%, which would be indicative of the trees' biomasses, since the circumferences were similar. This is the similar to the ratio of the tree water-uses presented above, *viz.* 68%. The Lulu S1 trees yielded 67.5 kg of dates per tree, whereas the S3 trees produced just 45.9 kg each. The date yield ratio S1:S3 of 68% is also essentially the same as the ratio of the tree leaf areas and the tree water-uses, as expected (Hanks, 1983). The annual amount of irrigation applied to each of the S1 trees was 86 kL, whereas the measured water-use by the S1 trees was just 51.1 kL. For the S3 trees, the irrigation schedule applied 65% of the S1 treatment, or some 56 kL, and the measured water use was only 36.8 kL. So the date productivity in relation to water applied for the S1 trees was 0.78 kg kL^{-1}, and 0.82 kg kL^{-1} for the S3 trees. In other words, we observed similar productivity in relation to the amount of water transpired. The productivity in terms of water applied would be much lower in S3 when the standard irrigation amount was applied. Therefore for best management of the groundwater resource, irrigation practices need to be improved to match irrigation better the size of the date palms.

Table 4.1. Tree dimensions and Lulu date yield at the 2017 harvest for the three salinity levels: S1 (5 dS m^{-1}); S2 (10 dS m^{-1}); and S3 (15 dS m^{-1}). Values are mean ± SD across three trees per treatment. The experiments began in 2001.

Salinity Treatment	Tree height (m)	Trunk circumference (m)	Leaf area (m^2 $tree^{-1}$)	Lulu date yield (kg $tree^{-1}$)
S1	3.58 ± 0.48	1.59 ± 0.11	62.1 ± 13.0	67.5 ± 8.1
S2	3.03 ± 0.22	1.61 ± 0.20	56.2 ± 13.6	55.5 ± 5.3
S3	2.62 ± 0.31	1.65 ± 0.05	41.7 ± 8.4	45.9 ± 14.9

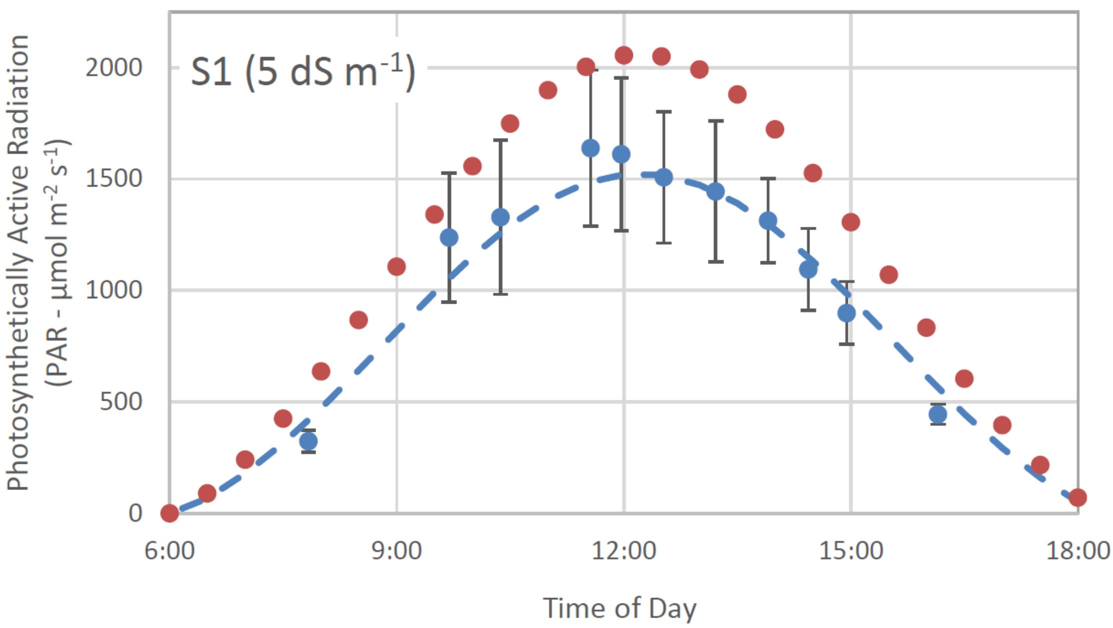
Furthermore, we can use *LI* to infer the crop coefficient K_c, using the effective area of shade (*EAS*) approach of Goodwin et al. (2006). Their *EAS* is our *LI*. The use of this technique for dates are shown in Table 4.2 for the S1 and S3 treatments. From the light-stick measured *LI*, and the sapflow-measured K_c values, we calculate the ratio of K_c/LI to be 1.12 for the S1 dates, and 1.00 for the S3 treatment. These ratios fit within the reported range in the values for K_c/LI of 1-1.2 for apples (O'Connell et al., 2008), peaches (Goodwin et al., 2006) and pears (Goodwin et al., 2015). So in the future, we will use our light stick measurements of *LI* to infer the K_c values for different date varieties, different tree ages, and different planting densities.

Table 4.2. The average light interception (*LI*, %) values that we have measured with the light stick from Figure 4.10, along with the crop coefficient *K*c [-] measured from our sapflow monitoring, for the date palms in the S1 treatment (5 dS m^{-1}), and for the S3 trees (15 dS m^{-1}). The last column is the ratio of *K*c to *LI*.

Salinity Treatment	Light Interception, *LI* (%)	Crop coefficient K_c [-]	Ratio $K_c\ LI^{-1}$
S1	0.26	0.29	1.12
S3	0.20	0.20	1.00

4.4.5 Light stick and canopy light interception

The results from the intensive use of the light stick on the 19th September 2015 are shown in Figure 4.10. The diurnal trace of the incident *PAR* is shown (red dots), as is *PAR* measured by the light stick from multiple passes underneath both the S1 trees (top) and S3 trees (bottom). From the average of these traces, we calculate that the for the S1 trees some 74% of the incident light is transmitted through to the ground surface. The light interception (*LI*) is therefore 26%. For the smaller S3 trees, *LI* = 20%. The ratio of the *LI* between S3 and S1 is 76%, which is of the same order as the ratio of the leaf areas (67%) (Table 4.1), as well as the tree water use ratio (68%) and the difference in date yield (68%). Thus the easy measurement of *LI* by the light stick provides us with a good measure of the palm trees' canopy characteristics, and tree performance.



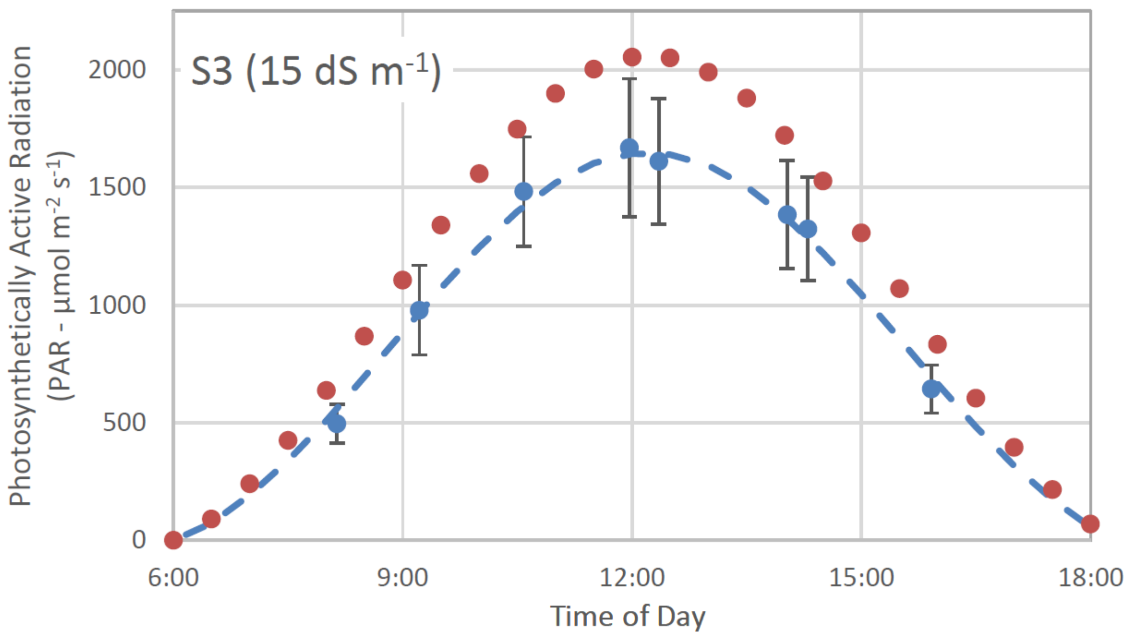


Figure 4.10. The photosynthetically active (*PAR*, µmol m^{-2} s^{-1}) radiation from the sky over 19th September 2015 (Day of Year, DOY 262) (red dots), in relation to the *PAR* measured under the canopy using a light stick. Top: Measurements of the transmitted *PAR* under the canopies of the S1 trees during 11 transits with the light stick reveals a transmission of 74% of the incident *PAR*. Bottom. The measurements of the transmitted *PAR* under the canopies of the S3 trees from 8 transits showing a light transmission of 80%.

4.4.6 Law 5 and irrigation allocations

In 2017, in order to protect groundwater, EAD announced the Government's new Law No. 5 (2016), the Groundwater Organisation Law for the Abu Dhabi Emirate. Groundwater extraction limits and usage allowances will be set under Law 5. We now describe the initial assessments of the usage allowances that we have suggested to EAD to be considered in the regulations for the irrigation of Lulu date palms with water of different salinities.

For groundwater irrigation we consider this should involve seasonally-adjusted replacement of the trees' daily water use, ET_c, rather than just a single daily rate applied throughout the year, as happens now. Furthermore we have suggested that there be an add-on of 25% as a factor of safety to account for inefficiencies in the irrigation reticulation system, and also the natural variation in tree sizes. As well, we have suggested another 25% add-on to ensure salt leaching, which we have verified here as being sufficient to avoid a build-up of salts, even with irrigation water at 15 dS m^{-1}. For simplicity, we suggest that the 1.5 ET_c values be aggregated into monthly averages, with the monthly maximum ET_c to be used as the reference value for that month. The ET_c values are easily estimated using the FAO-56 ET_o, and the knowledge of the crop factor *K*c that we have presented here for the S1 and S3 treatments.

The suggested monthly allocations, based on 1.5 ET_c, are shown in Table 4.3. In annual sum, the average daily water-use of the S1 trees is 140 L d^{-1}. Using the seasonally adjusted 1.5 ET_c allocation would provide, on annual average, a daily application of 210 L d^{-1}, some 25% less than the current application of 275 L d^{-1}, and a saving of 25%. For the smaller S3 trees, the annually averaged daily water allocation need only be 137 L d^{-1}, a saving of 50% by taking into account their smaller tree sizes.

We have provided practical information for the implementation of Law 5, however this only relates to one variety, Lulu, at one tree spacing, 8 × 8m, at two salinities, 5 and 15 dS m^{-1}. The challenge that we are now working on is to extend these findings to other varieties, of different ages and spacings, and at different groundwater salinities. The key tool for a practical assessment of leaf-canopy size, and hence the crop factor, will be our light-stick, which can, through proximal sensing, provide us with information on the light interception characteristics of the various canopy structures and tree sizes across commercial date farms in Abu Dhabi. These data will enable us to infer the crop coefficient K_c which we can then use in FAO-56 to suggest irrigation allocations at 1.5 ET_c.

Table 4.3. The monthly average of the daily water use of date palms (ET_c) in L d^{-1} for irrigation with groundwater (GW) at 5 dS m^{-1}. This is taken from the 2016 envelope curve in Figure 4. Also shown is the monthly irrigation requirements, in terms of daily irrigation amounts, for irrigation with GW at 5 dS m^{-1} with a factor-of-safety of 25% and salt leaching fraction of 25%, therefore in sum being 1.5 ET_c. As well, the monthly irrigation requirements for GW at 15 dS m^{-1} are also shown, based on the *ET*c of the S3 trees being 65% of those in S1. Current practice is to apply 275 L d^{-1} to all trees on every day of the year, except there is no irrigation on Fridays.

	Tree water use, ET_c	**Irrigation GW @ 5 dS m^{-1}**	**Irrigation GW @ 15 dS m^{-1}**
Month	**L d^{-1}**	**L d^{-1}**	**L d^{-1}**
Jan	88	132	86
Feb	113	170	110
Mar	144	216	140
Apr	167	251	163
May	184	276	179
Jun	190	285	185
Jul	185	278	180
Aug	169	254	165
Sep	146	219	142
Oct	118	177	115
Nov	95	143	93
Dec	81	122	79
Daily annual average	140	210	137

4.5 Conclusions

Currently saline groundwater is used in the UAE to irrigate date palms. The common practice is to irrigate each tree with 275 L d^{-1} throughout the year, except on Fridays, for religious reasons. We have shown through experiments with Lulu date palms using sapflow measurements of daily tree water use, ET_c, that for 5 dS m^{-1} water, date palm water use ET_c is up to 190 L d^{-1} in summer, and down to 80 L d^{-1} in winter. With 15 dS m^{-1} irrigation water, tree water-use is just 68% of that rate. We had proposed that sustainable irrigation would be 1.5 ET_c, by taking into account a 25% factor-of-safety, and 25% salt-leaching fraction. Our *in situ* measurements confirm that with this rate, there is no noticeable build-up of salt within the irrigation-basin part of the rootzone, even at the higher salinity. We did however measure high salinities outside the basins, along the periphery of the wetted zone where the salt had been shunted laterally.

We have shown that our device that we have called the 'light-stick' can be used for proximal sensing of the trees' shadow areas to estimate the canopy intercepted radiation. These interception data can be used to infer the crop coefficient K_c in the FAO-56 model for predicting tree water use from the reference evapotranspiration, ET_o. These results are being used in formulation of irrigation allocation allowances in Law 5 (2016), the Groundwater Organisation Law recently passed by the government of Abu Dhabi. We are extending these findings to other date varieties, tree sizes and spacings, and for groundwaters of different salinities, in the form of a decision support tool for EAD to be applied across the Abu Dhabi Emirate, to support Law 5 for policy and planning.

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CHAPTER 5

5 Water Requirements for Irrigation with Saline Groundwater of Three Date-Palm Cultivars with Different Salt-Tolerances in the Hyper-Arid United Arab Emirates

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The applicability and value of using the Compensation Heat Pulse Method (CHPM) has been demonstrated in Chapters 3 and 4. Here in Chapter 5 the CPHM is applied to determine the water use, *ET*c (L d^{-1} and L y^{-1}) of three date cultivars of varying salinity tolerances. The cultivars were the salt-tolerant 'Lulu', the moderately tolerant 'Khalas', and the salt-intolerant 'Shahlah'. The trees were irrigated with groundwater at either 5 dS m^{-1} (Treatment S1) or 15 dS m^{-1} (Treatment S3). These experiments were carried out at an experimental trial at the International Centre for Biosaline Agriculture (ICBA) near Dubai. The water use of the S3 treatment was about 43-46% of the S1 treatment. Proximal sensing of the light interception fraction by the trees, *LI*, was related to the crop factor of *ET*c / *ET*o, where *ET*o is the reference evapotranspiration. Across all varieties and salinities, the ratio $Kc\ LI^{-1}$ was found to 0.95, which enables the irrigation requirements to be found as a function of salinity. However, the date yield differences between the S1 and S3 treatments varied greatly between cultivars, and reflected their salt tolerances. The ratio of the consumed water productivity, *CWP* (kg-dates kL^{-1}), for S3 over S1 was 1.24 for the salt-tolerant 'Lulu', unity for the moderately tolerant 'Khalas', and 0.89 for the salt intolerant 'Shahlah'.

In the next Chapter, a method to extrapolate the experimental trial results of this Chapter 5 to commercial farms was developed in order to provide sustainable irrigation practices for date farmers.

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5.1 Abstract

Direct measurement of sap flow enabled determination of the seasonal pattern of water use, *ET*c, of three dates varieties irrigated with groundwater at different salinities: S1 at 5 dS m^{-1} and S3 at 15 dS m^{-1}. For S1, the salt-tolerant 'Lulu' used 50 kL $tree^{-1}$ y^{-1}, the moderately tolerant 'Khalas' consumed 43.1 kL $tree^{-1}$ y^{-1}, and the salt-intolerant 'Shahlah' transpired 57.3 kL $tree^{-1}$ y^{-1}. The *ET*c at the higher salinity was 43-46% lower across all varieties. The crop factor, *K*c, was computed from *ET*c / *ET*o where *ET*o is the reference evapotranspiration. By proximal sensing using a light stick, we measured the fraction of light intercepted, *LI*, by the trees' canopies. For all varieties and salinities, we found the ratio *K*c LI^{-1} to be about 0.95, which enables proximal sensing to be used to predict *ET*c for all varieties and across salinities. These predictions can then be used to schedule irrigation the recommended rate of 1.5 *ET*c, which accounts for a 25% factor-of-safety and a 25% salt leaching fraction. Whereas the drop in *ET*c across all varieties was similar between S1 and S3, there were large differences in the drop in date production. Date production between S1 and S3 dropped 29% for 'Lulu', 43% for 'Khalas', and 52% for 'Shahlah'. The consumed water productivity, *CWP* (kg-dates kL^{-1}) provides a metric of salt tolerance. For the tolerant 'Lulu' the *CWP* for S3 was higher (2.21 kg-dates kL^{-1}) than that for S1 (1.78 kg-dates kL^{-1}), although production was higher with S1 (89.1 kg $tree^{-1}$) than S3 (62.9 kg $tree^{-1}$). The *CWP* for 'Khalas' was the same for both treatments (≈ 1 kg-dates kL^{-1}). For the salt intolerant 'Shahlah', *CWP* dropped between S1 (1.5 kg-dates kL^{-1}) and S3 (1.34 kg-dates kL^{-1}). Based on the price of dates, the *CWP* can also be used to assess the economic value of irrigation water by variety and salinity.

5.2 Introduction

The date palm (*Phoenix dactylifera* L.) is well adapted to the desert environment, for it can withstand high temperatures, saline conditions, and severe drought. Indeed the date palm is often considered a symbol of life in the desert (Brouk and Fishman, 2016). Barreveld (1993) even went as far to say that "… had the date palm not existed, the expansion of the human race into hot and barren parts of the 'Old World' would have been much more restricted". Brouk and Fishman (2016) added that the date palm "… is one of the oldest trees from which man has derived benefit, and it has been cultivated since ancient times".

The date palm, along with olives, grapes and figs seem to have been the first principal fruit crops domesticated in the Old World, with definite signs of olive and date-palm domestication in the Levant and Mesopotamia about 6,800-6,300 years before the current era (BCE) (Zohary and Hopf, 2000). With the spread of Islam, and via Spanish exploration of the New World, dates spread well beyond their historical provenance of the Middle East. Dates have great aesthetic, environmental, cultural and spiritual importance to many peoples. There has been active selection for the best date palms over millennia. This long history of cultivation and selection results from extensive sharing of germplasm, dioecism, and exchanges of seedlings (Chao and Kreuger, 2007). Chao and Kreuger (2007) concluded that there are now thousands of named cultivars across the Arabian Peninsula, the Middle East, and North Africa.

The Food and Agriculture Organisation (FAO, 2017) reports that the top seven countries for date production are: Egypt, Iran, Algeria, Saudi Arabia, Pakistan, and the United Arab Emirates (UAE). Ground water is used to irrigate modern date plantations, as most of these areas are hyper-arid. There are critical water shortages in all the nations, in general, and in the main date-growing regions of Al Ain and the Liwa Oases of Abu Dhabi in the UAE, in particular. Furthermore, as the stocks of groundwater decline in these regions of Abu Dhabi, the water used to irrigate the date palms is becoming more saline (MOEW, 2014).

An age-old adage suggests that the date palm has "… its feet in the water and its head in the fire". We would also add that the water in which the date is said to have its feet, is now 'salty'. Zekri et al. (2010) found that in the Batinah region of Oman, gross farm margin, in Omani Rials per hectare, dropped by one third when the groundwater salinity rose from 5 to 15 dS m^{-1}. Yet, date palms have adapted to, or have been bred for tolerance to salinity, as well as heat and drought. The various date-palm cultivars have differing tolerances and sensitivities to water stress and salt stress. In the UAE there are over 200 cultivars producing dates, and 68 of these are commercially important (Jaradat and Zaid, 2004). The goal of this paper is to quantify the tree water-use, ET_c (L d^{-1}), and salt-tolerance of three major cultivars of dates in the UAE. These are the salt-tolerant 'Lulu' from the UAE, the moderately tolerant 'Khalas' from Saudi Arabia, and the salt-intolerant 'Shahlah' from the UAE.

Tripler et al. (2011) determined the long-term growth, water consumption, and yield of the date cultivar 'Medjool' as a function of salinity. The landrace cultivar 'Medjool' is of Moroccan origin, and well-adapted to North African conditions. It is widely grown in the Levant. Tripler et al. (2011) concluded the long-term irrigation with saline water of electrical conductivity, *EC*, of between 8-12 dS m^{-1}, was not commercially practical as growth and date yield were severely reduced. Sperling et al. (2014) showed that the ET_c and yield reduction with increasing salinity were a result of the decrease in stomatal conductance, g_s (mol m^{-2} s^{-1}), with increasing salinity. The threshold for the decline in g_s was about 1 dS m^{-1}, and by 8 dS m^{-1} water the maximum value of g_s had halved. Sperling et al. (2014) were able to propose an irrigation schedule for the palms that decreased irrigation water-use by 20%. They assessed the FAO-56 method for predicting the ET_c of the date palms using the crop-factor approach, K_c, to determine the ET_c from $K_c.ET_o$, where ET_o is the weather-based reference evapotranspiration, ET_o, from Allen et al. (1998).

The protection of groundwater resources, and the minimisation of salinity issues, are both being urgently addressed in the UAE. The Government of Abu Dhabi recently passed Law 5 to limit groundwater use. Under Law 5, all farmers will need to modify their irrigation practices to reduce the amount of water used for irrigation. Yet overwatering of crops must still be allowed to avoid salt accumulation in the root zone. Al-Muaini et al. (2019a) recommended that implementation of Law 5 be based on daily irrigation at the rate of 1.5 ET_c, which allows a 25% factor-of-safety, and a 25% salt-leaching fraction

However, there has been limited research into the adaptability, and the rates of ET_c, of the multitude of these date cultivars to the varying salinities of irrigation water, and on the impact on date production of these cultivars with the limited irrigation schedules that might be applied via Law 5 in the future. We have carried this out for three date varieties at the two rates of irrigation water salinity of 5 and 15 dS m^{-1}.The objectives of our paper are to investigate the options for date production under constrained conditions of groundwater quantity and salinity. These are fivefold:

- To quantify the *ET*c of three varieties of three date palm cultivars with decreasing salt tolerances: 'Lulu', 'Khalas', and 'Shahlah'.
- To assess the crop factor, *K*c, of these cultivars to establish best-practice irrigation schedules that use the minimum amount groundwater for irrigation, as a function of salinity.
- To provide via proximal sensing using a light stick, the light interception fraction, *LI* [-], of the palms' canopies as a function of variety and salinity.
- To predict the crop factor, *K*c, from measurements of the light interception fraction, *LI*.
- To determine the impact of the salinity of the irrigation water on the water productivity of dates (kg-dates L^{-1}) and provide a metric for characterising the differing salt tolerances of these cultivars. Economic productivity is also considered.

5.3 Materials and methods

In Al-Muaini et al. (2019a) we described the details of our water-use experiments with the date variety 'Lulu' that was irrigated with groundwater at the two salinities of 5 (S1) and 15 (S3) dS m^{-1}. The current paper extends this work for 'Lulu', and brings in the two new varieties; 'Khalas' and 'Shahlah'. Therefore only salient details of the experimental set-up are repeated here.

5.3.1 Study site

Our experiments were carried out over the years 2015-2017 at the International Centre for Biosaline Agriculture (ICBA) (25.09° N; 55.39° E; 48 m a.s.l.) near Dubai. The date trial at ICBA commenced in 2001 and 2002 and considered 18 varieties, with 10 being UAE cultivars and the remaining eight coming from Saudi Arabia. The 18 cultivars encompassed a wide range of tolerances to salt. We have reported early results from our studies on the salt-tolerant 'Lulu', an Emirati cultivar. Here we extend the 'Lulu' analyses, and add in data from the moderately salt-tolerant 'Khalas' from Saudi Arabia, and the salt-intolerant "Shahlah' from the UAE. The trial considers three rates of irrigation water salinity: S1 = 5, S2 = 10 and S3 = 15 dS m^{-1}. This classification of salt tolerance comes for the understanding of tree performance and date yield across the 18 varieties and three salinities over 15 years at

ICBA. Over several years, the hourly pattern of ETc was measured using the compensation heat pulse method (CPHM) in just the two treatments S1 and S3 for each of the three varieties.There were five trees of each variety in the S1 treatment, and five in the S3 treatment. The centre three trees of each treatment were fitted with instruments, with the outer two acting as guard trees. Details of the use of the CPHM in date palms have been described by Al-Muaini et al. (2019a).

The soil of the field site is a Typic Torriorthent sandy-skeletal hyperthermic soil (Abdelfattah, 2013) with a sand content of over 90%. The date palms were all planted on an 8 x 8 m grid spacing, such that there are 156 trees per hectare.

A weather station located at ICBA measured solar radiation, air temperature and relative humidity at 2 m, wind speed at 2 m, and rainfall. The weather data were used to estimate hourly and daily values of the reference evapotranspiration (ETo) using the standard FAO-56 approach (Allen et al. 1998). The transpiration of the date palms is related to ET_O (mm d^{-1}) through the dimensionless crop factor, K_C (Eq. 5.1):

$$ET_C = K_C . ET_O \quad , \qquad \text{Eq. [5.1]}$$

where ET_C is the crop water use (mm d^{-1}) and K_C is determined from the ratio of the measured daily sapflow to the reference ETo. Here we used our measurements of ETc and ETo to compute the daily pattern of Kc over several years for the three varieties and the two rates of irrigation-water salinity.

5.3.2 Tree characteristics and date yield

At the end of the 2017 growing season, ICBA measured the date yield, and date-palm canopy characteristics of trunk height, leaf area per tree, number of branches, and branch length. As well, we gained access to ICBA’s records of the date yields of the three varieties across the two salinity treatments for the years of 2012 to 2015 inclusive.

5.3.3 Light stick

A hand-held light stick (Al-Muaini et al. 2019a) was used to record the percentage of visible light being transmitted through the canopy via a series of understory transits. The percentage of light intercepted, as calculated from our light stick measurements, provides a proxy measure of the canopy size and leaf density. Each transit took 30 s, and encompassed the shadow areas of 3-4 trees. Multiple transits of 4–5 sweeps, depending on sun angle, were used to cover the full shadow areas of the row of the 3-4 trees in each of treatment blocks.

5.3.4 Water productivity

To gain insights into the differing salt tolerances of the three varieties, we sought to use a metric of the productivity of water (*PW*, kg L^{-1}). Molden (1997) developed definitions of *PW* in relation to the gross or net inflow of water, the depleted water, the process depleted water, or available water. We follow his approach by using the process depletion of water. There is effectively no rainfall in the date-growing regions of the UAE, such that irrigation supplies all the water for *ET*c. Under Law 5, the suggested rate of irrigation for dates is 1.5 *ET*c to cover a factor-of-safety and salt-leaching. So Molden's (1997) inflow *PW* would be 1.5 times the process-depletion *PW*. Thus in our case, Molden's (1997) definition of the process-depletion *PW* is simply based on the depletion of *ET*c, the transpiration. This then is the same as Viets (1962) definition of the crop productivity per unit of water consumed in transpiration. For clarity and efficiency of communication (Perry, 2007), we use the term consumed water productivity (*CWP*, kg-dates L^{-1}). This is defined as the annual yield (*Y*, kg-dates) divided by the annual amount of consumed water, *ET*c (L).

The *CWP* is essentially a reciprocal form of the water footprint (*WF*, L kg^{-1}) (Hoekstra et al. 2011). Elsewhere, we have quantified the green, blue, and grey *WF*s of date production to assess the environmental impacts of date production, the value of groundwater for irrigation, and the benefit-cost ratio of using desalinated water for irrigating dates (Chapter 7; Al-Muaini et al. 2019b).

Here, however, we seek to use the inverse metric of *CWP* to understand better the differences in the biophysical performances of the three varieties in relation to their tolerances to irrigation-water salinity.

5.4 Results and discussion

We first describe the impact of the two rates of irrigation-water salinity on the canopy characteristics and date yield for the three varieties, and then proceed to discuss the temporal pattern and values of the *K*c values for the varieties. We then show it is possible to predict *K*c from proximal measurements of *LI*. We conclude with a discussion of how the *CWP* can provide a metric of the salt tolerance for the three varieties.

Table 5.1. The effect of two rates of irrigation-water salinity of tree performance and date yield of three date varieties at the International Center for Biosaline Agriculture (ICBA) near Dubai, UAE. There were five trees per treatment and the average results are presented. The length of each branch was measured and the total branch length per tree was estimated by multiplying the number of branches by the mean branch length. These data and the first column of yield data relate to the 2017 season. The last column of yield data are the averaged yields per tree over the years 2012-2015.

Variety and Salt Tolerance	Irrigation Salinity	Trunk height	Number branches	Branch length	Total branch length	Date Yield 2017	Date Yield 2012-15
	dS m^{-1}	m		m $branch^{-1}$	m $tree^{-1}$	kg $tree^{-1}$	kg $tree^{-1}$
'Lulu'* - high	5	3.75	67	3.47	232.5	80.9	97.2
'Lulu'*	15	2.51	52	2.88	149.8	61.2	64.6
'Khalas' -medium	5	2.45	75	3.53	264.8	39.3	43.2
'Khalas'	15	1.63	52	3.24	168.5	26.3	20.8
'Shahlah' - low	5	3.06	70	4.48	313.6	87.7	84.3
'Shahlah'	15	1.75	42	3.29	138.2	44.6	38.7

5.4.1 Tree characteristics and date yield

The increase in salinity stunted the height of the date palms with reductions of 33, 34 and 43% for 'Lulu', 'Khalas' and 'Shahlah', respectively, between treatments S1 and S3 (Table 5.1). There were similar reductions in the other canopy characteristics of the palm trees, as listed in Table 5.1. The date yield reductions between treatments S1 and S3 were 29%, 43% and 52% for the varieties 'Lulu', 'Khalas', and 'Shahlah', and as expected they were in the order of their presumed salt tolerance.

5.4.2 Tree water use and the crop factors

The year-to-year variation in the weather in the hyper-arid deserts of Abu Dhabi is very small. There is an absence of significant rain, with the number of rain days, or even cloudy days, being very small. Given this lack of year-to-year variability, we present our multi-year *ET*c and *K*c results in Figures 5.1-5.6 on single graphs using day-of-year (DOY) as the abscissa. There are some gaps in our daily *ET*c measurement records caused by the inevitable equipment failures, as expected from sensitive electronic devices operating in such a harsh desert environment. However, these gaps do not limit our ability to gain understanding of the palms' water-use dynamics, interactions with the prevailing weather, and an assessment of the impact of the salinity of the groundwater used for irrigation.

In the graphs of the seasonal pattern of *ET*c (Figures 5.1-5.6), because of the different tree sizes and leaf areas, the daily rates of water use vary greatly. In each graph we wish to show the coherence between *ET*c and *ET*o, so the left-hand ordinate axis is scaled for each graph to show how *ET*c tracked the seasonal pattern in *ET*o. The units of both axes are mm d^{-1}, and to convert the tree water-use measured by sap flow in L d^{-1} to mm d^{-1}, we used the tree spacing of 8 x 8 m. The largest left-hand axis is for 'Shahlah' S1 where *ET*c peaked at over 4 mm d^{-1}, and the smallest was for 'Khalas' S3 where the peak *ET*c was just 1.75 mm d^{-1}.

The data for the graphs of *K*c used the quotient of measured *ET*c / *ET*o, and all the ordinate axes range from 0 to 0.5.

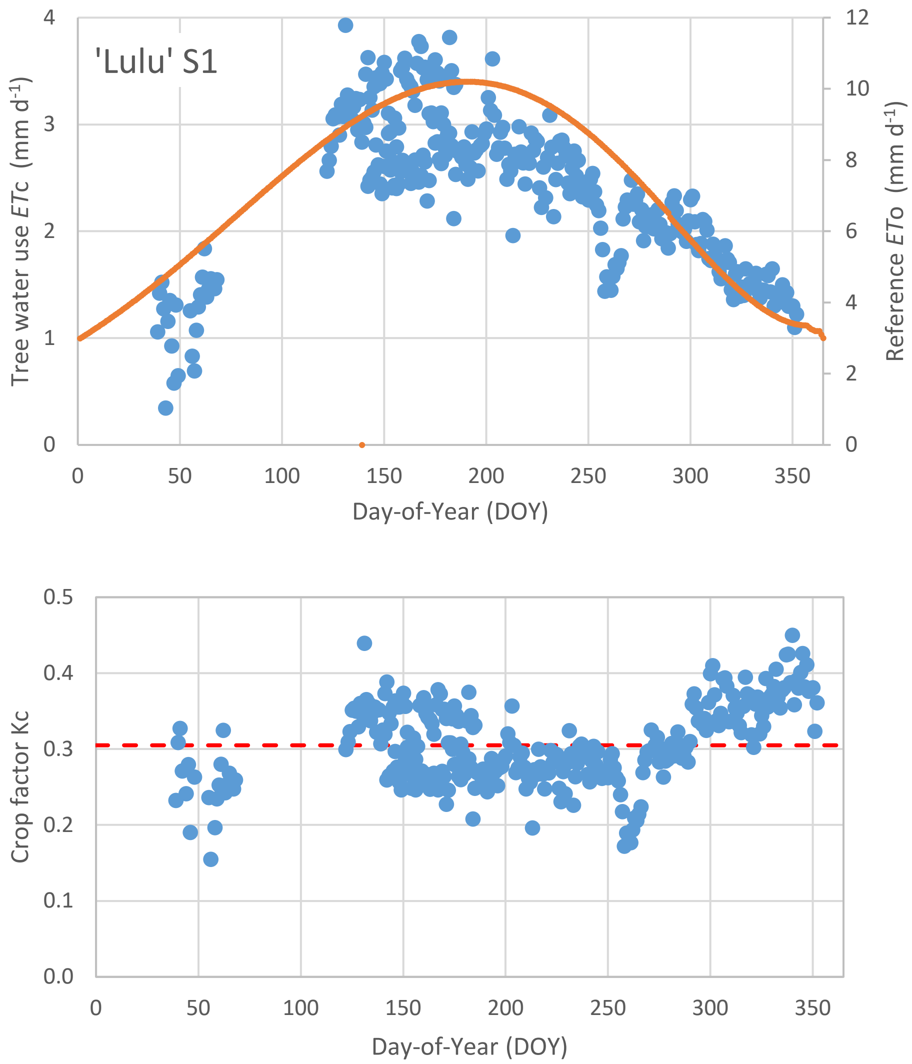


Figure 5.1. Top. The 'Lulu' S1 treatment (5 dS m^{-1}) tree water-use, *ET*c (mm d^{-1}), as measured using sap-flow monitoring (blue dots, left axis). The data are presented in relation to day-of-year (DOY) and comprise measurements over 2.2 years from 20/5/2015 through until 4/7/2017. These data extend the results of Al-Muaini et al. (2019). The conversion to mm d^{-1} is based on the tree spacing of 8 x 8 m. The reference evapotranspiration, *ET*o, from the FAO-56 method is shown as the redline (right axis). Bottom. The seasonal pattern throughout the year in the crop factor, *K*c (= *ET*c / *ET*o), derived from the data above, with the red-dotted line being the annual average *K*c.

'Lulu'

The patterns of *ET*c and *K*c for the salt-tolerant 'Lulu' S1 treatment are shown in Figure 5.1. Whereas the peak *ET*o was about 12 mm d^{-1}, the peak *ET*c was just 4 mm d^{-1}. There is a coherence between the two traces, albeit with some deviations due to various challenges in maintaining the correct rates of irrigation at 1.5 *ET*c. The trace of *K*c in Figure 5.1 revealed a slight rise in *K*c late in the year, which we consider to be due to a seasonal growth of leaf area in autumn. The average *K*c for 'Lulu' S1 was 0.31 (±0.05) (Table 5.2).

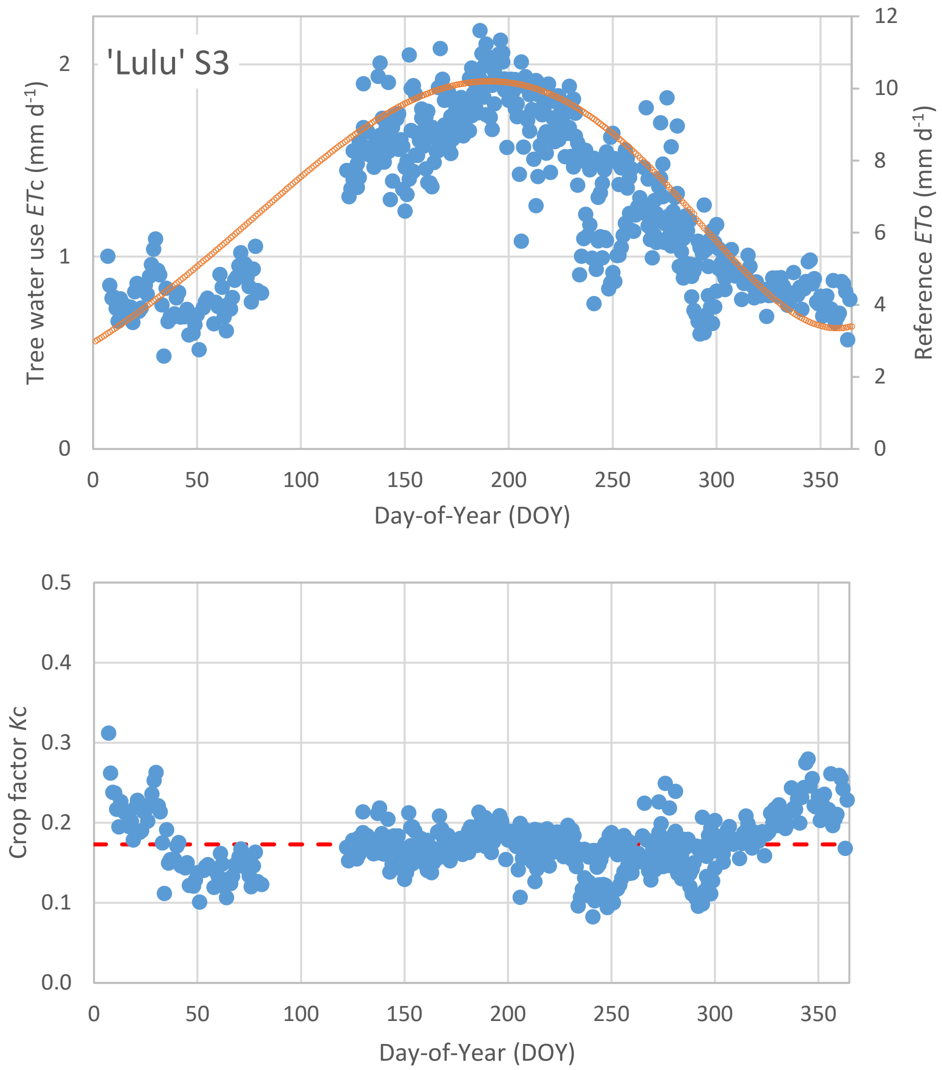


Figure 5.2 Top. The 'Lulu' S3 treatment (15 dS m^{-1}) tree water-use, *ET*c (mm d^{-1}), as measured using sap-flow monitoring (blue dots, left axis). The data are presented in relation to day-of-year (DOY) and comprises measurements over 1.7 years from 4/5/2015 through until 19/1/2017. These data extend the results of Al-Muaini et al. (2019). The conversion to mm d^{-1} is based on the tree spacing of 8 x 8 m. The reference evapotranspiration, *ET*o, from the FAO-56 method is shown as the red line (right axis). Bottom. The seasonal pattern throughout the year in the crop factor, *K*c (= *ET*c / *ET*o), derived from the data above, with the red dotted line being the annual average *K*c.

Table 5.2. The effect of two rates of irrigation-water salinity on the water use, leaf area, and light interception of three date varieties at the International Center for Biosaline Agriculture (ICBA) near Dubai, UAE. The leaf area per trees was determined by leaf scanning a sub-sample of 10% of the leaves on a tree. The annual average crop factor, *K*c, is taken from Figures 5.1-5.6, and the trees' total annual *ET*c (kL y^{-1}) is found from this average value times the annual reference evapotranspiration *ET*o (mm d^{-1}), given a tree spacing of 8 x 8 m. The light interception, *LI*, values come from Al-Muaini et al. (2019) for 'Lulu', and from Figures 5.7 and 5.8 for the other two date varieties.

Variety and Salt Tolerance	Irrigation Salinity	Annual *ET*c	Leaf Area	Light Interception *LI*	Crop Factor, Kc	Ratio *K*c LI^{-1}
	dS m^{-1}	kL y^{-1} $tree^{-1}$	m^2 $tree^{-1}$	[-]	[-]	[-]
'Lulu'* - high	5	50.0	62.1	0.26 (±0.05)	0.31 (±0.05)	1.19 (±0.25)
'Lulu'*	15	28.4	41.7	0.20 (±0.03)	0.17 (±0.03)	0.85 (±0.23)
'Khalas' -medium	5	43.1	65.0	0.31 (±0.05)	0.26 (±0.05)	0.84 (±0.25)
'Khalas'	15	23.2	46.2	0.19 (±0.04)	0.14 (±0.03)	0.74 (±0.30)
'Shahlah' - low	5	57.3	77.0	0.34 (±0.08)	0.35 (±0.05)	1.03 (±0.28)
'Shahlah'	15	31.1	32.6	0.18 (±0.03)	0.19 (±0.05)	1.06 (±0.30)
* from Al-Muaini et al. (2019)					**Average**	**0.95**

The *ET*c and *K*c results for 'Lulu' S3 are shown in Figure 5.2, and the rates of water use were just under about half of those of the S1 treatment, with the average *K*c being 0.17 (±0.03) (Table 5.2). Again there was a rise in *K*c in late October, and now a drop in *K*c can be seen over the first two months of the year. This period is when the date fruit are filling.

However, it would seem that in both salinity treatments assuming a seasonally constant *K*c is reasonable, at least for practical purposes. The annual rates of water use were 50 kL $tree^{-1}$ for the S1 trees and 28.4 kL $tree^{-1}$ for S3 (Table 5.2), a drop of 43%.

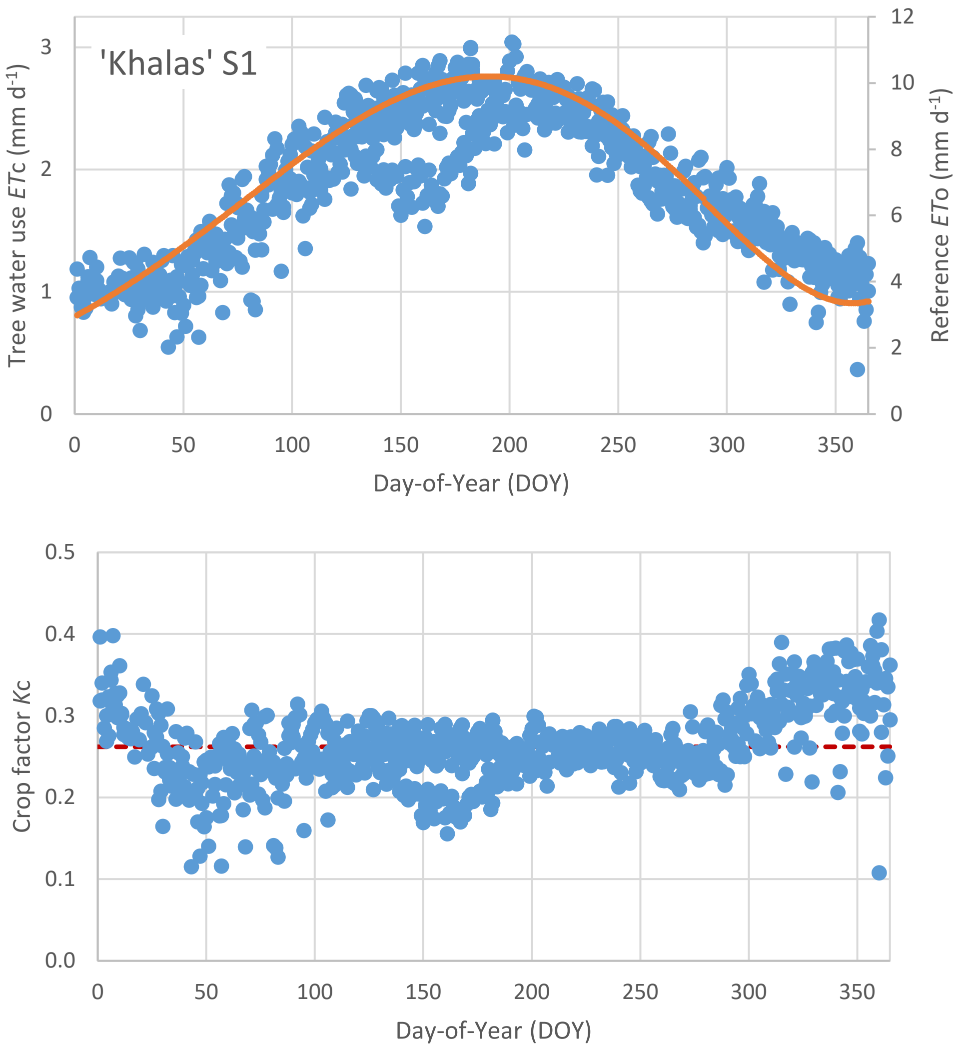
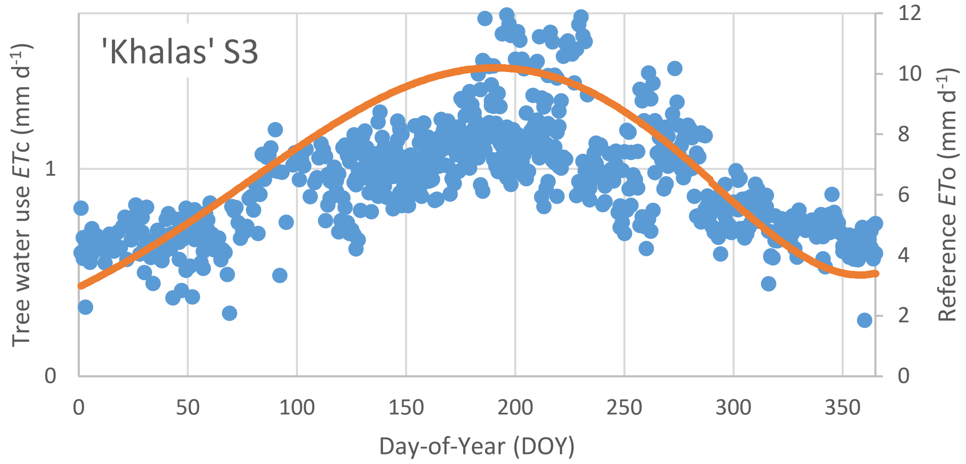


Figure 5.3 Top. The 'Khalas' S1 treatment (5 dS m^{-1}) tree water-use, *ET*c (mm d^{-1}), as measured using sap-flow monitoring (blue dots, left axis). The data are presented in relation to day-of-year (DOY) and comprise measurements over 2.3 years from 4/5/2015 through until 16/9/2017. The conversion to mm d^{-1} is based on the tree spacing of 8 x 8 m. The reference evapotranspiration, *ET*o, from the FAO-56 method is shown as the redline (right axis). Bottom. The seasonal pattern throughout the year in the crop factor, *K*c (= *ET*c / *ET*o), derived from the data above, with the red-dotted line being the annual average *K*c.



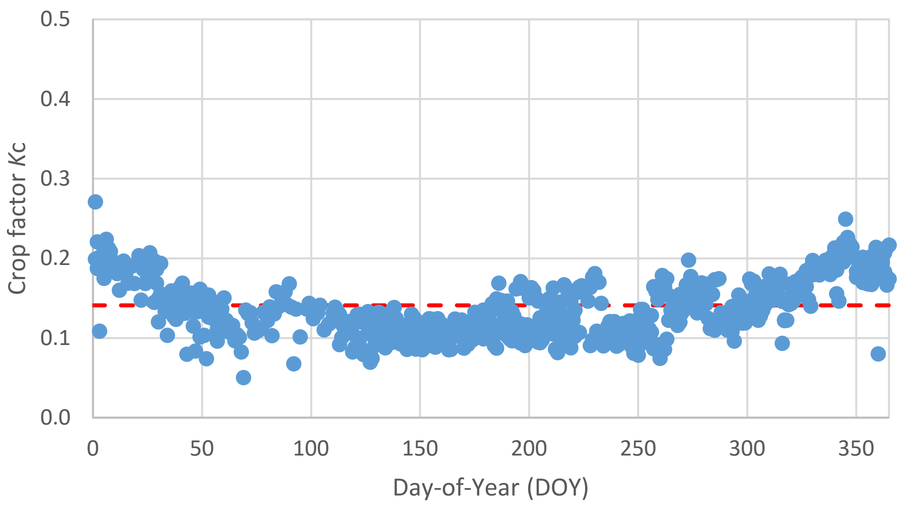
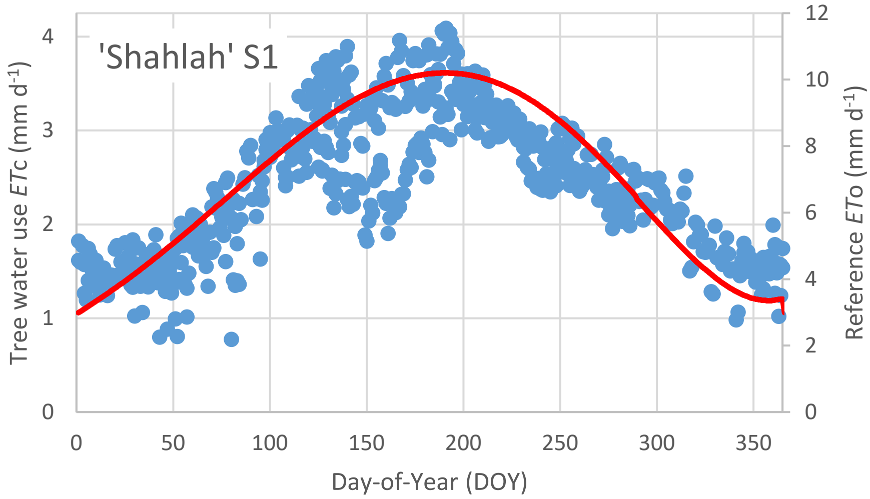


Figure 5.4 Top. The 'Khalas' S3 treatment (15 dS m^{-1}) tree water-use, *ET*c (mm d^{-1}), as measured using sap-flow monitoring (blue dots, left axis). The data are presented in relation to day-of-year (DOY) and comprise measurements over 2.3 years from 4/5/2015 through until 16/9/2017. The conversion to mm d^{-1} is based on the tree spacing of 8 x 8 m. The reference evapotranspiration, *ET*o, from the FAO-56 method is shown as the redline (right axis). Bottom. The seasonal pattern throughout the year in the crop factor, *K*c (= *ET*c / *ET*o), derived from the data above, with the red dotted line being the annual average *K*c.

'Khalas'

The 'Khalas' trees are smaller (Table 5.1) and have a lower leaf area (Table 5.2) than the equivalent 'Lulu' trees. Their rates of *ET*c were correspondingly less (Figures 5.3 and 5.4). Within the variability resulting from difficulties with irrigation management the rates of *ET*c tracked *ET*o. The annual average *K*c values for the 'Khalas' trees were 0.26 (±0.05) for S1 and 0.14 (±0.03) for S3, and both traces also showed a slight four month-long peak in *K*c during winter.

The total annual water-use values by the 'Khalas' trees were 43.1 kL tree^{-1} (S1) and 23.2 kL tree^{-1} (S3), a drop of 46% (Table 5.2).



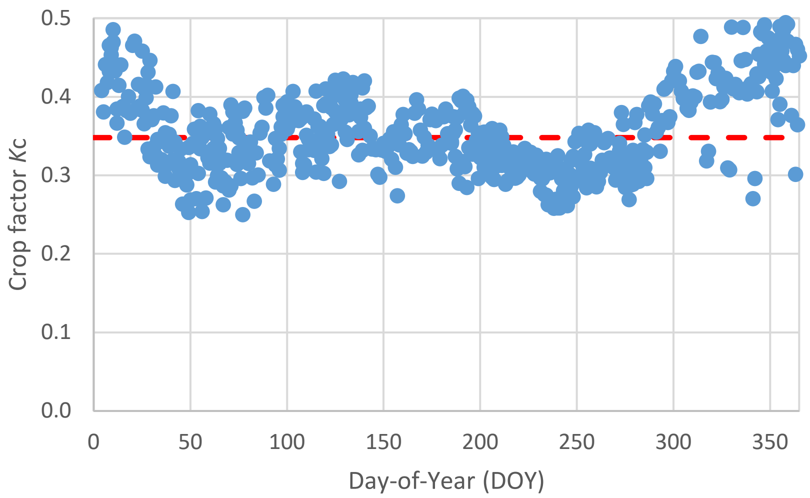


Figure 5.5. Top. The 'Shahlah' S1 treatment (5 dS m^{-1}) tree water-use, *ET*c (mm d^{-1}), as measured using sap-flow monitoring (blue dots, left axis). The data are presented in relation to day-of-year (DOY) and comprise measurements over 2.3 years from 4/5/2015 through until 16/9/2017. The conversion to mm d^{-1} is based on the tree spacing of 8 x 8 m. The reference evapotranspiration, *ET*o, from the FAO-56 method is shown as the redline (right axis). Bottom. The seasonal pattern throughout the year in the crop factor, *K*c (= *ET*c / *ET*o), derived from the data above, with the red dotted line being the annual average *K*c.

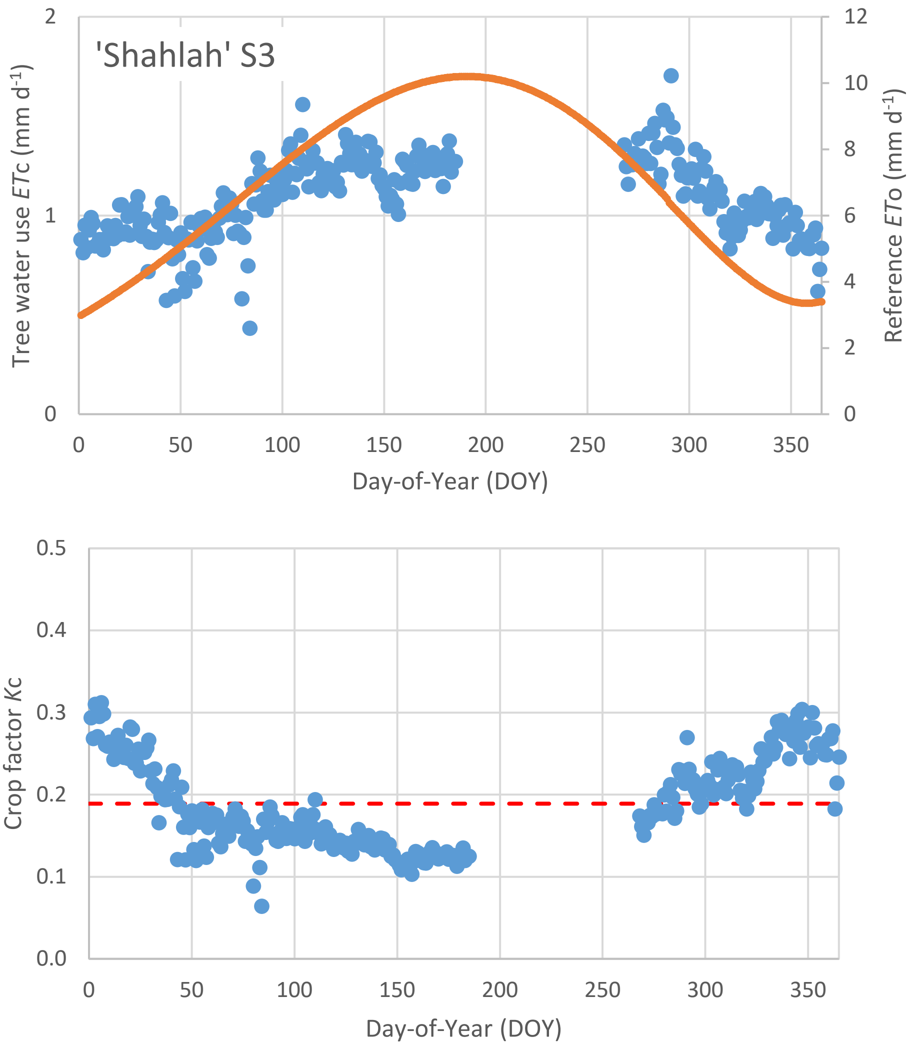


Figure 5.6. Top. The 'Shahlah' S3 treatment (15 dS m^{-1}) tree water-use, *ET*c (mm d^{-1}), as measured using sap-flow monitoring (blue dots, left axis). The data are presented in relation to day-of-year (DOY) and comprise measurements over 2.2 years from 4/5/2015 through until 4/7/2017. The conversion to mm d^{-1} is based on the tree spacing of 8 x 8 m. The reference evapotranspiration, *ET*o, from the FAO-56 method is shown as the redline (right axis). Bottom. The seasonal pattern throughout the year in the crop factor, *K*c (= *ET*c / *ET*o), derived from the data above, with the red dotted line being the annual average *K*c.

'Shahlah'

The salt-intolerant 'Shahlah' S1 trees had the largest leaf area per tree (Table 5.2), whereas the S3 trees had the smallest leaf area per tree of all trees. The seasonal patterns of *ET*c and *K*c were similar to those of the other two varieties (Figure 5.5 and 5.6). The S1 *K*c was 0.35 (±0.05), the largest of all treatments, whereas the *K*c of the S3 treatment was 0.19 (±0.05) (Table 5.2).

We sought to see if it were possible to predict *K*c values through use of proximal sensing of the fractional light interception, *LI*, using a light stick

5.4.3 Light interception and the crop factor

On day-of-year (DOY) 260 in 2015, 19 September, an intensive campaign of *LI* measurements was undertaken using the light stick under the canopies of all six plots of the trees of the three varieties at the two salinities. This date was chosen to provide detailed observations of *LI* at that time of year, in autumn, when the crop factor, *K*c, was close to the annual average value (Figures 5.1-5.4). We have already published the *LI* results for 'Lulu' (Al-Muaini et al. 2019a), and they were 0.26 (±0.05) for the S1 treatment and 0.20 (±0.03) for S3 (Table 5.2). Here, in Figures 5.7 and 5.8, we present the results for 'Khalas' and 'Shahlah' at the two salinities.

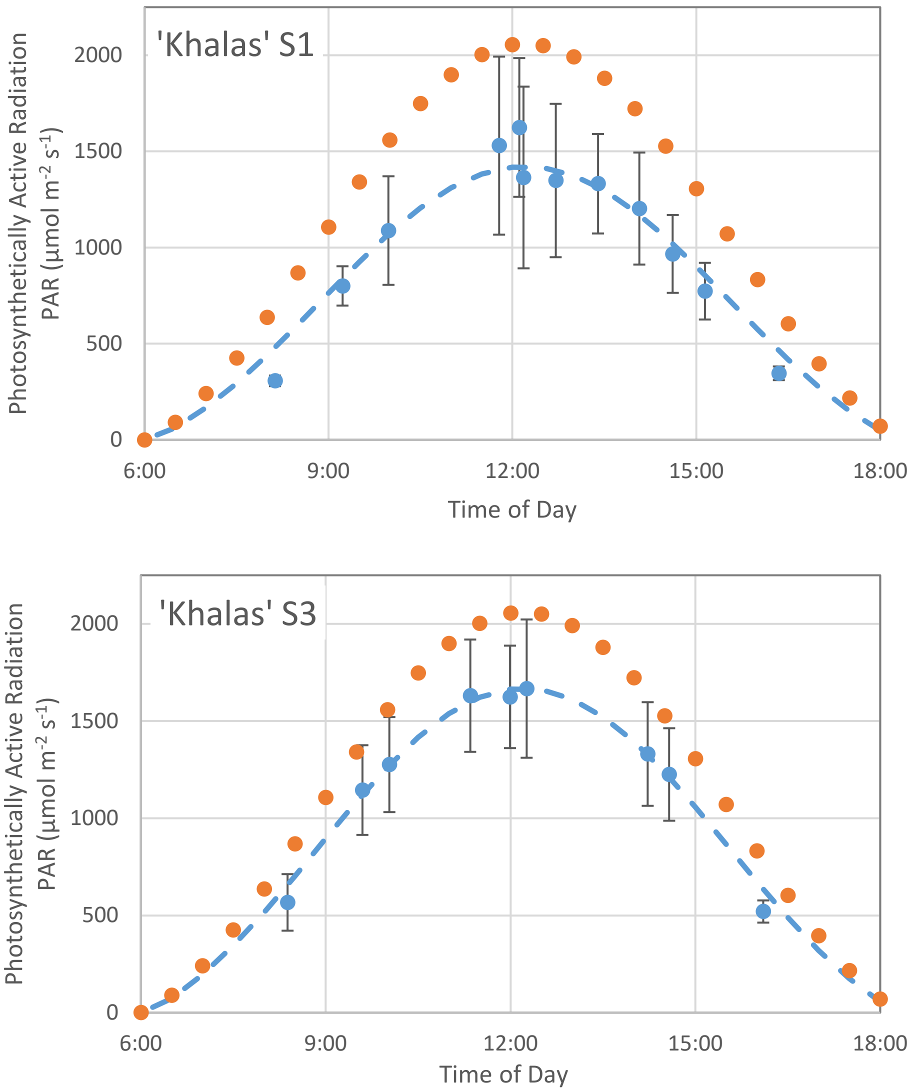


Figure 5.7. Top. The photosynthetically active (*PAR*, µmol m^{-2} s^{-1}) radiation from the sky over 19 September 2015 (Day of Year, DOY 262) (red dots), in relation to the *PAR* measured under the canopy of the 'Khalas' S1 treatment (5 dS m^{-1}) using a light stick (blue dots). The light interception, *LI*, measurements were made during 12 transits with the light stick. Bottom. As above, but for the 'Khalas' S3 treatment (15 dS m^{-1}) using nine transects during the day.

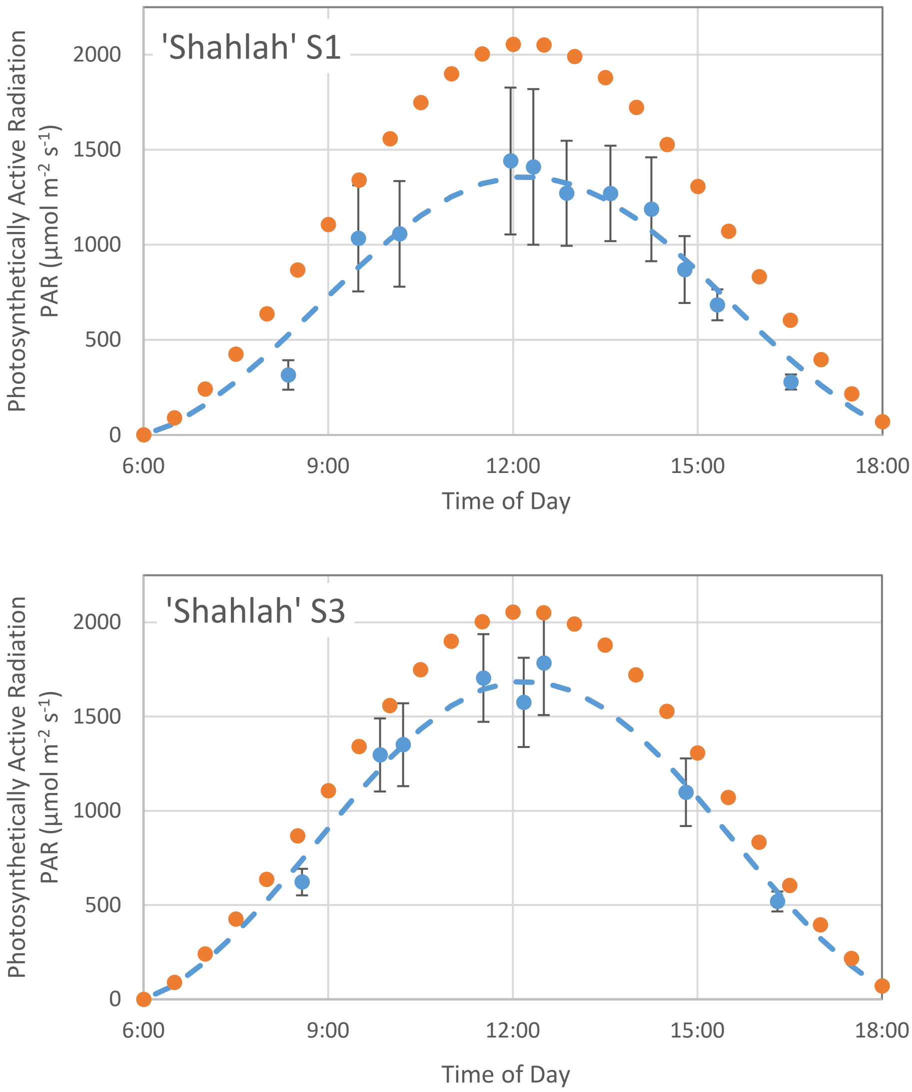


Figure 5.8. Top. The photosynthetically active (*PAR*, µmol m^{-2} s^{-1}) radiation from the sky over 19 September 2015 (Day of Year, DOY 262) (red dots), in relation to the *PAR* measured under the canopy of the 'Shahlah' S1 treatment (5 dS m^{-1}) using a light stick (blue dots). The light interception, *LI*, measurements were made during 11 transits with the light stick. Bottom. As above, but for the 'Shahlah' S3 treatment (15 dS m^{-1}) using eight transects during the day.

The transits with the light stick shown in Figure 5.7 and 5.8 were used to compute the respective *LI* values. For 'Khalas' the values of *LI* were found to be 0.31 (±0.05) for S1 and 0.19 (±0.04) for S3 (Table 5.2). The corresponding values for 'Shahlah' were 0.34 (±0.08) and 0.18 (±0.03).

O'Connell et al. (2008) and Goodwin et al. (2015) found the ratio *Kc* LI^{-1} to be 1-1.2 for apples and pears. Al-Muaini et al. (2018) reported, using a different *Kc* data-set for 'Lulu', that the 'Lulu' *Kc* LI^{-1} was 1-1.1. Our revised 'Lulu' values provide corroboration. The values of *K*c LI^{-1} for 'Khalas' and 'Shahlah' were very similar (Table 5.2). On average for all varieties and salinity treatments, the mean *K*c LI^{-1} was 0.95. Given the errors of observation in *K*c LI^{-1}, a simple average was taken, and it would not be possible to carry out a sensitivity analysis on the various factors that might control this ratio. That this value is not too dissimilar, although somewhat lower than the values for apples and pears, would seem to be a measure of how well adapted the date palms are to this hot and saline environment, for given their interception of radiant energy, they could still maintain reasonable rates of transpiration despite the heat and salinity.

In contrast, Al-Yamani et al. (2019a) found much lower ratios for the xerophytic and halophytic arid-forest species of Al Ghaf (*Prosopis cineraria*) and Al Sidr (*Zizphus spina-christi*) with *K*c LI^{-1} being 0.4-0.6. Al-Yamani et al. (2019b). They found *K*c LI^{-1} to be just 0.1 for the hardy and woody xerophytic Al Samr tree (*Acacia tortilis*).

The values of *K*c LI^{-1} we have found here for three date varieties did not show any difference in relation to their respective degrees of salt tolerance. This is convenient for being able to predict *K*c, and hence *ET*c, from proximal measurements of *LI* for irrigation scheduling and implementation of Law 5. We have recommended that irrigation be applied daily at 1.5 *ET*c to account for a 25% factor-of-safety and a 25% salt-leaching fraction (Al-Muaini et al. 2019a).

By use of this characterisation that *K*c LI^{-1} is 0.95 for dates, it will be possible to use the light stick to extend the *LI* results from these 8 x 8 m plantings to commercial farms with different tree spacings and varying tree-canopy characteristics to predict the *K*c. It is considered that this value of *K*c LI^{-1} being 0.95 for dates will only apply to these hyper-arid conditions with a degree of salt and water stress. Under less severe conditions, it is anticipated that the *K*c LI^{-1} ratio would increase and trend towards the 1-1.2 found by Goodwin et al. (2015) for temperate fruit crops

However, the differing salt tolerances of these date varieties means that in terms of date yield, there will be differing economic returns from the date trees, and the economic values derived for irrigation water will be different between varieties, and will differ according to the salinity of the groundwater used for irrigation.

Therefore we sought to find a metric that would characterise the value of irrigation to date production in relation to water salinity.

5.4.4 Consumed water productivity and salt tolerance

As indicated above, we considered the consumed water use, *CWP*, to be *ET*c, and the annual values of *ET*c are reproduced in Table 5.3, along with the respective date yields, *Y*. The computed *CWP* revealed an interesting pattern with salinity by variety (Table 5.3). Whereas, between treatments S1 and S3, the drop in *ET*c was 43-46% for all varieties, there were clear differences in the drop in yield. The percentage loss in yield between S1 and S3 was just 29% for 'Lulu', and 43% for 'Khalas', and 52% for the salt-intolerant 'Shahlah'. In terms of the ratio of the S3 value of *CWP* to the *CWP* for S1, for 'Lulu' it was greater than one, being 1.24. So despite the drop in water use, the salt-tolerant 'Lulu' was still able to maintain a reasonable productivity of dates. For the moderately tolerant 'Khalas', the ratio was unity, since water use and date production declined in equal proportion. For the salt-intolerant 'Shahlah' the *CWP* dropped from 1.5 to 1.34 kg-dates kL^{-1} as the salinity rose from 5 to 15 dS m^{-1}.

Table 5.3. The consumed water-use productivity (*CWP*, kg kL^{-1}) of three date palm varieties at the International Center for Biosaline Agriculture (ICBA) near Dubai, UAE. The average annual yield, *Y* (kg), is calculated from the 2012-15 and 2017 data from Table 5.1, and the annually consumed water-use *ET*c comes from Table 5.2. The *CWP* is the yield divided by the water use, and the last column is the ratio of the *CWP* of the S3 (15 dS m^{-1}) trees to that of those in S1 (5 dS m^{-1}).

Variety & Salt Tolerance	Average Yield, *Y*	Consumed Water Use, *ET* c	Consumed Water Productivity, *CWP*	Salinity Ratio (S3/S1) of *CWP*
	kg $tree^{-1}$	kL $tree^{-1}$	kg kL^{-1}	[-]
'Lulu'* - high	89.1	50.0	1.78	
'Lulu'*	62.9	28.4	2.21	1.24
'Khalas' -medium	41.3	43.1	0.96	
'Khalas'	23.6	23.2	1.02	1.06
'Shahlah' - low	86.0	57.3	1.50	
'Shahlah'	41.7	31.1	1.34	0.89

The *CWP* metric provides a useful measure to characterise the salt tolerance of date cultivars. Furthermore the *CWP* could be rephrased in economic terms (Molden, 1997) say by using the date price in UAE dirhams (Dhs) per kilogram. This provides a measure of the value of the groundwater being used for irrigating the dates, in Dhs kL^{-1}, as a function of salinity. Al-Muaini et al. (2019b) considered the current price for dates to be Dhs 10 per kilogram (February, 2019). So the *CWP* column in Table 5.3 would be in Dhs kL^{-1}, if multiplied by 10. This could be used to demonstrate the value of groundwater, as related to salinity and cultivar. Such an economic assessment could be carried out for a wider range of date varieties through determination of *ET*c using proximal measures of *LI*, and from data on date yields by variety and groundwater salinity. Nonetheless, beyond this simple valuation of water, it is important to note that for the date grower, farm gross margin (Zekri et al. 2010) will be dominated by the date price (Dhs kg^{-1}) multiplied by the absolute yield, *Y* (kg), not the value of the water as the ratio of Dhs kL^{-1}. But it is interesting, in passing, to compare this computed value of groundwater, which is of the order of 10-20 Dhs kL^{-1}, with the cost of desalinating brackish groundwater, which is 5.5 Dhs kL^{-1} (Al-Muaini et al. 2019b).

5.5 Conclusions

Through direct measurements using devices to measure sap flow, we have quantified the *ET*c of three date varieties irrigated with water at two salinities, 5 and 15 dS m^{-1}. From these results, we calculated the respective *K*c values, so that the trees' water use, *ET*c, could be predicted from the reference evapotranspiration, *ET*o. By proximal sensing using a light stick, we measured the fraction of light intercepted, *LI*, by the trees' canopies, as a function of variety and salinity. The ratio *K*c LI^{-1} was about 0.95, which enables proximal sensing via a light stick to be used to predict *ET*c for all varieties and both salinities. These predictions will then be able to be used to schedule irrigation at the recommended rate of 1.5 *ET*c, accounting for a 25% factor-of-safety and a 25% salt leaching fraction.

Whereas the drop in *ET*c across all varieties was 43-46% between the 5 and 15 dS m^{-1} irrigation treatments, there were large differences in the drop in date production by variety. Date production between S1 and S3 dropped just 29% for 'Lulu', 43% for 'Khalas', and 52% for 'Shahlah'. The consumed water productivity, *CWP* (kg-dates kL^{-1}) provides a metric of the varying degrees of salt tolerance. For the salt-tolerant 'Lulu' the *CWP* for S3 was higher (2.21 kg-dates kL^{-1}) than that for S1 (1.78 kg-dates kL^{-1}), although production was higher with S1 (89.1 kg $tree^{-1}$) than S3 (62.9 kg $tree^{-1}$). The *CWP* for the moderately tolerant 'Khalas' was the same for both treatments (≈ 1 kg-dates kL^{-1}). For the salt-intolerant 'Shahlah', *CWP* dropped from S1 (1.5 kg-dates kL^{-1}) to S3 (1.34 kg-dates kL^{-1}). By using the price obtained for dates, the *CWP* can also be used to assess the value of irrigation water by variety and groundwater salinity.

5.6 References

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CHAPTER 6

6 Irrigation Water Requirements for Date Palms Growing on Commercial Farms in the Hyper-Arid United Arab Emirates

In Chapters 4 and 5, the Compensation Heat Pulse Method (CHPM) was used to monitor the water use of date palms, *ET*c (L d^{-1}, or kL y^{-1}). This work was carried out at the International Center for Biosaline Agriculture (ICBA) near Dubai on three cultivars of different salt tolerances (‘Lulu’, ‘Khalas’, and ‘Shahlah’), and two irrigation salinities (5 and 15 dS m^{-1}). These results established how the FAO-56 formulation of *ET*c = *K*c *ET*o could be used to predict water use from the measured crop factor, *K*c [-], and monitoring of the reference evapotranspiration *ET*o. In Chapter 5, proximal sensing using a light stick enabled determination of the light interception fraction, *LI* [-], of the date palm’s canopies. The relation between the crop factor and light interception was found to be, on average, *K*c = 0.95 *LI* across cultivars and salinities. Here in Chapter 6, the results from a survey on 10 commercial farms are presented, and the goal was to predict water use by date palms on commercial farms. The *LI* of date canopies on these commercial farms was determined by proximal sensing with a light-stick across a range of tree densities, tree ages, and groundwater salinities. Then a link was established between *LI* to the fractional ground cover, *FGC*, obtained by analysis of remotely sensed satellite images. So by remote sensing it became possible to determine the *ET*c of date palms across all of these commercial farms, and potentially beyond. Some very high rates of *ET*c were predicted. In the conclusion of this Chapter 6 it is considered that reductions in irrigation can be achieved by more aggressive pruning of the leaf branches to reduce *LI*, and hence *ET*c, without compromising date yield. This would reduce the water footprint of date production, an issue that is addressed in Chapter 7.

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6.1 Abstract

The production of dates in the hyper-arid deserts of the United Arab Emirates (UAE) is economically and culturally important. All of the commercial date palms need to be irrigated, and the prime source of this water is groundwater. However the quantity and quality of the groundwater resources in the UAE are being compromised by groundwater extraction at 25 times the rate of recharge, and a rise in salinity as the reserves dwindle. Rates of groundwater use on commercial farms need to be the minimum required for date production and the leaching of salts from the rootzone. We have shown that tree water use, *ET*c, can be predicted from 0.95 *LI* x *ET*o where *LI* is the fraction of incoming visible light intercepted by the canopy, and *ET*o is the reference evapotranspiration. We now surveyed 10 commercial date farms in Abu Dhabi and determined the *LI* of date canopies by proximal sensing with a light-stick across a range of tree densities, tree ages, and groundwater salinities. We were able to link *LI* to the fractional ground cover, *FGC*, obtained by analysis of satellite images. Thus it was possible to determine *ET*c of date palms across all of these commercial farms, and potentially all the UAE. The median *ET*c of the 10 farms was 70 kL y^{-1}, which was about twice that observed in our experiments at a research station near Dubai. Some 10% of the trees on these commercial farms were predicted to use over 100 kL y^{-1}. It is suggested that irrigation should be at 1.5 *ET*c to account for a 25% factor-of-safety, and a 25% salt-leaching fraction. Reductions in irrigation would be achieved by more aggressive pruning of the fronds to reduce *LI*, and hence *ET*c, without compromising date yield.

6.2 Introduction

The date palm (*Phoenix dactylifera* L.) is one of the most important plants of the desert. Not only does it underpin the stability of desert-oasis ecosystems, dates also have significant nutritional, economic, social and heritage values (Aly and Al-Hewiety, 2011). Rashoud (2016) noted that the relationship between the people of the United Arab Emirates (UAE) and the date palm is deeply rooted in the past, yet the strength of the peoples' bond to this 'blessed tree' remains today. The founding President of the UAE, the late Sheikh Zayed bin Sultan Al Nayhan, made the date palm the central foundation of his agricultural and environmental projects for "greening the desert" (Rashoud, 2016). In the UAE today there are over 40 million date palms of 70, or so, varieties. In the Emirate of Abu Dhabi alone there are 33 million date palms, and these are primarily concentrated in the region surrounding Al Ain in the east, and along the Liwa Oases in the west. In 2015, the Food and Agriculture

Organisation (FAO) of the United Nations recognised the Al Ain and Liwa Oases as globally important agricultural heritage systems for dates because of their importance as repositories of genetic resources, biodiversity and cultural heritage (Gulf News, 2015).

All these date palms require irrigation. The rainfall in this hyper-arid region is generally less than 100 mm y^{-1}, whereas the reference evapotranspiration, *ET*o, (Allen et al., 1998) exceeds 2500 mm y^{-1}. Groundwater is the prime source of this irrigation water, and about one-third of all groundwater extracted in Abu Dhabi is used to irrigate date palms (MOEW, 2015). However groundwater is being used at over 25 times the rate at which it is being recharged, such that the groundwater table is dropping at between 1 and 5 m per year (EAD, 2019 a). The salinity of the groundwater is also increasing such that only 20% of groundwater usable for agriculture is without desalination (Environment Agency – Abu Dhabi, EAD, 2019b). EAD (2019a) estimate that at the current rate of extraction, usable groundwater will be exhausted within the next two generation. Environment Agency – Abu Dhabi (EAD, 2019b) have quoted H.H. General Sheikh Mohammed bin Zayed Al Nayhan, the Crown Prince of Abu Dhabi as saying “Water is more important than oil for the UAE. We are preoccupied by this major issue. We have to come up with ways to meet future demand and preserve natural resources for the coming generations.”

EAD report that there are 118,183 identified groundwater wells in Abu Dhabi, with some 73,184 in the date growing region of Al Ain, and another 38,507 in Al Dhafrah in the west which includes the date-growing area of the Liwa Oases. Unfortunately, EAD estimates there are around another 56,000 wells that have not been formally identified and logged. Law 6 of the Abu Dhabi government prohibits the drilling of any more wells in the so-called ‘red-zones’ where the water table is dropping at high rates. Between 2013 and the first half of 2014 there were 35 successful prosecutions under Law No. 6.

In November 2016, the Executive Council of the Abu Dhabi Government passed Law No. 5 which states that the withdrawal and use of groundwater will be governed by rules and limits established by EAD. Our water-use experiments on date palms at the International Center for Biosaline Agriculture (ICBA) suggested for Law 5 that the sustainable rate of irrigation for date palms should be 1.5 *ET*c, where *ET*c (L d^{-1}) is a daily rate of water transpiration by the date palm (Al-Muaini et al. 2019a). This multiplier of 1.5 includes a 25% factor-of-safety, plus a 25% salt-leaching fraction. Al-Muaini et al. (2019a) showed that this would mean application of 66 kL y^{-1} with irrigation groundwater at 5 dS m^{-1}, and 43 kL y^{-1} for water at 15 dS m^{-1}. This is 25-50% less than the 275 L d^{-1} that was previously be applied by ICBA every day of the year, except on Fridays. Friday is an official holiday.

The challenge, however, is to implement these findings on commercial date farms. EAD (2019b) reported that the Abu Dhabi Farmers Service Center (ADFSC) had set up an Efficient Irrigation Fund. Whereas some date farmers were using 1,500 L d^{-1} (470 kL y^{-1}), they have now manged to reduce this to 300 L d^{-1}, a saving of 80%. But there is clearly still more to be done to reduce further groundwater use for irrigation on commercial date farms. As the Crown Prince of the UAE has said, we need to be "… preoccupied by this major issue". This preoccupation is the goal of the research described in this paper.

The first challenge is to translate the scientific findings from the controlled experimental trial at ICBA. There the date palms were planted on an 8 x 8 grid, and pruned regularly, such that the light interception fraction, *LI* (-), by the palm tree canopy ranged from 0.20-0.35, as measured using proximal sensing of light interception measured by a light-stick. Al-Muaini et al. (2019b) measured volumetric sap flow in the trunk to determine the palm tree water use, *ET*c, expressed in L d^{-1} and then divided by the area per plant of 64 m^2, to derive the crop coefficient, $K\text{c} = ET\text{c} / ET\text{o}$, of Allen et al. (1998). They found that $K\text{c} = 0.95\ LI$ across three different date varieties irrigated at two different salinities. In this way, they could predict date-palm water use from proximal sensing of *LI* to infer *K*c, and then use the meteorological records of *ET*o to find *ET*c as 0.95 *LI*.*ET*o.

Unlike the experimental plots at ICBA, commercial date farms can have plantings as close as 3 x 3 m spacings between the palms, and *LI* values can be very high, as sometimes there are also low rates of pruning activity. To realise our goal of providing information that can be used to manage better groundwater irrigation on commercial date farms, our objectives were:

- To assess whether the light interception fraction, *LI*, on commercial farms can be predicted from information of tree spacing, tree age, or groundwater salinity
- To determine whether remote sensing via satellite imagery can be used to calculate the fractional ground cover, *FGC* (-), of date canopies on commercial farms, and whether *FGC* can be linked to *LI*.

- To use measured values of *FGC* from remote sensing of commercial farms to predict the probability distribution function of *ET*c for date palms growing on commercial farms, and compare these with the *ET*c values measured for date palms in the experimental plot at ICBA.
- To suggest ways by which canopy management can be used to reduce *ET*c and lower the need for the extraction of groundwater for irrigation.

6.3 Materials and methods

The sap-flow techniques used for the measurement of tree water-use, *ET*c, and the details of the use of the light-stick (Figure 6.1, left) to monitor, *LI*, have been given by Al-Muaini et al. (2019 a, b), so no further descriptions are provided here.

Ten commercial date farms were selected for proximal sensing of *LI* and remote assessment of *FGC*. Five farms were in the western region of Al Dhafrah, and the five other farms were near Al Ain (Table 6.1). This selection covered a range of cultivars, tree ages, tree densities, and groundwater salinities.

Table 6.1. Details of the 10 commercial date farms sampled for assessment of the light interception fraction, *LI*, of date palms using proximal sensing with a light-stick. There were 3-4 transects on each farms, and the varieties and tree ages of the 3-4 transects are given in respective order. The total number of tree per farm, and the average salinity of the water used for irrigation on each farm, are also given.

No.	Area	Varieties	Number of trees per farm	Tree ages (y)	Tree density (stems ha^{-1})	Groundwater salinity (dS m^{-1})	Location
1	Saih Al Khair	Khalas, Sheshe, Khalas	524	5, 7, 10	204, 205, 214	4.53	23°21'45.4"N 53°47'04.6"E
2	Madinat Zayed	Khalas, Sheshe, mixed	283	5, 10, 12	156, 158, 162	3.17	23°36'48.2"N 55°33'43.5"E
3	Al Mezair'a	Khalas, Khalas, mixed	283	7, 10, 15	181, 194, 204	10.50	23°08'24.7"N 53°58'51.1"E
4	Al Hasan	Barhi, Khalas, mixed	898	4, 10, 12	204, 205, 214	9.48	23°03'33.4"N 53°30'14.0"E
5	Al Thrwania	Khalas, Khalas, Zamli	307	10, 12, 20	147, 147, 179	3.47	23°21'38.5"N 53°46'36.1"E
6	Al Oya/ Al Wagan	Khalas, Khalas, Fardh	1400	12, 15, 27	228, 228, 230	2.68	23°36'54.1"N 55°33'49.2"E
7	Al Oya/ Al Wagan	Khalas, Fardh, mixed	1456	12, 15, 27	204, 205, 214	7.54	23°36'48.2"N 55°33'43.5"E
8	Al Oya/ Al Wagan	Khalas, Khals, mixed	1246	12, 17, 30	204, 205, 214	0.98	23°35'54.3"N 55°32'47.1"E
9	Al Hayer	Khalas, Ayasa, Zamli	396	10, 12, 18	152, 152, 172	1.20	24°36'20.4"N 55°44'54.8"E
10	Al Shawib	Mixed, mixed, mixed, mixed	947	13, 17, 18, 20	152, 158, 159, 163	3.47	24°43'16.5"N 55°47'03.7"E

On each farm, some six to eight transects were made with the light-stick (Figure 6.1, right) along a well-defined path to encompass the full shadow pattern of the selected line of four or five trees. Observations were made at three times of the day (1000, 1200 and 1400 hours) to

cover a range of sun angles. This was repeated across three locations on each farm. A total of 30 values of *LI* were generated from the use of the light stick on 10 commercial farms.
A comparison is carried out here between the *ET*c and *LI* results we had collected at ICBA (Al-Muaini et al. 2019b) and those found on the commercial farms.

The remote sensing *FGC* of date palms at ICBA and on the commercial farms used a simple approach based on easily available, low-resolution images from Google Earth Pro™. A distance scale-marker and the images were transferred to Microsoft PowerPoint®. Then ellipses drawn around a selection of trees, to enable calculation of the ground-projected area (*GPA*) of each tree. A ground-based assessment was made of light transmission through the foliage by analysing specific parts the traces from the light-stick when it was directly under the leaf canopy. The light transmission through the foliage was about 10-15% across the farms. Combining these with the values of *GPA* enabled the *FGC* to be calculated. This simple procedure provided good estimates of *FGC* for our purposes here, and shows how remote sensing of plant canopies can be made using easily available data, albeit that in our case this assessment was made easier because of the contrast between the palm trees' canopies, and the golden sand of the desert underneath.

6.4 Results and discussion

6.4.1 Light interception and farm characteristics

The general characteristics of the surveyed farms are presented in Table 6.1. Our initial thoughts were that the light interception fraction, *LI*, might show a general relationship with tree age, tree density, or the salinity of the groundwater used for irrigation.

Figure 6.1. Left. The light-stick that was used to measure the light interception fraction. Here the reference value of full sunlight is being recorded. The light-stick is 1 m long and comprises 20 equi-spaced quantum sensors that record photosynthetically active radiation (*PAR*) at 2 Hz (Al-Muaini et al., 2019a). Right. The operation of the light-stick on a commercial date farm at Al Wagan, near Al Ain in the east of Abu Dhabi. Here the palm trees are at a 6.5 x 6.5 m spacing.

Figure 6.2 shows the relationship between *LI* and palm tree density for the commercial farms (black markers). Also shown as the red squares are the results from our work at ICBA. Not surprisingly, as the spatial density of stems increases there is greater light interception by the trees. However, for the purposes of using *LI* to predict *ET*c, the relationship with plant density is not strong enough to provide robust predictions of tree water use. Obviously tree management through different pruning practices provides a source of the variation.

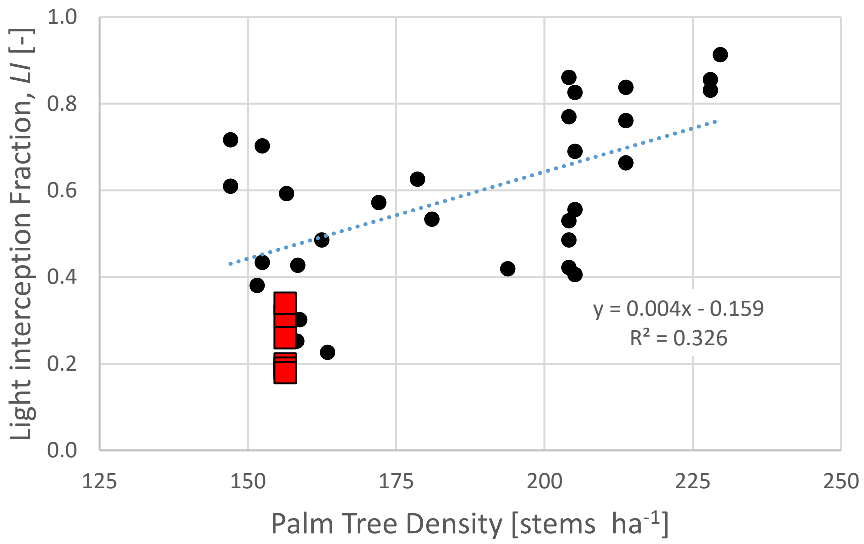

Figure 6.2. The light-interception fraction, *LI*, as a function of the palm tree density (stems ha^{-1}). The black circles are from transects using the light-stick on 10 commercial date farms, and the red squares are from measurements made on three date cultivars at the International Center for Biosaline Agriculture (ICBA) (Al-Muaini et al., 2019b).

The link between tree age and *LI* shown in Figure 6.3 also only reveals a weak trend with increasing age, but again the relationship is inadequate for predicting *ET*c from *LI* by using tree age alone as the independent variable.

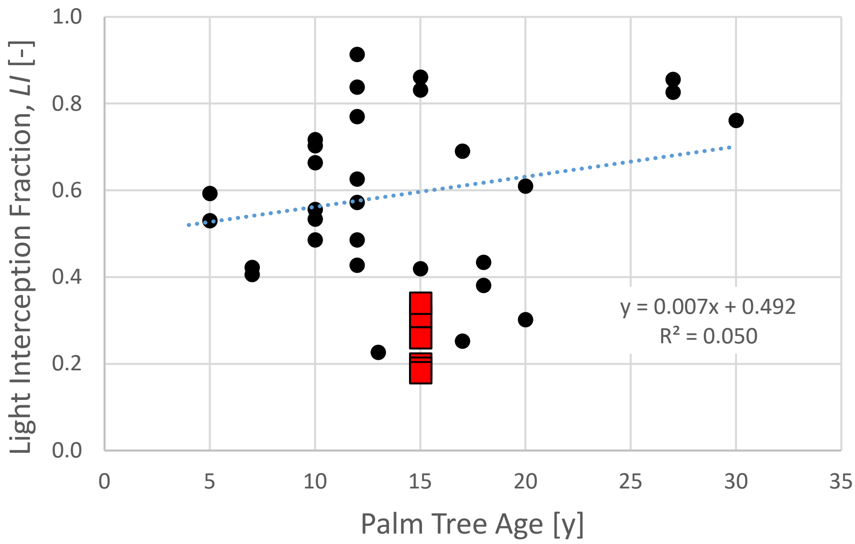

Figure 6.3. The light-interception fraction, *LI*, as a function of the palm-tree age in years. The black circles are from transects using the light-stick on 10 commercial date farms, and the red squares are from measurements made on three date cultivars at the International Center for Biosaline Agriculture (ICBA) (Al-Muaini et al., 2019b).

Figure 6.4 shows the decline in *LI* with the increase in salinity of the water used for irrigation. For date palms of a similar age and management, the leaf area declines with increasing water salinity (Al-Muaini et al. (2019 a,b), and Figure 6.4 confirms this behaviour for commercial farms. Again, however, the relationship is insufficiently strong to enable useful predictions of *ET*c from *LI* predicting solely using the electrical conductivity, *EC* (dS m^{-1}) of the water used for irrigation.

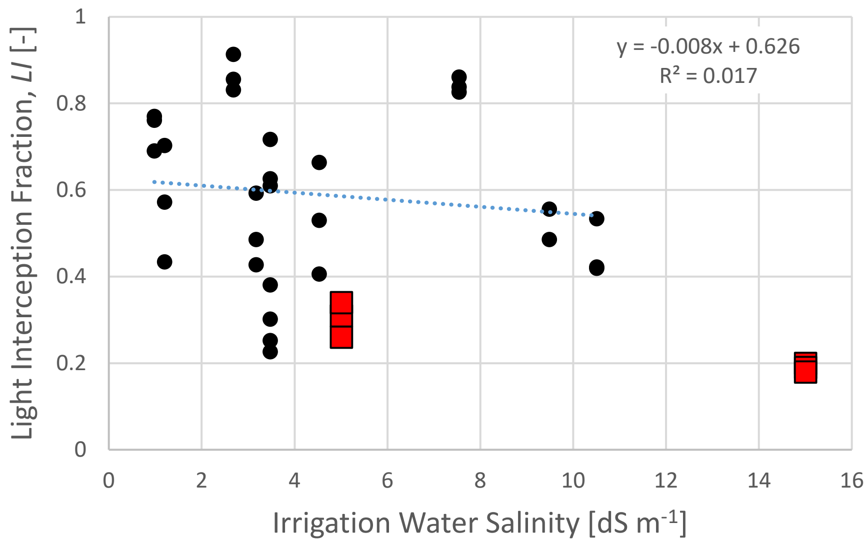

Figure 6.4. The light-interception fraction, *LI*, as a function of the salinity (dS m^{-1}) of the water used for irrigation. The black circles are from transects using the light-stick on 10 commercial date farms, and the red squares are from measurements made on three date cultivars at the International Center for Biosaline Agriculture (ICBA) (Al-Muaini et al., 2019b).

6.4.2 Light interception and fractional ground cover

Given the inability of the general characteristics of the date farms to predict *LI*, we sought an alternative approach using remote sensing of *FGC*. In Figure 6.5 we show an example of how ellipses were drawn onto images of the palm trees' canopies obtained from Google Earth Pro™. On the left of Figure 6.5 are the ellipses around the five 'Shahlah' trees of Treatment S1 (*EC* = 5 dS m^{-1}), and on the right of Figure 6.5 are shown the five ellipses circumscribing the five 'Shahlah' palm trees of Treatment S3 (15 dS m^{-1}). The yellow line is the scale measure of 28 m. The *FGC* of 'Shahlah'-S1 was calculated to be 63% using this method. The FGC of 'Shahlah'-S3 was calculated to be 32%. Similar analyses were carried out on the other two varieties of 'Lulu' and 'Khalas' that we studied at ICBA under the two salinity treatments (Al-Muaini et al. 2019b).

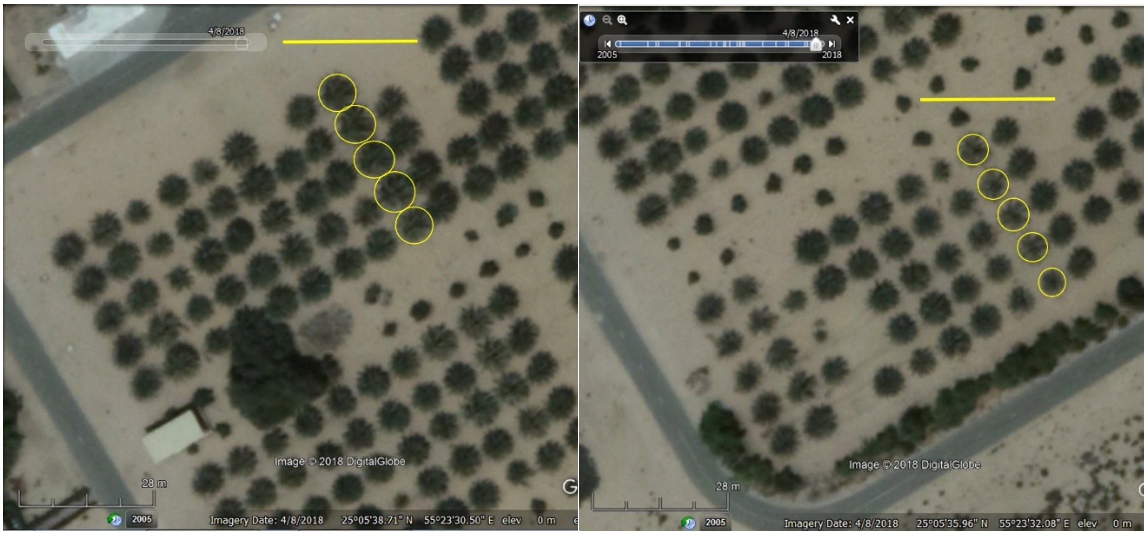

Figure 6.5. Google Earth images of part of the plantation of dates at the International Centre for Biosaline Agriculture (ICBA) of which our experiments were carried out (Al-Muaini et al. 2019 a, b). The left panel is the cultivar 'Shahlah' under the treatment S1 (5 dS m^{-1}). The right panel is 'Shahlah' under the treatment S3 (15 dS m^{-1}). The circles show the approximate outlines of the trees' projected canopy areas. The yellow bar is a scale representing 28 m. This GIS image data-base was used to infer the fractional ground cover (*FGC*).

The relationship found between *LI* and *FGC* is presented in Figure 6.6. The data used to establish this relationship were taken from our earlier studies at ICBA, and included an analysis of *FGC* from four of the farms in the survey, namely Farms 1 and 2 from Al Dhafrah, and Farms 5 and 8 from the Al Ain region. The *LI* and *FGC* data cover a wide range of canopy conditions, with *FGC*s as low as about 0.3, right up to overlapping canopies where *FGC* exceeds unity at 1.04. Thus we conclude that remotely sensed *FGC*, using a simple approach based on Google Earth Pro™, enables prediction of *LI* with sufficient accuracy to enable its use in assessing tree water use. We are in the process of automating the procedure of *GPA* and *FGC* determination, and also using high-resolution imagery from drones to determine in greater detail the foliage density.

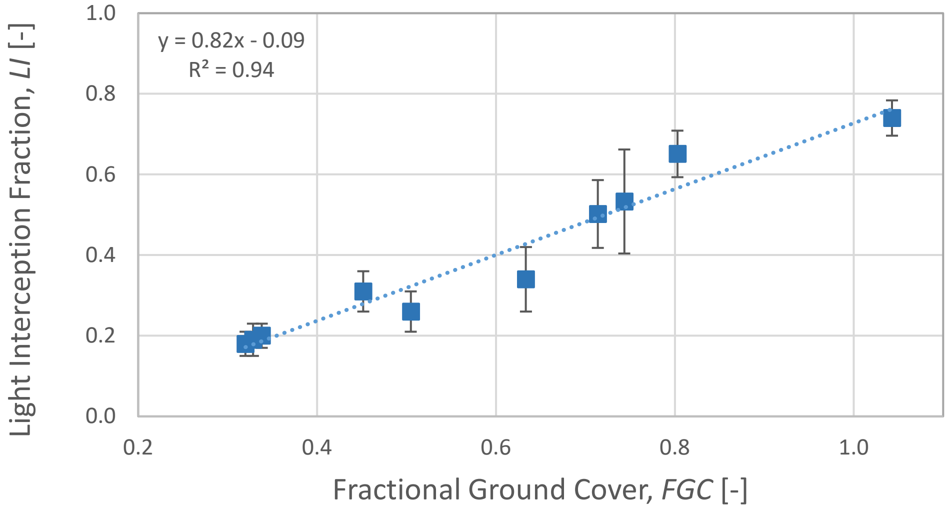

Figure 6.6. The relationship between fractional ground cover, *FGC*, estimated using low-resolution satellite images from Google Earth, and the light interception fraction, *LI* (-), of date palms measured using the light-stick device. Error bars represent +/- one standard deviation (n=3) of the *LI* from our research at the International Center for Biosaline Agriculture (ICBA) on three varieties and two salinities (Al-Muaini et al. 2019b), and from the results from four commercial farms (Numbers 1, 2, 5, and 8) where satellite images were analyzed for *FGC*. A fractional ground cover greater than 1.0 means that the leaf canopies were overlapping.

6.4.3 Tree water use on commercial farms

In our previous work, we showed that *ET*c could be predicted using *K*c.*ET*o, where *K*c was, on average, found to be 0.95 *LI* for the varieties of differing salt tolerances of 'Lulu', 'Khalas' and 'Shahlah' (Al-Muaini et al. 2019b). So from the *LI* values found from the three, or four, path lengths of the transects made by the light-stick on the 10 commercial date farms it is possible to find the probability distribution function (pdf) of the annual values of *ET*c in kL y^{-1} using 0.95 *LI*.*ET*o, and knowledge of the tree spacing. The pdf of *ET*c for the trees on the 10 commercial date farms are shown in Figure 6.7, along with the annual *ET*c values of the 'Lulu', 'Khalas' and 'Shahlah' palms at ICBA for both treatments S1 and S3.

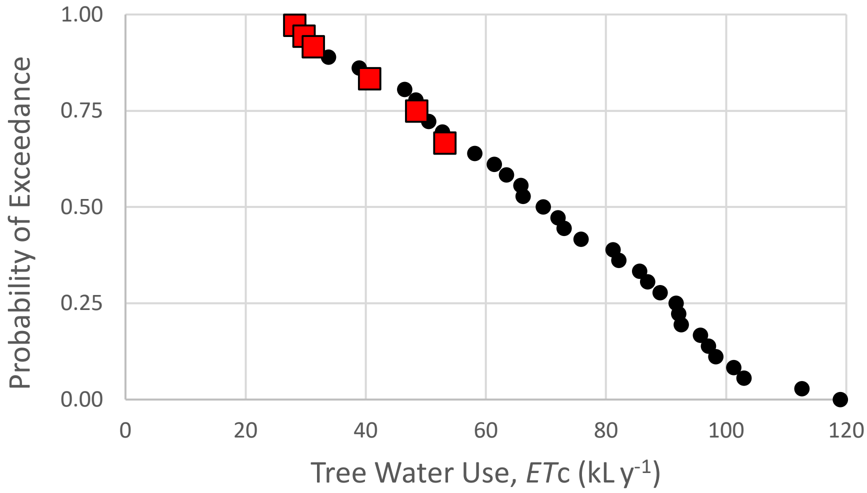

Figure 6.7. The probability distribution function of tree water use, *ET*c (kL y^{-1}) calculated for a wide range of date palms from commercial farms in the Emirate of Abu Dhabi. The black circles represent data from 10 commercial farms and the red square markers represent data from the salinity *ET*c experiments at the International Center for Biosaline Agriculture (ICBA) near Dubai. In each case the annual tree water use has been calculated using daily climate data for the reference evapotranspiration, *ET*c (mm d^{-1}) obtained from the National Climate Centre combined with a crop coefficient, *K*c, estimated from 0.95 *LI* (Al-Muaini et al. 2019b), where *LI* is the light interception fraction [-] predicted from the fractional ground cover, *FGC*, determined from satellite imagery (Figure 6.6).

The comparison highlights the challenge in estimating the water use of crops on commercial farms based on data from experiments carried out under controlled conditions on research farms. The average water use of the larger S1 trees at ICBA was 50.1 kL y^{-1}, and that for the smaller S3 trees was 27.6 kL y^{-1}. The lowest 25% of trees on commercial farms had annual *ET*c values of less than 50 kL y^{-1}. The median value of water use from trees on commercial farms was nearly 50% more at 75 kL y^{-1}. Some 10% of trees on the commercial farms had *ET*c exceeding 100 kL y^{-1}. Proximal sensing of *LI* and remote sensing of *FGC* has enabled us to place in context the results gathered from controlled experimental conditions at ICBA.

Our earlier work has suggested that under Law 5, irrigation should be applied at 1.5 *ET*c to account for a 25% factor-of-safety, and a 25% salt-leaching fraction. The data presented in Figure 6.7 can be used on these farms for scheduling irrigation at 1.5 *ET*c. Furthermore, additional work on using automated remote-sensing to find *FGC*, say by drones, would enable this procedure to be extended easily to farms across the main date-growing regions of the UAE.

This would aid the Abu Dhabi Farmers Service Center (ADFSC) to implement efficient irrigation schedules that would reduce the amount of groundwater being used for irrigation. We found a wide variation in the *ET*c by palm trees across the sampled farms, and this reflects the wide variation in pruning practices between farmers. For growers, one of the most important pruning practices is to control the number of fruiting female spathes. Generally, the number of spathes is reduced to eight, so that the dates will be of a marketable size. Less attention seems to be directed towards balancing the leaf-area to fruit-mass ratio, in terms of setting the number vegetative branches, or fronds, relative to the number of spathes left. Some farms have very dense canopies such that the *FGC* is upwards of 0.7, and *LI* is greater than 0.5. We consider that more aggressive pruning of the fronds could reduce the *LI* and *FGC*, and thereby reduce *ET*c without compromising date yields. Our work at ICBA showed that very good date yields of about 80-100 kg tree^{-1} can be achieved with an *LI* of just 0.3-0.35. The trade-offs between light interception, photosynthetic capacity, and tree water-use would seem a profitable avenue of future research.

6.5 Conclusions

Previously, we had found that tree water use, *ET*c, could be related to the light interception fraction, *LI*, by the canopies of the date palms (Al-Muaini et al., 2019b). We have now found that on commercial farms the light interception, *LI*, by date palms is not singularly related to such general factors as tree density, tree age, or the salinity of the groundwater used for irrigation. Rather, tree and canopy management by the growers overrides these general characteristics in determining *LI*. So there is a need to be able to estimate *LI* easily so that *ET*c can be predicted on commercial date farms. We have carried out a survey of *LI* using proximal sensing with a light-stick on 10 commercial date farms across the two major date-growing regions of Abu Dhabi. By remote sensing we were able to link the fractional ground cover, *FGC*, determined from low-resolution satellite images to our values of *LI*. Across the 10 commercial farms we surveyed, we were able to predict their trees' annual transpiration, *ET*c. The median water use by trees on the commercial farms of 70 kL y^{-1} was nearly twice what was observed in an experimental trial at ICBA. Some 10% of trees on commercial farms used more than 100 kL y^{-1}. This *ET*c can be linked to the consumption of irrigation water, since it is recommended that irrigation be at the rate of 1.5 *ET*c to allow for a 25% factor-of-safety, and a 25% salt-leaching fraction. The number of fruiting female spathes on each date palms is managed to be about 8, and strands within each spathe are thinned as well, so as to provide fruit of a marketable size. So there would be appear to a canopy leaf area per tree in excess of what is needed for economic date production. Therefore, it is suggested that more aggressive pruning of fronds would enable the rates of tree water use to be lowered, without compromising date yield. This will be a topic for future investigation.

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CHAPTER 7

7 The Blue and Grey Water Footprints of Date Production in the Saline and Hyper-Arid Deserts of United Arab Emirates

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The results presented in Chapters 4, 5, and 6 show that a good understanding of the water use, *ET*c (L d^{-1}) and salt dynamics of date palms of different salt tolerances have been obtained using direct monitoring of sap flow by the Compensation Heat Pulse Method (CHPM), measurements in the soil water and salt dynamics with Time Domain Reflectometry (TDR), plus proximal sensing with a light stick, and remote sensing via satellite. These results have enabled quantification of the water footprints of date production, and these are detailed here in Chapter 7. There is essentially no rainfall in the hyper-arid UAE, so the green –water footprint, WF_{green} (L kg-dates^{-1}). Irrigation with groundwater is proposed to be at 1.5 *ET*c, to account for a 25% factor-of-safety and a 25% salt-leaching. So we consider that 0.5 *ET*c is returned to the blue-water resource of groundwater. So the blue-water footprint, WF_{blue}, is based on *ET*c, and for the three varieties studied this was 646.6 L kg^{-1}. There are two 'grey water' pollutants leaching from date farms: nitrogen and salt. The nitrogen WF_{grey} was 523 L kg^{-1}, and the WF_{grey} for salt was 970 L kg^{-1}, the largest footprint. The impacts of salinity on date productivity could be mitigated using desalinated water, the benefit-cost ratio of using desalinated water to dilute the brackish groundwater was found to be 1.4. However, there will need to be solutions found for the disposal of the rejected brine. Next, in the final chapter of this thesis, Chapter 7, suggestions are made for future research that will further minimise the water footprint of date production, and ideas are proposed for making better use of desalinated water to sustain production of the culturally and economically important date.

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Al Muaini, A., O. Sallam, S.R. Green, L. Kennedy, P. Kemp and B.E. Clothier 2019. The blue and grey water footprints of date production in the saline and hyper-arid deserts of the United Arab Emirates. *Irrigation Science*. https://doi.org/10.1007/s00271-019-00642-6

7.1 Abstract

Dates are economically and culturally important in the UAE. The Emirates has a hyper-arid climate, such that rainfall (green water) is irrelevant for date production. Date farmers rely on irrigation with brackish groundwater (blue water) to grow the dates, however the quantity of groundwater left in the underground reserves is diminishing. Leaching of nitrogen and salts (grey water) from the rootzone of the date palms is compromising the quality of the remaining groundwater reserves. Quantifying the water footprints of WF_{green}, WF_{blue} and WF_{grey}, in L kg^{-1} of dates produced, can be used to assess the magnitude of the impacts of date production on the quantity and quality of the UAE's valuable groundwater resources. We have used results from our water-use experiments on dates near Dubai to determine these footprints. We measured the water use, ETc (m^3 y^{-1}) of three date varieties of 'Lulu' (salt tolerant), 'Khalas', and 'Shahlah' (salt intolerant), irrigated with water at two rates of salinity with electrical conductivities of 5 and 15 dS m^{-1}. The $WF_{green} = 0$, because of the negligible rainfall. Our recommendation is for irrigation to be at 1.5 ETc to enable the leaching of salts. So there is drainage of 0.5 ETc back to groundwater. The WF_{blue} is therefore ETc / Y, where Y is the yield of dates (kg). We found $WF_{blue} = 646.6$ L kg^{-1}. The grey water footprints were $WF_{grey} = 523$ L kg^{-1} for nitrogen and 970 L kg^{-1} for salt. The salt WF_{grey} had the largest magnitude. The economic benefit-cost ratio (*BC*) of the prior dilution of the brackish groundwater with desalinated water was found to be 1.4. However, the externality of the environmental impact of the disposal of the rejected brine from desalination will need to be addressed.

7.2 Introduction

The United Arab Emirates (UAE) has a very dry climate. The reference FAO-56 evapotranspiration (*ET*o) of Allen et al. (1998) exceeds 2000 mm. But there is an average annual precipitation (*RF*) of around just 50 mm y-1, so it is classed as hyper-arid, as the ratio *ET*o/*RF* is less than 2.5%. There are very high summer temperatures, frequently exceeding 40 ºC, and there are virtually no surface water resources. Groundwater is relied upon for irrigation. The agricultural, forestry, and landscape sectors account for nearly 60% of the annual water demand of 4.2 km^3 across all of the UAE. But the water-tables are falling rapidly, primarily due to pumping for agriculture, which greatly exceeds the natural recharge rates from the scant rainfall. Wada et al. (2012) reported that in the Emirates the groundwater resource is being depleted at a rate of some 1.18 (±0.4) km^3 y^{-1}. Annual rainfall in the UAE does not provide for adequate recharge of the groundwater resources which are currently declining and becoming more saline (Figure 7.1). The UAE HydroAtlas (MOEW, 2014) reported that groundwater levels had dropped at 10 m per decade until the mid-nineties in many places (Figure 7.1), such that in many places the drop has exceeded 100 m, especially in the so-called 'red zone' around Al Ain in the east of Abu Dhabi. Furthermore there have been substantial increases over the last four decades in the salinity of groundwaters in the main date-growing regions of Al Ain and Liwa of around 8-30 dS m^{-1}.

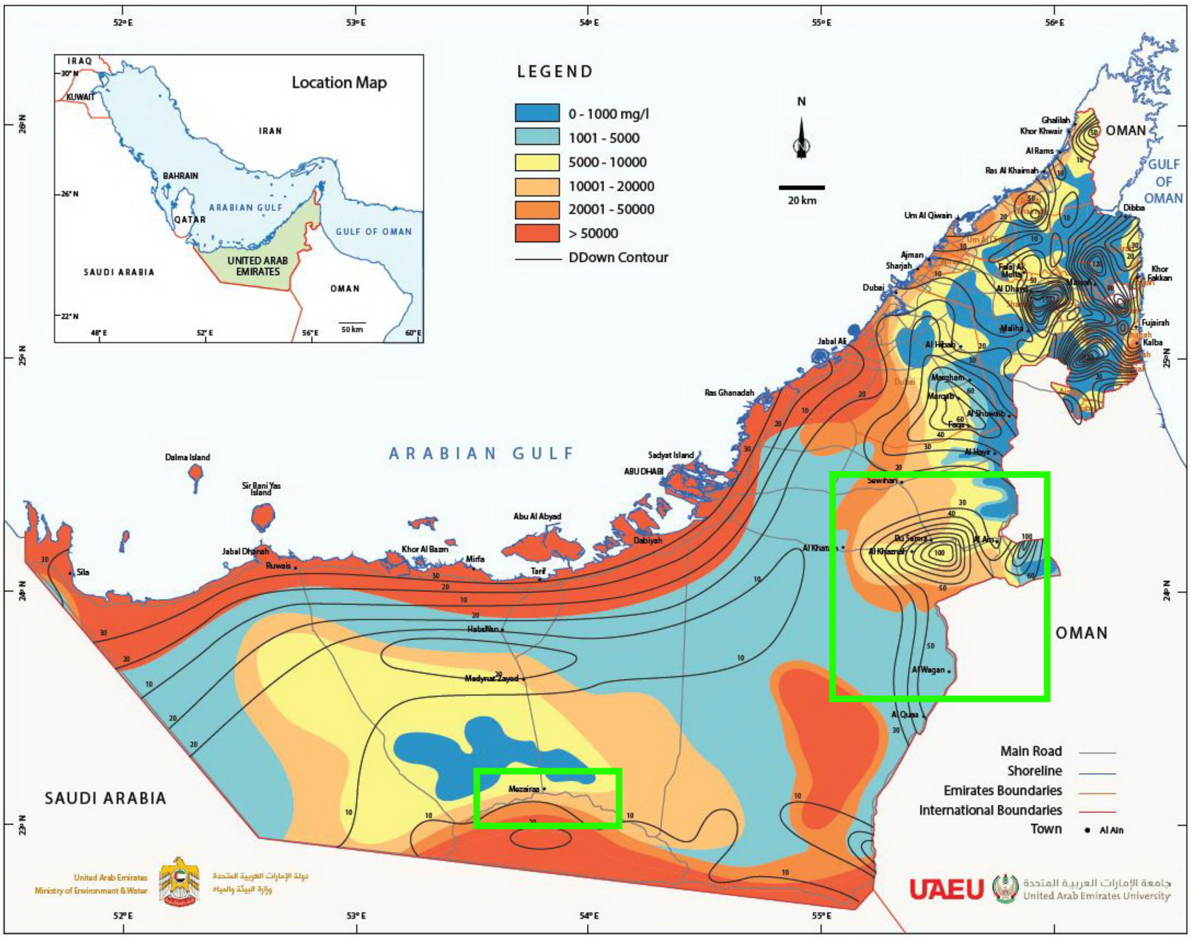


Figure 7.1. A contour map of the decline in the depth to groundwater in metres in the United Arab Emirates, along with the change in the salinity of the underlying aquifers in mg L-1 between 1969 and 2012. The highlighted squares in green are the major date growing regions of Al Ain (left) and Liwa (middle). In the so-called 'red-zone' surrounding Al Ain, there has been up to 100 m of groundwater decline, and salinity rises of between 5-20,000 mg L^{-1} (8-30 dS m^{-1}), whereas the Liwa oases have had lower declines in the water table of 10-20 m, but the same rises in salinity. [Source: MOEW 2014. HydroAtlas of the United Arab Emirates, pp 112. Reproduced with the permission of the Ministry of Climate Change and Environment (MOCCAE) and the United Arab Emirates University (UAEU)].

Irrigation is essential in the United Arab Emirates (UAE) for agriculture. Dates (Phoenix dactylifera L) are an important crop in the UAE, both for economic and cultural reasons. They consume one-third of all irrigation abstraction from groundwater (MOEW, 2015). There are now well over 40 million date palms (Jaradat and Zaid, 2004). The Emirates are the 4th largest date producer in the world, accounting for over 10% of global production (Jaradat and Zaid, 2004).

Thus the sustainability of the groundwater resource, and protection of its salinity are issues being addressed in the UAE. The Government of Abu Dhabi recently passed Law 5 to restrict groundwater use. Under this regulation, all farmers will need to modify their irrigation practices to minimise the amount of water they are using. Some overwatering of crops must still be allowed, however, to avoid salt accumulation in the root zone. All groundwater extractions will be monitored by Environment Agency-Abu Dhabi (EAD) and all farmers will need to comply.

The MOEW (2015) State of the Environment Report pointed out critical issues associated with the declining water-table and increasing salinity of the groundwater stocks in the major date-growing regions of Al Ain and Liwa, and data on these were presented in the 2015 HydroAtlas of the UAE (MOEW, 2014).

So there are concerns about the on-farm water footprint of date production in the UAE. Understanding the magnitude of the water footprints of date production in relation to quantity and quality are therefore needed to help advance measures to protect groundwater.

7.2.1 Water footprinting

The water footprint (*WF*) concept, based on the embedded virtual-water notion of Allan (1993), was first introduced by Hoekstra (2003). Hoekstra (2003) quantified this *WF* as the amount of water that is needed to produce different goods and services, and was further refined to describe the water footprint of countries (Chapagain and Hoekstra, 2004). A WF comprises three components: the blue WF (WF_{blue}), green WF (WF_{green}), and grey WF (WF_{grey}). The WF_{blue} is the volume of water extracted from water resources such as rivers, lakes, and groundwater to produce a product or service. The WF_{green} refers to consumption of rain water that had been stored in the soil. The WF_{grey} is a measure of volume of water 'polluted' as a result of the production of goods and services. This is referenced as the volume of water that is required to dilute the pollutants so that the water quality meets agreed water quality standards (Hoekstra and Chapagain, 2007).

A Water Footprint Network (WFN) has been established (https://waterfootprint.org/en/) and the protocol they have adopted for water footprint assessment has been published by Hoekstra et al. 2011). In climates where there is seasonal rainfall that leads to the recharge of blue-water resources, such as in New Zealand, Deurer et al. (2011) and Herath et al. (2013) proposed a hydrological formulation for the WF_{blue} that accounts for just the net use of blue water. In the case of date production in the UAE, there is effectively no rainfall, so all palm-tree water use, *ET*c, is blue water.

There have been several studies of the water footprints of oil-palm production, where the product footprint was referenced to the oil yield (Francke and Castro, 2013; Hashim et al., 2014; Kaenchan and Gheewala, 2013; Silalertruksa et al., 2017). However, there are no reports on the water footprints of date-palm production. Hence, the main goal of this research is to quantify the blue, green, and grey-water footprints for dates grown in the UAE based on the WFN methodology.

7.2.2 Objectives

Water is a critical resource in the hyper-arid UAE. There are no surface water resources. Therefore the users of groundwater resources need to ensure that the minimum amount is used to realise the desired goals, and that in so using the groundwater, the water quality of the water bodies receiving leachates is not degraded. Quantification of the blue, green and grey-water footprints enables assessment of this, and points to future options for the best use of water resources. Therefore our goals here are to:

- Establish the magnitude of the WF_{green} in date production in a hyper-arid environment.
- Determine the WF_{blue} of date production in a hyper-arid environment, and assess the economic value of groundwater used for irrigation.
- Assess the protocols, and their merits, for determination of WF_{grey} for the groundwater pollutants of nitrogen and salt.
- Propose a new formulation for the WF_{grey} for salt when irrigating using brackish groundwater.
- Quantify the economic benefit-cost ratio of diluting brackish groundwater with desalinated water in date production, and consider the impact of this on the salt WF_{grey}.

7.3 Materials and Methods

Since 2014 we have carried out water-use experiments on three date varieties at the International Center for Biosaline Agriculture (ICBA) near Dubai. The three varieties are the salt tolerant 'Lulu', and moderately salt-tolerant 'Khalas', and the salt intolerant 'Shahlah'.

For our analysis of the *WF* we draw on the results from these experiments. Only salient details are presented here, as the details have been published by Al-Muaini et al. (2019a, 2019b).

7.3.1 Study site

Our field experiments were carried out at ICBA (25.09° N; 55.39° E; 48 m a.s.l.) near Dubai. The soil of the field site is a Typic Torriorthent sandy-skeletal hyperthermic soil with a sand content of over 90%. The dates palms were planted in 2000/01, and we studied in detail just three varieties of the 18 varieties in the trial. Three rates of water salinity were applied: S1 = 5, S2 = 10 and S3 = 15 dS m^{-1}, although our water-use measurements were carried out only on the S1 and S3 treatments. Direct measurements of tree water-use, *ET*c, were made every 30 minutes using the compensation heat-pulse method (Green and Clothier 1988; Al-Muaini et al., 2019b).

We use date yield information from experiments with nine date varieties carried out at ICBA over the three years of 2012-2015 (Dr Abdullah Dakheel, pers. comm.). This data-set includes the three varieties that we had instrumented to measure ETc, namely 'Lulu', 'Khalas' and 'Shahlah'. The six other varieties were 'Abu Mann', 'Barhi', 'Farad', 'Khnizi', 'Naghal' and 'Rothan'.

To monitor soil-solution salinity, six Campbell Scientific CS655 probes were installed at the depth of 150–270 mm in the irrigation basin which surrounds each of the instrumented trees in the 'Lulu' S1 and S3 plots. Prior to installation the probes were calibrated in the laboratory using soil from the site (Al-Muaini et al. 2019a). These data were then used to enable us to infer the soil solution *EC* from the bulk soil *EC*b measured by the CS655 probes.

7.3.2 Water footprinting protocols

The water footprint of an agricultural crop comprises the *ET*c which is maintained by irrigation with blue-water, and rainfall of green-water (WF_{green}), most of which is consumed via crop transpiration (Hoekstra et al., 2011). The third component of water footprint, is the grey water which is the notional volume of water necessary to dilute pollutants, such as fertilizers and salt, which reach and contaminate surface or groundwater resources (Franke et al., 2013).

The water footprint of a process step, WF_{proc}, is the volume of per unit time of water used in that process step (Hoekstra et al., 2011).

The process-step green-water footprint for date palms is:

$$WF_{\text{proc,green}} = GreenWaterEvapotranspiration + GreenWaterIncorporation \quad [7\text{-}1]$$

In this hyper-arid environment of the UAE, rainfall is an extreme rarity, and the contribution of rainfall to the hydrological balance of the date palms is negligible. So small is the contribution of green water to ETc that it is acceptable to ignore it. Thus the WF_{green} for date production in the UAE is negligible. We consider that ETc simply comprises the blue water of the groundwater irrigation supplied to the palms.

The process step for the blue-water footprint of dates comprises:

$$WF_{\text{proc,blue}} = BlueWaterEvapotranspiration + BlueWaterIncorporation + LostReturnFlow. \quad [7\text{-}2]$$

Here any *LostReturnFlow* is the drainage that is not available for reuse.

In our recommendations to EAD on the implementation of Law 5 we have suggested that irrigation using the blue, saline groundwater be at a rate of 1.5 ETc. This comprises the ETc for the crop, plus a 25% factor of safety, and a 25% salt-leaching fraction. If we consider that the 25% factor-of-safety is also effectively drained below the rootzone, there is a return flow to groundwater of 0.5 ETc as required to remove the salts from the rootzone. This return flow is not, however, lost. Rather it is returned to the aquifer for future use, albeit that the return flow is saltier than the water that was first drawn from the groundwater for irrigation. This increase in the salt concentration is addressed later through the WF_{grey}. Over the year we can ignore the amount of blue water that is incorporated into the palm tree and removed in the dates. So:

$$WF_{\text{proc,blue}} = ET\text{c} \quad . \quad [7\text{-}3]$$

Thus the blue-water footprint, WF_{blue} (L kg^{-1}) is

$$WF_{\text{blue}} = WF_{\text{proc,blue}} \,/\, Y = ET\text{c} \,/\, Y \quad , \quad [7\text{-}4]$$

where Y is the annual yield of dates from the palm.

When assessing the $WF_{\text{proc,grey}}$ of a process step, the footprint for each contaminant is calculated separately. Here we consider the two pollutants of concern in the UAE in relation to date production: nitrogen and salt. Unlike the WFN protocol we do not assign the WF_{grey} to the largest value, rather we discuss them separately, for seeking sustainable remedies to minimise the impacts of salt and nitrogen on groundwater requires that they be addressed separately. Simply treating the largest WF_{grey} would leave unresolved the impacts of the lesser WF_{grey}.

The WFN defines the $WF_{\text{proc,grey}}$ in a process step as "… the volume of fresh water that is required to assimilate the load of pollutants based on natural background concentrations and existing ambient water quality standards" (Hoekstra et al., 2011; Franke et al., 2013). Hoekstra et al. (2011) noted that $WF_{\text{proc,grey}}$ could be understood as "dilution water requirement", but that this meaning should be avoided, and rather the $\text{WF}_{\text{proc,grey}}$ should be thought of as an indicator of the magnitude of the pollution. If c_{nat} (mg L^{-1}) is the natural concentration of the receiving water body, and c_{max} (mg L^{-1}) is the maximum acceptable concentration, and if the leaching load of pollutant is L (kg y^{-1}) then

$$WF_{\text{proc,grey}} = \frac{L}{(c_{max} - c_{nat})} . \qquad [7\text{-}5]$$

For diffuse sources of pollution such as with agriculture, the WFN considers that

$$L = \propto . Appl \ , \qquad [7\text{-}6]$$

where *Appl* is the application rate of the pollutant, and α is leaching fraction of the applied amount.

So the grey-water footprint, WF_{grey} (L kg-1) is:

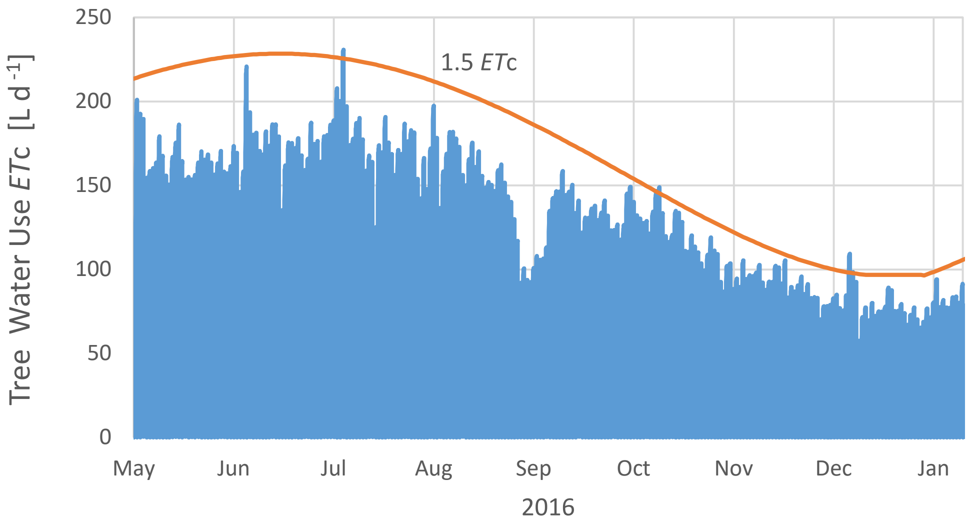
$$WF_{\text{grey}} = WF_{\text{proc,grey}} \, / \, Y \qquad . \qquad [7\text{-}7]$$

7.4 Results and Discussion

The impact of the differing salinity rates of 5 (S1) and 15 (S3) dS m^{-1} on tree performance can be seen in Figure 7.2 where photographs are shown of trees from the S1 and S3 treatments. The S1 trees are 40% higher than those in S3, and there is a 50% difference in the canopy leaf areas of the S1 trees compared with those in S3 (Al-Muaini et al. 2019a). The *ET*c scales directly with canopy leaf area.

Figure 7.2. Left: One of the instrumented 'Lulu' date palms from the S1 treatment that was irrigated with water at 5 dS m^{-1}. The height (*h*) was 3.6 m, and the irrigation bund surrounding the tree can be seen.
Right: One of the instrumented 'Lulu' date palms from the S3 treatment that was irrigated with water at 15 dS m^{-1}. The tree height was 2.6 m. These photographs were taken during 2016 at the International Center for Biosaline Agriculture (ICBA) near Dubai in the United Arab Emirates.

The water use of date palms is therefore strongly influenced by the salinity of the applied groundwater that is used for irrigation. In Figure 7.3 we show selected excerpts from the annual records of daily measurement of *ET*c from the sapflow device in the S1 and S3 trees of the 'Lulu' variety (Al-Muaini et al. 2019a). Also shown in Figure 7.3 is the envelope trace of 1.5 *ET*c that was used to schedule the irrigation.



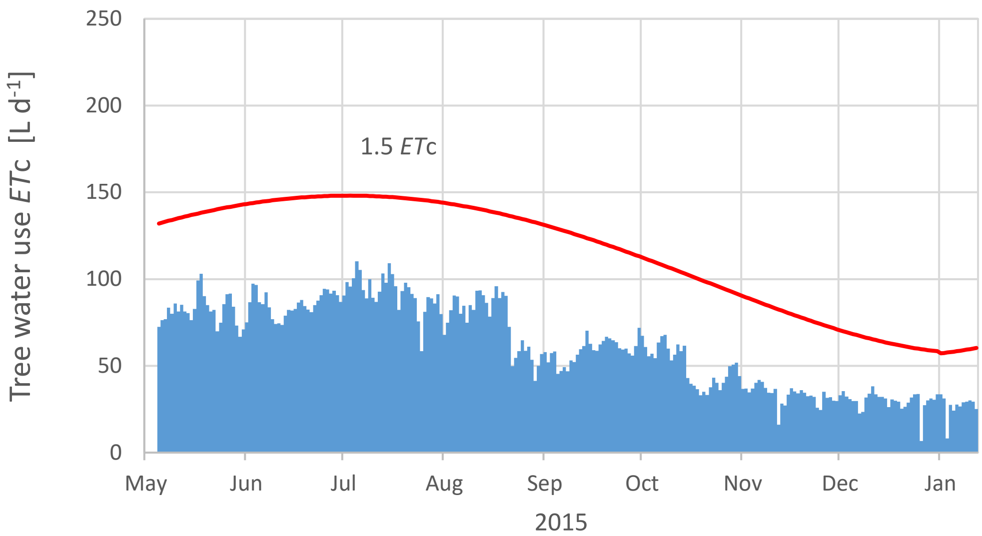


Figure 7.3. Top. The average daily tree water-use (*ET*c L d^{-1}) of three 'Lulu' date palm trees at the International Center for Biosaline Agriculture (ICBA) near Dubai, UAE, as measured by the compensation heat-pulse method (blue bars) over part of the years 2016 and 2017 for treatment S1 (5 dS m^{-1}). These data extend those presented by Al Muaini et al. (2019a), and on this graph we have also represented in red the smoothed envelope curve of 1.5 *ET*c from which the annual irrigation requirement was calculated.

Bottom. The average daily tree water-use (*ET*c L d^{-1}) of three 'Lulu' date palm trees at the International Center for Biosaline Agriculture (ICBA) near Dubai, UAE, as measured by the compensation heat-pulse method (blue bars) over part of the years 2015 and 2016 for treatment S3 (15 dS m^{-1}). Also shown in red is the smoothed envelope curve of 1.5 *ET*c from which the annual irrigation requirement was calculated.

From all the *ET*c data sets for the three varieties, we can compute the annual average daily water, *ET*c, and assess the comparative performance of the three varieties to the two rates of salt loading. There was a 55-60 L d^{-1} difference in the annual average daily *ET*c between the S1 and S3 treatments for 'Lulu' and 'Khalas', while there was a difference of 70 L d^{-1} for the salt-intolerant 'Shahlah' (Table 7.1). The date yield of 'Khalas' was much lower than the other two varieties, irrespective of salinity.

Table 7.1. Components compromising the blue water footprint WF_{blue} of date production for three varieties of dates as assessed using results from experiments at the International Center for Biosaline Agriculture (ICBA) near Dubai, UAE (Dr Abdullah Dakheel, pers. comm.). Here *ET*c is the trees' water use on annual average (L d^{-1}), and irrigation was applied at 1.5 *ET*c (m^3 y^{-1}) to account for a factor-of-safety and salt-leaching requirement. There were two irrigation treatments, one with water at an electrical conductivity (*EC*) of 5 dS m^{-1}, and the other at 15 dS m^{-1}. The annual irrigation total of 1.5 *ET*c assumes that irrigation is not applied on Fridays

Variety	Irrigation water salinity, *EC*	Annual average *ET*c	Annual irrigation total: 1.5 *ET*c	Annual irrigation total	Process-step $WF_{proc,blue} = ETc$	Date yield	Blue water footprint, WF_{blue}	Value of irrigation water*
	dS m^{-1}	L d^{-1} $tree^{-1}$	m^3 y^{-1} $tree^{-1}$	m^3 ha^{-1}	m^3 ha^{-1} y^{-1}	t ha^{-1}	L kg^{-1}	Dhs m^{-3}
'Lulu'	5	137.2	64.4	10051	6700	15.2	440.8	22.7
'Lulu'	15	77.9	36.6	5707	3804	10.1	376.7	26.5
'Khalas'	5	118.1	55.5	8651	5768	6.8	848.2	11.8
'Khalas'	15	63.5	29.8	4652	3101	3.3	939.7	10.6
'Shahlah'	5	156.9	73.7	11494	7662	13.2	580.5	17.2
'Shahlah'	15	85.2	40.0	6241	4161	6.0	693.5	14.4
* @ 10 Dhs kg^{-1} [US$≈ Dhs 3.67]						Averages	646.6	17.2

7.4.1 The blue water footprint: WF_{blue}

From the annual average *ET*c we show in Table 7.1 what the annual average irrigation requirements should be, namely 1.5 *ET*c. This irrigation allows for a 25% factor-of-safety and 25% salt-leaching fraction. So, in essence there is a return flow of 0.5 *ET*c (Eq. 2). However as noted above this return flow is not 'lost' as it is returned to the aquifer where it can again be used for irrigation. Since we do not consider this 'lost', the $WF_{proc,blue}$ is simply then the *BlueWaterEvapotranspiration* (Eq. 7.2), namely *ET*c. This $WF_{proc,blue}$ is presented in Table 7.1 for the three date varieties, each at two rates of salinity. From the data given in Table 7.1 on the yield of dates for these palm trees, we can calculate WF_{blue}. This can be seen to range from a low footprint of 377 L kg^{-1} for the S3 treatment of the salt-tolerant 'Lulu', through to 940 L kg^{-1} for the low-yielding 'Khalas' in treatment S3.

The average WF_{blue} was 646.6 L kg^{-1}. To assess the magnitude of this footprint of dates grown in a hyper-arid climate using saline groundwater, it is illustrative to compare this with the combined blue and green *WF*s of apples. Mekonnen and Hoekstra (2011) suggest that the global average *WF* for an apple is 820 L kg^{-1}. In temperate New Zealand, with high yielding trees, Green et al. (2012) found the consumptive *WF* for apples to be 120-140 L kg^{-1}. Our dates lie somewhere in between, which is somewhat surprising considering they are growing in a hyper-arid environment and being irrigated with brackish groundwater. Maybe, the moderate *WF* we have found for dates reflects the halophytic and xerophytic adaptability of date palms to this desert environment.

7.4.2 The economic value of blue water

The price received for dates ranges from 5-7 Dhs kg^{-1} for average quality dates, through to 15-16 Dhs kg^{-1} for good quality dates. One UAE dirham (Dhs) is currently worth US $0.27 (February, 2019). For heuristic purposes we consider the general price for dates to be 10 Dhs kg^{-1}. In Table 7.1 we present calculations of the economic return in Dhs for the dates in relation to the water consumed to produce the dates. The average value received from the groundwater via an economic return on the dates is therefore 17.2 Dhs m^{-3}.

It is interesting to assess the value of this irrigation water in relation to the cost of desalinating the brackish groundwater. We consider the cost of desalination to be US$ 1.5 (±0.25) m^{-3}, as given by the company Advisian for small desalination plants (https://www.advisian.com/en/global-perspectives/the-cost-of-desalination). At the current exchange rate, this translates to 5.5 (±0.9) Dhs m^{-3}.

This indicates how economically valuable the groundwater resource is. Whereas, the relatively cheap cost of desalination hints at enhanced management options when using brackish groundwater, as we show below.

7.4.3 The grey water footprint: WF_{grey}

We consider that the two groundwater pollutants from date production are nitrogen and salt. We treat these separately.

7.4.4 The WF_{grey} for nitrogen

The Abu Dhabi Water Resources Master Plan (EAD, 2009) found that from a monitoring network of 228 wells, some 80% of the wells exceeded the World Health Organisation's (WHO) guideline concentration for drinking water of 11.3 mg NO_3-N L^{-1} (50 mg NO_3 L^{-1}). We use this WHO guideline as c_{max}. A survey by the United States Geological Survey (USGS) found concentrations below this guideline value, except along the crescent of the Liwa oases (Moreland et al. 2007). The USGS found increases in the concentrations near Liwa over the period 1997-2006, and in one case the rise was from 20 to 220 mg NO_3-N L^{-1}. Agriculture in general, and date farming in particular, is implicated in the contamination of groundwater by nitrates. So whereas c_{nat} now is high, prior to intensive agriculture we consider that c_{nat} would have been zero.

Equations 7.5 and 7.6 can then be used to compute the WF_{grey} for nitrogen [Eq. 7.7]. The key to applying Eqs 7.6 and 7.7 is to determine the load of the pollutant, L, and the fraction, α, that leaches.

From a survey of 10 date farms, five in the Liwa oases, and five near Al Ain, we obtained information about the load, L, of nitrogen being applied to dates. There was a wide range in farmers' practices. In Table 7.2 we present a representative breakdown of the components of nitrogenous fertilisers being used. There is about an average L of 2.65 kg N y^{-1} per tree being applied. This is in excess of 1.8 kg N y^{-1} being exported from each tree that is embedded within the dates themselves. So it seems there is a risk of nitrogen leaching.

Table 7.2. Representative nitrogenous fertiliser practices assumed for date farmers in the UAE that were used for inference of the nitrogen grey-water footprint of date production.

Fertiliser applied	Type of fertilizer	Date applied	Nitrogen applied
kg tree^{-1}			kg tree^{-1}
50	Organic*	October	1.25
50	Organic*	December	1.25
0.1	Urea-N	January	0.1
0.1	NPK-N	June	0.05
* 2.5% N		**Total N**	**2.65**

Estimation of the leaching fraction, α, is challenging, although increasingly this can be monitored using tension fluxmeters (Gee et al. 2009). In the absence of measurements, we turned to the review of Comte et al. (2012) to infer α. They reviewed five studies under oil palm plantations and found α for nitrogen to range from 1% to 34%, with an average of 12%. Given the wide range of values, we simply considered α to be 0.1.

With these assumptions, we calculated the nitrogen WF_{grey} for the three date varieties at the two salinities (Table 7.3). For the conditions, and given these assumptions, the nitrogen WF_{grey} is 522.7 L kg^{-1} for dates. The magnitude of this footprint, as an indicator of environmental impact, is of the same order as value of the WF_{blue}. Since groundwater is not used as a potable source of water, and since there are no surface water resources in the UAE connected to groundwater, the environmental impact of nitrogen leaching is not as great as in other more humid regions.

Table 7.3 Components compromising the nitrogen grey-water footprint WF_{grey} of date production for three varieties of dates as assessed using results from experiments at the International Center for Biosaline Agriculture (ICBA) near Dubai, UAE (Dr Abdullah Dakheel, pers. comm.). The permissible groundwater concentration c_{max} is taken as the World Health Organisation's drinking water standard, and it is assumed that the original natural concentration of nitrogen, c_{nat}, would be zero. There were two irrigation treatments, one with water at an electrical conductivity (*EC*) of 5 dS m^{-1}, and the other at 15 dS m^{-1}.

Variety	Irrigation water salinity, *EC*	Nitrogen load, *L*	Leaching fraction *f*	Nitrate NO_3-N c_{max}	Nitrate NO_3-N c_{nat}	Tree density	Date yield	Grey water footprint, *Wfgrey*
	dS m^{-1}	g $tree^{-1}$	[-]	g m^{-3}	g m^{-3}	trees ha^{-1}	t ha^{-1}	L kg^{-1}
'Lulu'	5	2650	0.1	11.3	0	156	15.2	240.7
'Lulu'	15	2650	0.1	11.3	0	156	10.1	362.2
'Khalas'	5	2650	0.1	11.3	0	156	6.8	538.0
'Khalas'	15	2650	0.1	11.3	0	156	3.3	1108.6
'Shahlah'	5	2650	0.1	11.3	0	156	13.2	277.2
'Shahlah'	15	2650	0.1	11.3	0	156	6.0	609.7
							Average	**522.7**

7.4.5 The WF_{grey} for salt

When irrigating with saline groundwater, salts will accumulate in the root zone if there is insufficient leaching of the salts that are left over after the plant has extracted freshwater through its roots. Intentionally over-irrigating ensures leaching is effective in these desert sands for removal of these salts from the root zone. Ayers and Westcot (1985, 1994) noted that when the electrical conductivity (*EC*) of the irrigation water exceeds 2.7 dS m^{-1}, the yield of dates begins to drop, such that the yield is halved when the *EC* is 12 dS m^{-1}. They considered that when irrigated with water with an *EC* of 21 dS m^{-1}, the palms would effectively yield no dates.

Ayers and Westcot (1994) developed a formula for the leaching requirement (*LR*) to achieve an *EC* in the soil at the sought-after yield percentage, given the *EC* of the water being used for irrigation.

At first glance, it seemed to us that this *LR* fraction could be used as the α fraction in the $WF_{\text{proc,grey}}$ formulation of Eq. 7.6. However, on closer inspection we realized that this did not faithfully represent the salt dynamics in the rootzone of the date palms being irrigated with saline groundwater, nor the practices being used by date farmers in the UAE. The main reason for this is that the farmers do not irrigate considering a *LR* to achieve a desired yield. Rather, they irrigate with their local groundwater and manage the yield and date quality by agronomic practices such as the spacing of trees and controlling the number of flowering branches. So date palm performance, and yield, are simply dependent on the *EC* of the local groundwater source, which reflects the salt concentration c_{nat} (Figure 7.2).

Rather than have a variable *LR*, we have proposed that irrigation of date palms with saline groundwater, irrespective of its *EC*, be at a daily rate of 1.5 *ET*c. This 50% over-irrigation accounts for a 25% factor-of-safety, and a 25% salt leaching fraction. Using this 1.5 *ET*c protocol we have shown that there is effective 'piston displacement' of the salts that have built up in the desert sand during the day after the tree has removed the daily transpiration amount of *ET*c as freshwater (Al-Muaini et al., 2019a; Al-Yamani et al., 2019). Here we present a new formulation for the $WF_{\mathrm{proc,grey}}$ in relation to salt.

7.4.6 Salt dynamics in the rootzone

We installed CS655 probes in the soil of the rootzone of the 'Lulu' date palms, which, *inter alia*, record the bulk EC_{b} of the soil between the depths of 150 and 270 mm. Al-Muaini et al. (2018) used a calibration procedure to predict the soil-solution *EC* and presented the normalised values of the soil solution *EC*. Here, in Figure 7.4, we present the actual values of the soil solution *EC* to reveal the details of the rootzone salt dynamics during irrigation with saline groundwater.

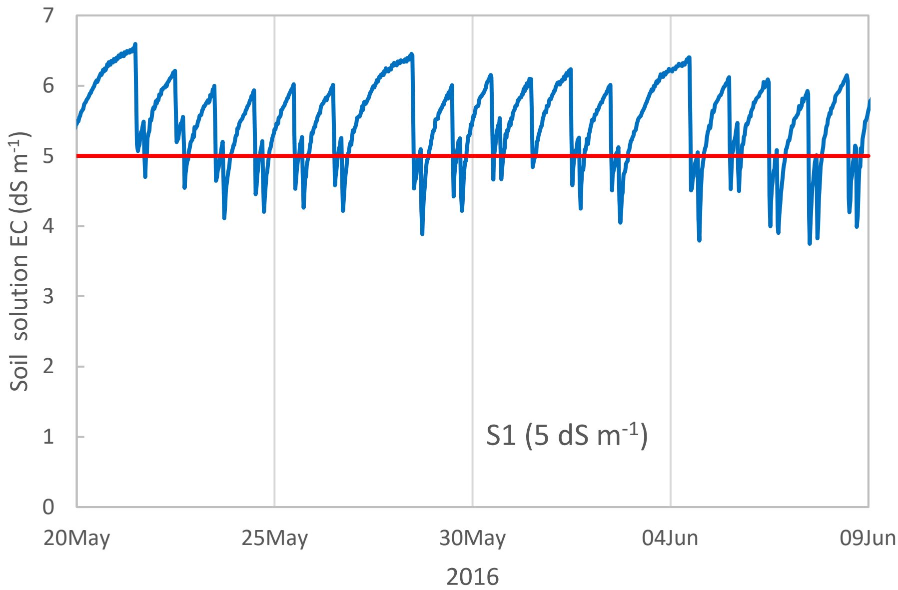


Figure 7.4. The soil-solution electrical conductivity *EC* predicted from the measured water content (θ) and bulk soil electrical conductivity EC_b for a date palm in the S1 (5 dS m^{-1}) treatment. These data were for a period during mid-May in 2016. The irrigation regime, I, was on weekly average I = 1.5 *ET*c, to account for a 25% factor-of-safety, and a 25% salt-leaching fraction. The EC_b and θ were measured using Campbell CS655 probes at a depth of 150-270 mm within the irrigation dam. Two daily irrigations were carried out, one in the morning, and the other in the afternoon. There were no irrigations on Fridays. The horizontal line is the *EC* of the irrigation water at 5 dS m^{-1}.

The trace in the soil-solution *EC* in Figure 7.4 is for the S1 treatment (5 dS m^{-1}) of the 'Lulu' variety. There is an early-morning drop in the *EC* with the first irrigation of the day, and then as the tree extracts freshwater to supply *ET*c, the salinity rises. It again drops with the early-afternoon irrigation. Then the *EC* rises steeply during the late afternoon as transpiration draws more freshwater from the rootzone, resulting in a rise in soil-solution *EC*. This trend is exacerbated on Fridays when there is no irrigation, such that the surface rootzone soil-solution *EC* exceeds 1.3 times that of the irrigation water. It is this rise in salt concentration in the rootzone that use of a salt-leaching fraction seeks to mitigate by flushing salts out of the rootzone. As noted by Al-Muaini et al. (2018), and reflected in Figure 7.4, an irrigation regime of 1.5 *ET*c is effective at the leaching of excess salts.

So the $WF_{proc,grey}$ needs to account for the salt that is being pushed out through the over-irrigation at 1.5 *ET*c to ensure salt leaching. A daily mass-balance calculation, assuming steady-state conditions, as is shown to hold in Figure 7.4, can provide a measure of the salt concentration of the leachate, c_{ret}, being returned to groundwater. Here c_{nat} is the concentration of irrigation water, and the amount of water applied is 1.5 *ET*c. The date palm transpires fresh water at *ET*c. We include the factor-of-safety into the drainage, so that there is leaching of 0.5 *ET*c at concentration c_{ret}. Simple arithmetic shows that $c_{ret} = 3\ c_{nat}$. This provides insight into the deleterious salt loading on aquifers from the best-practice use of a salt-leaching fraction in agriculture. And this identifies why rates of salinity in the UAE groundwater systems have been rising (Figure 7.1). The impact of the salt leaching is therefore a more critical issue than the grey-water footprint for nitrogen.

Nevertheless, this calculation in terms of leachate concentration [mg L^{-1}], although insightful, does not help when trying to quantify the process-step grey-water footprint, $WF_{proc,grey}$, which has units of [volume/time].

7.4.6.1 Defining a WF_{grey} for salt

The definition of $WF_{proc,grey}$ is as a 'dilution volume' (Hoeskstra et al. 2011). And in this case for salt, it is the volume of water that would be required each year, so that $c_{ret} = c_{nat}$. From the calculation above, this would require that there be a three-fold increase in drainage to maintain such equality. Rather than a leaching fraction of just 0.5 *ET*c, it would need to be 1.5 *ET*c. So the $WF_{proc,grey}$ for salt, under this regime is 1.5 *ET*c. This is, by definition, half as big again as the $WF_{proc,blue}$ of *ET*c

From Table 7.1, it can be seen that the WF_{blue} for date production is, on average, 646.6 L kg^{-1} of dates. The WF_{grey} for nitrogen is of the same order: 522.7 L kg^{-1}. Whereas the WF_{grey} for salt is some 50% larger at 970.0 L kg^{-1}. This highlights the role of degradation of groundwater through the brackish drainage of the salt-leaching fraction.

7.4.6.2 The benefit-cost of 'diluting' the WF_{grey} with desalinated water

The concept of a 'dilution volume' for $WF_{proc,grey}$ is notional, but it is useful to assess the magnitude of the environmental impact of the leaching of pollutants, such as salt, to groundwater. However, in the case of date production using saline groundwater for irrigation, this 'volume' actually has some practical implications, as pre-dilution of the brackish groundwater, prior to irrigation, is feasible, and is being adopted around the world. This is especially so as new low-cost technologies such as solar-powered Capacitive Deionisation (CDI) are becoming practical and more widely adopted (Bales et al. 2019).

Private desalination plants are located on some 1150 farms in Abu Dhabi. This is under 5% of the 25,000 farms in the Emirate. The farmer's desalination plants are mainly used to irrigate vegetables in greenhouses, or shade houses. However there is a small and growing number of date farms that have begun to install desalination units.

We carried out a heuristic exercise to assess the benefit-cost ratio (*BC*) of pre-dilution of groundwater destined for irrigation of dates. We sought to determine the *BC* of diluting 15 dS m^{-1} brackish groundwater down to 5 dS m^{-1} to be used for irrigation. So a dilution volume of two thirds was required. We considered that the annual average daily water use of a date palm irrigated with 5 dS m^{-1} water was 140 L d^{-1}, as for 'Lulu' S1 (Table 7.1). So the annual water use is about 50 m^3 y^{-1}. Irrigation was to be taken at 1.5 *ET*c, or 75 m^3 y^{-1}, so there would need to be a dilution volume of desalinated water per tree of 50 m^{-3} y^{-1}.

As given above, we took the cost of desalinating the brackish groundwater to be 5.5 (±0.9) Dhs m^{-3}. So the annual cost for the dilution volume per tree of 75 m^3 y^{-1} would be Dhs 275 (±45).

From the date yield information from nine date varieties at ICBA over the years 2012-2015 (Dr Abdullah Dakheel, pers. comm.), the 15 dS m^{-1} treatments produced 37.4 (±13.3) kg of dates per tree, whereas the 5 dS m^{-1} treatments yielded 74.1 (±18.8) kg $tree^{-1}$. So the yield benefit with 5 dS m^{-1} water would be 38.7 (±7.9) kg $tree^{-1}$. We took the price for dates to be 10 Dhs kg^{-1}. Thus the annual benefit of using diluted and less saline water would be Dhs 387 (±79) per tree.

So the *BC* of using desalinated water to dilute brackish groundwater for the irrigation of date palms is 1.4 (±0.26). It would seem economically a worthwhile option to pre-dilute brackish groundwater prior to irrigation. Burn et al. (2015) note that desalination options are greatest for intensive horticulture for high-value crops, such as dates.

This dilution would result in the trees now increasing their leaf area and transpiration leading to a rise in *ET*c, and the need to use 1.5 *ET*c for irrigation. There will be a policy challenge as to how to handle this. Namely should the allocation limit be the *ET*c before the dilution, or after the dilution? The date yield would also increase, such that the WF_{blue}, and the WF_{grey} of date production would remain essentially the same (see Table 7.1).

However, there would now be the additional externality in the WF_{grey} of the disposal of the rejected brine from the desalination plant, which would add to an increased areal loading of salt. It is unclear how the $WF_{proc,grey}$ from the desalination plants might be allocated to date production to form the product footprint of WF_{grey}. So it is worthwhile considering how the rejected brine might be disposed of sustainably, or allocated to another product.

7.4.6.3 Reducing the $WF_{proc,grey}$ of rejected brine

Law 5 now regulates the installation of these desalination plants, as well as the methods used for the disposal of the rejected brine.

So given the benefit-cost ratio of augmenting groundwater use with desalinated water, there is an imperative to seek more sustainable ways of disposing of the rejected brine in order to protect the surface-soil's environment, and limit leaching downwards of the salt into the groundwater reserves.

Mohamed et al. (2005) assessed the impact of the land disposal of reject brine on soils and groundwaters in the UAE, and they provided six options for minimising the environmental impacts. These included solar ponds for electricity, a growth medium for *Spirulina*, mineral extraction and enhanced evaporation techniques. In Brazil Sanchez et al. (2015) considered that reject brine from inland plants could be used for the farming of fish such as tilapia, or be used for *Spirulina* production. They also assessed how it could be used for the irrigation of halophytic forage shrubs and crops, such as *Atriplex*. In the UAE, the reject brine could also be used for the irrigation of the halophytic bioenergy crop *Salicornia* (Al-Yamani et al. 2013). Thus options do exist for reducing the process grey-water footprint associated with desalinating water that could be used to dilute the brackish groundwater being used in date production.

7.5 Conclusions

Water footprinting through quantification of the green (WF_{green}), blue (WF_{blue}) and grey (WF_{grey}) water footprints can be used to assess the impact of date production of the quantity and quality of natural water resources. We have used results from our water-use experiments on date palms in the UAE to determine these water footprints in relation to the economically and culturally important production of dates. The UAE has a hyper-arid climate, such that rainfall is virtually non-existent, and is irrelevant in the hydrology of date farms. So $WF_{green} = 0$. The dates require irrigation to supply the palm's water use, ETc, and the groundwater used for irrigation is brackish, such that a salt-leaching fraction is required. We have recommended that irrigation be at 1.5 ETc, to enable a 25% factor-of-safety and a 25% salt-leaching fraction. Since the palm trees transpire ETc, and the 0.5 ETc of drainage is returned to the aquifer, the $WF_{\text{blue}} = ET\text{c} / \text{Y}$. We found WF_{blue} to be 646.6 L kg-1 of dates produced. The pollutants for WF_{grey} were taken to be nitrogen and salt, and these were found to be 522.7 L kg^{-1} and 970.0 L kg^{-1}, respectively. Salt is thus a critical issue. We assessed the economic benefit-cost ratio (*BC*) of the prior dilution of the brackish groundwater with desalinated water. The *BC* was found to be 1.4. The externality of disposal of the rejected brine from desalination must also be addressed.

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CHAPTER 8

8 Conclusions and Suggestions for Future Research

8.1 Synopsis

In Chapter 1 the important role that dates play in the economy and culture of the UAE was highlighted. Date palm production is sustained by the use of groundwater for irrigation, yet there is a limited lifetime of groundwater left, and the subterranean water reserves are becoming more saline. As a result, Environment Agency – Abu Dhabi established two large collaborative research projects to seek improvements in the irrigation practices used on date farms. The Objectives of my doctoral research (Section 1.1.3) were based on the goals of these two projects (Section 1.2). In this concluding Chapter, the achievement of my Objectives are detailed (Section 8.2), and then suggestions for future research are proposed in Section 8.3.

8.2 Conclusions

This section sequentially outlines the responses to the Objectives set in Section 1.1.3.

- Extend the knowledge gained in the 2014 Pilot Project

The results of the 2014 Pilot Project on 'Lulu' dates with 5 dS m^{-1} irrigation water were published by Al Yamani et al. (2018). In the work described in Chapter 3 this was extended to the cultivar 'Khalas' and this has been published as Al Muaini et al. (2018). Details of the profile of sap velocities within the trunk of the monocotyledonous date palm were determined for calculation of the diurnal pattern of the palm's water use, *ET*c (L h^{-1}) (Figures 3.1 and 3.3). The crop factor, *K*c (= *ET*c / *ET*o), was found, so that *ET*c could be found from the reference *ET*o. Previous studies to determine *ET*c had either used the empirical Granier heat-dissipation technique in the field (Sellami and Sifaou, 2003), or the heat-pulse technique in small potted palms (Madurapperuma et al. 2009). Tripler et al. (2011) and Sperling et al. (2014) measured date palm *ET*c in large lysimeters. The work described in Chapter 3 is the first use of a reliable technique for measuring *ET*c in mature date palms in the field.

- To investigate ways to improve irrigation management and optimise water usage

The challenge with optimising water usage for dates being irrigated with saline groundwater is to determine the minimum level of over-irrigation that is required to leach salts from the rootzone, after the tree has removed fresh water by osmosis to maintain daily tree water use, *ET*c (L d^{-1}). In Chapter 4, the pattern of soil-solution electrical conductivity, *EC* (dS m^{-1}) was shown under an irrigation regime of 1.5 *ET*c, which was considered to account for a factor-of-safety of 25% and a salt-leaching fraction of 25% (Figure 4.9). Over cycles of irrigation at this rate, there was no net rise in the soil's *EC*. So it is considered that irrigation at a rate of 1.5 *ET*c will optimise irrigation water use for dates palms (Al Muaini et al. 2019a). Sperling et al. (2014) described the impact of the salinity of the irrigation water of tree *ET*c and date yield of date palms growing in lysimeters. In Chapter 4 is described the salinity response of mature date palms growing in the field.

- To investigate the impact of different levels of water salinity (5 dS m^{-1} and 15 dS m^{-1}) on tree water use, irrigation need and date production.

For the cultivar 'Lulu' irrigated with 5 dS m^{-1} water, the seasonal pattern in the rates of tree water use *ET*c were presented in Table 4.3. The annual average daily *ET*c was found to be 140 L d^{-1}. For the 15 dS m^{-1} treatment the rate of water use was 65% of that. Table 4.3 shows the need for irrigation for both 5 and 15 dS m^{-1} irrigation water, considering the sustainable irrigation rate to be 1.5 *ET*c. In Table 4.2 the impact of irrigation water salinity on date yield is given. Between 5 and 15 dS m^{-1}, the yield dropped by 32%, as did the respective leaf areas of the trees (Al Muaini et al. 2019a)

- To investigate how different varieties of date palm respond to altered irrigation volumes and salinity levels. Three varieties of date palms of different salt tolerances would be considered: 'Lulu', 'Khalas' and 'Shahlah'.

Studies were carried out on the salt-tolerant 'Lulu', and moderately tolerant 'Khalas', and the salt-intolerant 'Shahlah' (Chapter 5). Irrigation was carried out at the prescribed rate of 1.5 *ET*c. The impact of this irrigation regime on the tree performance and date production of the three different cultivars is given in Table 5.1 (Al Muaini et al. 2019b). The salinity-response results of Sperling et al. (2014) were for the sole date cultivar 'Medjool' growing in lysimeters. In Chapter 5, the salinity responses tor three cultivars are provided for mature date palms growing in the field.

Using proximal sensing by the light stick of the canopies' light interception fraction, *LI* (-), it was found possible to predict the crop factor, *K*c, using *K*c = 0.95 *LI* across all treatments (Table 5.2). This ratio of 0.95 is lower than the 1.1-1.3 found by O'Connell et al. (2008) and Goodwin et al. (2015) for apples and pears, as would befit the xerophytic and halophytic nature of the *Phoenix dactylifera* L. palm.

- To investigate the combined effect of irrigation management and water salinity on final crop yield and fruit quality with ICBA.

The consumed-water productivities, *CWP* (kg-dates kL^{-1}) of the three cultivars, at two levels of salinity, are given in Table 5.3. Using an average value for the price of dates, the *CWP* was calculated to assess the economic value of the irrigation water by variety and salinity (Section 5.4.4) (Al Muaini et al. 2019b). In the end, the impact on fruit quality was not investigated.

- To determine how by using proximal sensing it would be possible to predict the water use of date palms on commercial date farms.

Through the Commercial Dates project, ten commercial date farms were studied using proximal sensing the light stick to determine the light interception fraction, *LI* (-), by the date palms' canopies. By remote sensing of the commercial farms, the fractional ground cover, *FGC* (-), of the date palms could be found. In Figure 6.6 it was shown the *LI* could be predicted from *FGC*. So by using remotely sensed values of *FGC*, and considering *K*c = 0.95 *LI* (Table 5.2), it was possible to predict the water use on commercial farms (Figure 6.7) (Al Muaini et al. 2019c)

- Quantify the green, blue and grey water footprints of date production and assess the benefit-cost ratio of using desalinated water to enhance date production.

Protocols were determined for calculation of the green (WF_{green}), blue (WF_{blue}), and grey (WF_{grey}) water footprints (L kg^{-1}) (Section 7.3.2). Because there is essentially no rain in the UAE, WF_{green} = 0. The WF_{blue} is *ET*c / *Y* where *Y* is the yield of dates. In Table 7.1 the WF_{blue} was shown to be 646.6 L kg^{-1}. Two pollutants were considered for the grey water footprint. For nitrogen, the WF_{grey} = 522.7 L kg^{-1} (Table 7.3). The largest footprint of all was for salt, WF_{grey} = 970 L kg^{-1} (Section 7.4.6.1). In addition it was found that the benefit-cost ratio of using desalinated water to dilute 15 dS m^{-1} groundwater to 5 dS m^{-1} water for irrigation was 1.4 (Section 7.4.6.2) (Al Muaini et al. 2019d). There have been no previous measurement studies on the water footprint of dates. Also the work described in Chapter 7 brings in a new perspective on salt as a pollutant in the grey-water footprint.

8.3 Suggestions for Future Research

Despite the realisation of all the Objectives of this research, the issues facing date production are still severe as there are further pressures to reduce the consumption of groundwater, and further requirements to reduce the degradation of groundwater from salt and nutrients. In the face of these concerns, I conclude my thesis with suggestions for future research that will help sustain date production, and both groundwater quantity and quality.

8.3.1 Different varieties, tree ages, canopy structures and planting densities

Although direct measurements of ET_c have been obtained on three cultivars at two groundwater salinities on a research station, it is considered that sap flow measurements of ET_c on commercial farms in trees of different varieties, tree ages, canopy structures, and planting densities would be beneficial in understanding the spectrum of water use by date palms. This would broaden the data base of K_c values to enable better determination of the irrigation requirements for date palms across the UAE. This would be achievable with the compensation heat pulse method for determining ET_c.

8.3.2 The water-saving value of frond pruning

In Chapter 6 it was suggested that more aggressive pruning of date palm fronds could reduce ET_c by reducing the frond-leaf area available for light interception, *LI*, without impacting upon date yield. Date yield and date size is controlled by limiting the number of spathes per tree. It was thought that there was an excess of fronds over and above that required to provide the photosynthates for date growth. However, no specific evidence was provided. It is considered worthwhile to test this conjecture.

8.3.3 The use of desalinated water to augment and dilute groundwater, and associated impacts

In Chapter 7, the benefit-cost ratio *BC* of using desalinated water to dilute the brackish groundwater used to irrigate dates was found to be 1.4. A more detailed economic assessment is called for. Furthermore, there would need to be associated studies to examine the environmental impacts of the rejected brine from the desalination plants, and an exploration of innovative possibilities to make use of the rejected brine on agricultural lands.

8.3.4 Quantification of the leaching losses of salt and nutrients

Throughout this thesis, reference has been made to the loss of salt, and nutrients, from the rootzone of the date palms as a result of the need to irrigate at 1.5 *ET*c in order for a salt leaching fraction. However, no measurements have ever been made of the concentrations and loadings of salt, and nitrogen, in particular, from date farms. It is known that the groundwater in date-growing regions is undergoing rises in levels of salt and nitrate contamination. Measurements using tension fluxmeters could be used to quantify the leaching losses, and explore options for reducing this. Biochar could be an option for reducing leaching loads, and improving fertiliser use efficiency

8.3.5 Education of Regulators and Farmers

All of the work decrsibed in this thesis is of a biophysical nature. From this science, it is possible to make recommendations to regulators, such as in the case here of Law 5 in Abu Dhabi, and to suggest to farmers better ways of managing water. Yet to achieve the outcome of sustainable irrigation and groundwater protection requires more than just biophysical science. It requires engagement, education, and extension with both regulators and farmers. These 3 "E"s are the key to the participatory action research (PAR) that can lead to changes in behaviours that could save water and sustain date production.

8.3.6 Treated sewage effluent

Given the seriousness of the water crisis in the UAE, all options to sustain date production must be considered. Although there are cultural and emotional objections presently to the use of tertiary-treated sewage effluent (TSE) for date palm irrigation, this option needs to be considered. This will involve PAR plus human and environmental health assessments.

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APPENDIX A

9 Appendix A: Record of Achievement

9.1 Record of Achievement: Ahmed Hassan Al-Muaini

9.1.1 Experience:

2016 – Present	Environment Agency – Abu Dhabi – Special Assignment	Abu Dhabi
2015 – 2016	Environment Agency – Abu Dhabi – Research Manager Groundwater	Abu Dhabi
2012 – 2014	Environment Agency – Abu Dhabi – Manager Groundwater Monitoring & Exploration	Abu Dhabi
2006 – 2012	Environment Agency – Abu Dhabi – Head of Licenses for Drilling Groundwater wells	Abu Dhabi
2002 – 2006	The UAE Ministry of Environmental and Water / Ministry of Agriculture and Fishers –Minister Office Director	Dubai-UAE
1992 - 2002	The United Arab Emirates University – Teaching Assistance	Al-Ain, UAE
1992	The UAE Ministry of Agriculture and Fisheries---Dubai, UAE	Irrigation Section

9.1.2 Qualifications

The Open International University Colombo, Sri Lanka

Degree of Doctor of Philosophy 2014

University of Florida, Florida, USA

Master of Science in Agriculture:
Majoring in Agriculture and Biological Engineering 2002

California Polytechnic State University, California, USA

Master of Science in Agriculture:
Concentrating in Agriculture Engineering Technology 1997

The United Arab Emirates University of Al Ain, UAE

Bachelor of Science in Soils, Irrigation and Mechanization 1991

9.1.3 Publications

1. Al Muaini, A., S. Green, R. Pangilinan, S. Dixon, A. Dakheel and B. Clothier, 2016. Sustainable Irriigation of Date Palms using Saline Groundwater. In: Integrated nutrient and water management for sustainable farming. (Eds L.D. Currie and R.Singh). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 29. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 4 pages

2. Al-Muaini, A., A. Dakheel, S. Green, A. Abdullah, A.Q. Abdul Rahman, W.A. Abou Dahr, S. Dixon & B. Clothier, 2017. Irrigation management with saline groundwater of date palm cultivars in the hyper-arid United Arab Emirates. In: Science and policy: nutrient management challenges for the next generation. (Eds L. D. Currie and M. J. Hedley). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 30. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 11 pages.

3. Al-Muaini, Ahmed, Steve Green, Abdullah Dakheel, Steve Dixon, and Brent Clothier. 2018. Trunk sap flow in date palms growing in the United Arab Emirates.

Acta Horticulturae 1222. ISHS 2018. DOI 10.17660/ActaHortic.2018.1222.29 Proc. of the X International Workshop on Sap Flow Eds.: L.S. Santiago and H.J. Schenk

4. Ahmed Al-Muaini, Steve Green, Abdullah Dakheel, Al-Hareth Abdullah, Wasel Abdelwahid Abou Dahr, Abdul Qader Abdul Rahman, Steve Dixon, Peter Kemp, & Brent Clothier. 2018. Abstract for the Sixth International Date Palm Conference Abu Dhabi, United Arab Emirates; 19 - 21 March, 2018. [Poster]

5. Abdullah Dakheel, Steve Green, Ahmed Al-Muaini, Steve Dixon, Peter Kemp, Simon Pearson and Brent Clothier, 2018. Modelling the effects of Salinity on Data Palm Production in the United Arab Emirates. Abstract for the Sixth International Date Palm Conference Abu Dhabi, United Arab Emirates; 19 - 21 March, 2018. [Oral presentation]

6. Al-Muaini, Ahmed, Steve Green, Abdullah Dakheel, Al-Hareth Abdullah, Wasel Abdelwahid Abou Dahr, Steve Dixon, Peter Kemp, and Brent Clothier. 2019a. Irrigation Management with Saline Groundwater of a Date Palm Cultivar in the Hyper-arid United Arab Emirates. *Agricultural Water Management* 211:123-131.

7. Al-Muaini, Ahmed, Steve Green, Abdullah Dakheel, Al-Hareth Abdullah, Osama Sallam, Wasel Abdelwahid Abou Dahr, Steve Dixon, Peter Kemp, and Brent Clothier 2019b. Water Requirements for Irrigation with Saline Groundwater of Three Date-Palm Cultivars with Different Salt-Tolerances in the Hyper-Arid United Arab Emirates. *Agricultural Water Management* [submitted].

8. Al Muaini, A., O. Sallam, S.R. Green, L. Kennedy, P. Kemp and B.E. Clothier 2019c. The blue and grey water footprints of date production in the saline and hyper-arid deserts of the United Arab Emirates. *Journal of Cleaner Production* [submitted]

9. Al-Muaini, Ahmed, Steve Green, Wasel Abdelwahid Abou Dahr, Lesley Kennedy, Peter Kemp, and Brent Clothier 2019d. Irrigation Water Requirements for Date Palms Growing on Commercial Farms in the Hyper-Arid United Arab Emirates. *Agricultural Water Management* [submitted].

APPENDIX B

10 Appendix B: Declaration

10.1 Declaration

The funding for the Date Extension Project (Chapters 3-5, 7) on the use of groundwater (GW) of different salinities to irrigate 3 date varieties at the International Center for Biosaline Agriculture (ICBA) near Dubai, was provided by my employee, Environment Agency – Abu Dhabi (EAD). This Extension Project followed on from a short Pilot Project by Plant & Food Research Ltd (PFR) and Maven International on testing the feasibility of a suite of technologies with just one date variety, Lulu, at one salinity (5 dS m^{-1}). The two-and-half year extension project commenced in May 2015 and the experiments were decommissioned in September 2017. This Date Extension Project was resourced by EAD at the level of AED 4.18 million, or NZ$ 1.32 million.

Furthermore, there was a subsequent project on the application of these scientific results to commercial date-palm farms, the so-called Commercial Dates Project (Chapter 6). This was resourced at AED 82,022, or NZD 30,378.

As an employee of EAD, I was granted full-time study leave to pursue my PhD through Massey University on the Date Extension and Commercial Dates Projects. Professor Peter Kemp and Dr Brent Clothier provided academic supervision.

These were complex projects, involving over NZ $254,000 in high-technology electronic sensing technologies, and some detailed soil and plant analyses. Furthermore there were many partners in this detailed and important project: EAD, Plant & Food Research Ltd, Massey University, Maven International, ICBA, the Abu Dhabi Food Control Authority (ADFCA), and the Abu Dhabi Farmers' Service Centre (ADFSC).

From EAD's perspective, I was the project leader. I managed all the interactions between the teams. The leadership of this project was mine.

Nonetheless, the outcomes of this project, and the intellectual achievements are shared between the participants, as would be expected for such a complex and substantially resourced job.

I make this declaration:

- The technology used in this project in relation to sapflow, soil measurements using time domain reflectometry (TDR), the light stick, the soil and plant analyses, were all derived from organisations who have proprietary claims to their technology and the analysis software that was used to provide the results purchased through this project. These companies provided results and spreadsheets that were purchased under the contracts. I understand the principles of the technology employed, but I am not an expert in their analyses, I am a user of the knowledge provided by these technologies.

- The data generation and the raw analyses were proprietary, as expected for the complex analyses of sapflow, TDR, light interception, and soil and plant analyses that were sought in this project. Whereas I understand the biophysical and chemical principles of theses proprietary analyses, I have sought to interpret and apply these knowledge advances.

- My role was in the interpretation of the results provided via the proprietary software, and the application of these to the practical objectives set out under multi-party contracts with EAD, and the academic goals of my doctoral research.

- Necessarily, the publications emanating from my research have many authors, all of whom have provided valuable support an insights into my PhD research. I provided the leadership

- The leadership and academic interpretations of my research is mine, and has been developed in conjunction with the many colleagues in my team.

I conclude by noting that the practical and intellectual outcomes of this work has provided value to EAD, increased the knowledge base concerning the sustainable management of saline-water irrigation for the production of dates, better enabled the protection of the

Emirates’ water resources through minimised irrigation in relation to Law 5, and helped strongly in my developing my scientific career.

Ahmed Al Muaini, March 2019

APPENDIX C

11 Statements of Contributions to Publications

DRC 16

MASSEY UNIVERSITY
GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
TO DOCTORAL THESIS CONTAINING PUBLICATIONS

(To appear at the end of each thesis chapter/section/appendix submitted as an article/paper or collected as an appendix at the end of the thesis)

We, the candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of Candidate: Ahmed Hassan Al Muaini

Name/Title of Principal Supervisor: Prof. Peter Kemp

Name of Published Research Output and full reference:
Al-Muaini, Ahmed, Steve Green, Abdullah Dakheel, Steve Dixon, and Brent Clothier. 2018. Trunk sap flow in date palms growing in the United Arab Emirates. Acta Horticulturae 1222. ISHS 2018. DOI 10.17660/ActaHortic.2018.1222.29 Proc. of the X International Workshop on Sap Flow Eds.: L.S. Santiago and H.J. Schenk

In which Chapter is the Published Work: Chapter 3

Please indicate either:

- The percentage of the Published Work that was contributed by the candidate: 70%

  and / or

- Describe the contribution that the candidate has made to the Published Work:
  Kindly refer to Appendix B for details

Ahmed Al Muaini Digitally signed by Ahmed Al Muaini Date: 2019.03.11 02:04:26 +04'00'
Candidate's Signature

11.03.2019
Date

Peter D Kemp Digitally signed by Peter D Kemp Date: 2019.03.13 12:03:26 +13'00'
Principal Supervisor's signature

13/03/2019
Date

GRS Version 3– 16 September 2011

MASSEY UNIVERSITY
GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION TO DOCTORAL THESIS CONTAINING PUBLICATIONS

(To appear at the end of each thesis chapter/section/appendix submitted as an article/paper or collected as an appendix at the end of the thesis)

We, the candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of Candidate: Ahmed Hassan Al Muaini

Name/Title of Principal Supervisor: Prof. Peter Kemp

Name of Published Research Output and full reference:
Al-Muaini, Ahmed, Steve Green, Abdullah Dakheel, Al-Hareth Abdullah, Wasel Abdelwahid Abou Dahr, Steve Dixon, Peter Kemp, and Brent Clothier. 2019. Irrigation Management with Saline Groundwater of a Date Palm Cultivar in the Hyper-arid United Arab Emirates. Agricultural Water Management 211:123-131.

In which Chapter is the Published Work: Chapter 4

Please indicate either:

- The percentage of the Published Work that was contributed by the candidate: 80%

  and / or

- Describe the contribution that the candidate has made to the Published Work:
  Kindly refer to Appendix B for details

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Principal Supervisor's signature

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Name of Candidate: Ahmed Hassan Al Muaini

Name/Title of Principal Supervisor: Prof. Peter Kemp

Name of Published Research Output and full reference:
Al-Muaini, Ahmed, Steve Green, Abdullah Dakheel, Al-Hareth Abdullah, Osama Sallam, Wasel Abdelwahid Abou Dahr, Steve Dixon, Peter Kemp, and Brent Clothier 2019. Water Requirements for Irrigation with Saline Groundwater of Three Date-Palm Cultivars with Different Salt-Tolerances in the Hyper-Arid United Arab Emirates. Agricultural Water Management [submitted].

In which Chapter is the Published Work: Chapter 5

Please indicate either:

- The percentage of the Published Work that was contributed by the candidate: 85%

  and / or

- Describe the contribution that the candidate has made to the Published Work:
  Kindly refer to Appendix B for details

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Date

Peter D Kemp Digitally signed by Peter D Kemp Date: 2019.03.13 12:06:04 +13'00'
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13/03/2019
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GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
TO DOCTORAL THESIS CONTAINING PUBLICATIONS

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We, the candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of Candidate: Ahmed Hassan Al Muaini

Name/Title of Principal Supervisor: Prof. Peter Kemp

Name of Published Research Output and full reference:
Al-Muaini, Ahmed, Steve Green, Wasel Abdelwahid Abou Dahr, Lesley Kennedy, Peter Kemp, and Brent Clothier 2019. Irrigation Water Requirements for Date Palms Growing on Commercial Farms in the Hyper-Arid United Arab Emirates. Agricultural Water Management [to be submitted].

In which Chapter is the Published Work: Chapter 6

Please indicate either:

- The percentage of the Published Work that was contributed by the candidate: 90%

  and / or

- Describe the contribution that the candidate has made to the Published Work:
  Kindly refer to Appendix B for details

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Candidate's Signature

11.03.2019

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GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
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Name of Candidate: Ahmed Hassan Al Muaini

Name/Title of Principal Supervisor: Prof. Peter Kemp

Name of Published Research Output and full reference:
Al Muaini, A., O. Sallam, S.R. Green, L. Kennedy, P. Kemp and B.E. Clothier 2019. The blue and grey water footprints of date production in the saline and hyper-arid deserts of the United Arab Emirates. Journal of Cleaner Production [submitted]

In which Chapter is the Published Work: Chapter 7

Please indicate either:

- The percentage of the Published Work that was contributed by the candidate: 95%

  and / or

- Describe the contribution that the candidate has made to the Published Work:
  Kindly refer to Appendix B for details

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