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Irrigation management with saline groundwater of a date palm cultivar in the hyper-arid United Arab Emirates

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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, ET_c, at two levels of irrigation-water salinity: Treatment S1 at 5 dS m^{-1}, and S3 at 15 dS m^{-1}. The mid-summer ET_c for the S1 Lulu trees is up to 190 L d^{-1}, on average, whereas for the S3 trees ET_c 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 ET_o, 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.

1. 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, whilst having an average annual precipitation of around just 50 mm y^{-1}. There are very high summer temperatures, often exceeding 40 °C, 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

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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.

1.1. 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.

1.2. 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.

2. Materials and methods

2.1. 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 S2. 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 day^{-1}) through the dimensionless crop factor, K_C (Eq. (1)):

$$ET_C = K_C.\ ET_O, \tag{1}$$

where ET_C is the crop water use (mm day^{-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.

2.2. 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.

2.3. 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 3–4 cm 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 5, 7.5, 10 and 12.5 cm, 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 (*F*m) and water (*F*l) in the sapwood were determined gravimetrically from core samples (*F*m = 0.35 and *F*l = 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 50 °C, 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.

2.4. 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.

3. Results and discussion

3.1. 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 Fig. 1. Also shown is the pattern in the reference evapotranspiration, ET_o (mm d^{-1}) as calculated from the

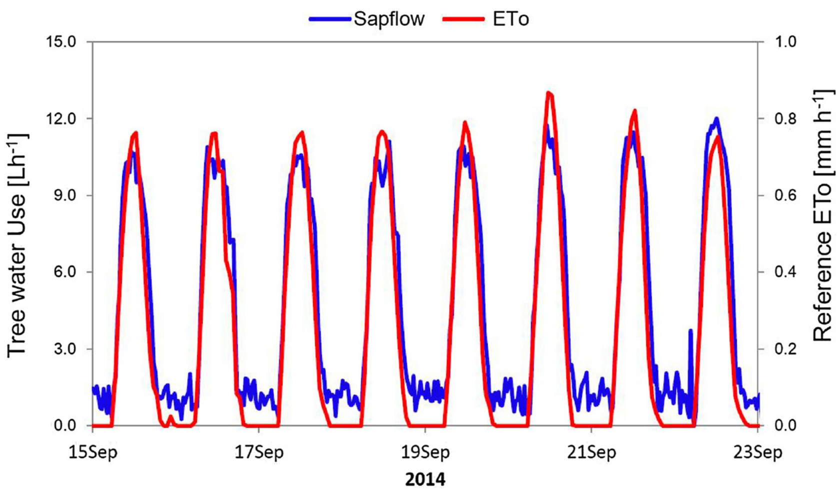

Fig. 1. Late-summer diurnal traces of average volumetric sapflow (L h^{-1}) measured every 30 min by three sets of probes in the trunk of one of the date palm trees (cv. Lulu, Treatment S1) at the International Center for Biosaline Agriculture (ICBA) near Dubai, UAE, and the hourly reference evapotranspiration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

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 (Fig. 1).

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 (Fig. 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. (1)), which here means that for these Lulu S1 trees, K_c = 0.29.

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 Fig. 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.

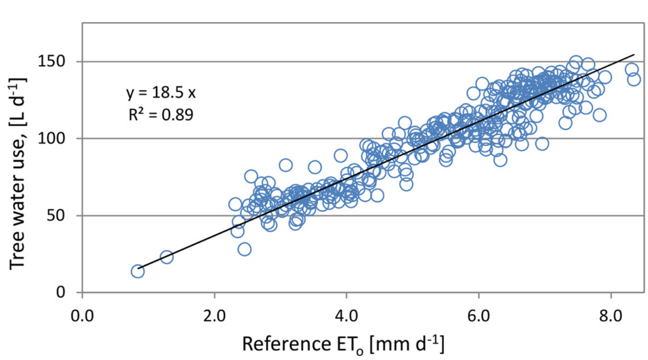

Fig. 2. A regression of the palm-tree water-use (ET_c, L d^{-1}) as determined by sap flow against the reference evapotranspiration (ET_o) as determined from the FAO-56 Penman-Monteith model. The slope of the regression (18.5), when divided by the area per tree (8 × 8 m) crop gives a crop factor, K_c,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

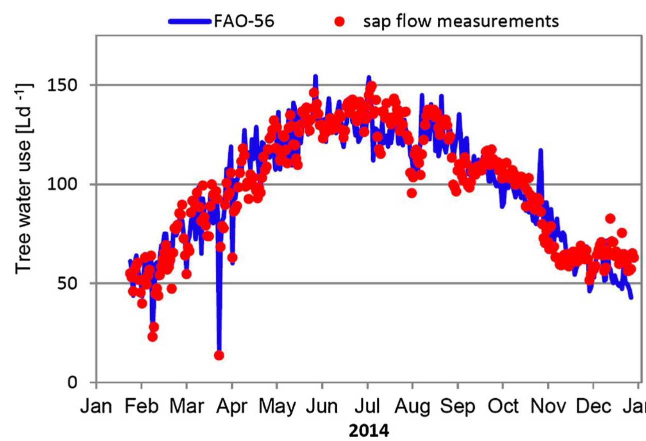

Fig. 3. The average daily tree water-use (ET_c L d^{-1}) of three date palm trees (variety Lulu) at the International Center for Biosaline Agriculture (ICBA) near Dubai, UAE, as measured by the compensation heat-pulse method (red dots) over the full year 2014 for treatment S1 (5 dS m^{-1}). The model 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 Fig. 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). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

From the seasonal traces in Fig. 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 Fig. 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 Fig. 4. Also shown in Fig. 4, for comparison, is the envelope curve of the maximum 1.25 ET_c for the Lulu S1 trees from Fig. 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

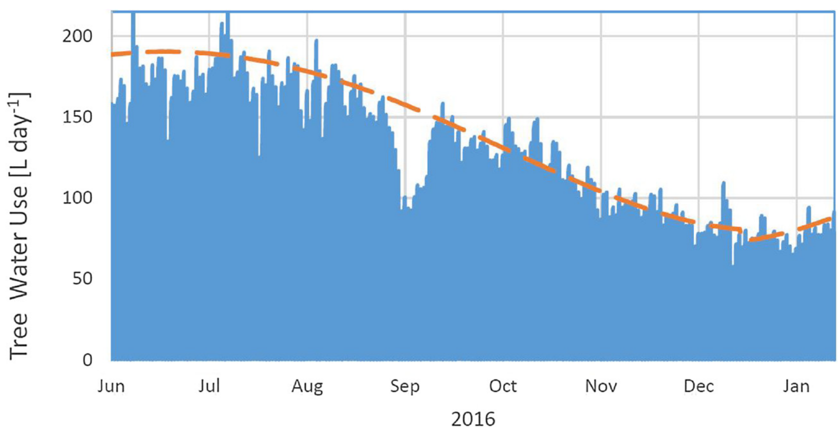

Fig. 4. The average daily tree water-use (ET_c, L d^{-1}) of two date palm trees (Trees 2 and 3: variety Lulu) at the International Center for Biosaline Agriculture (ICBA) near Dubai, UAE, as measured by the compensation heat-pulse method (blue bars) over the year 2016 for treatment S1 (5 dS m^{-1}). 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. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

salts.

Fig. 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 Fig. 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}). 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 of the tree 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 (Fig. 4).

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 and Soriano, 2007), and partial rootzone drying (Dry and Loveys, 1998), both of which rely upon root signalling (Davies and Zhang, 1991).

Prior to the failure of the irrigation system on Monday 12th, on Friday 9th the soil water content in the top meter within the basin, and on the outer side of the berm dropped (Fig. 6). This is normal on Fridays as there is never any irrigation for religious reasons. However the irrigations on the following Saturday and Sunday lifted both 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 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 (Figs. 4 and 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

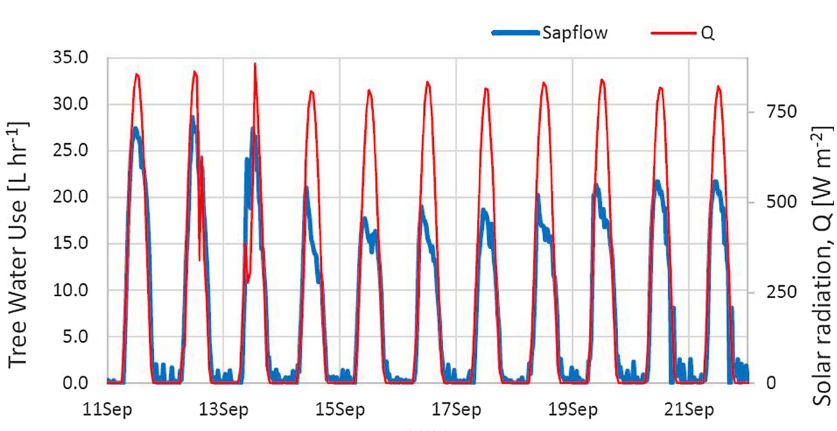

Fig. 5. The pattern of tree water-use (ET_c, L d^{-1}) of date palm Tree 3 at the International Center for Biosaline Agriculture (ICBA) near Dubai, UAE, as measured by the compensation heat-pulse method (blue line) every 30 min over 11 days in mid-September 2016 for treatment S1 (5 dS m^{-1}). The irrigation 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. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

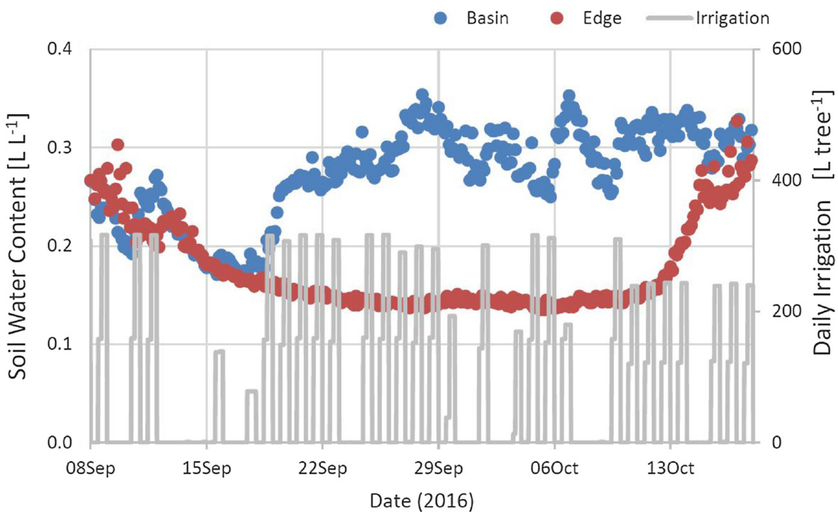

Fig. 6. The volumetric soil-water content (left axis, L L^{-1}) measured by two, 1 m long Time Domain Reflectometer (TDR) rods around Lulu date palm Tree 3 in the S1 treatment (5 dS m^{-1}). One set of rods was located within the irrigation basin (blue dots), whereas the other was just on the distal 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. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

management of water and salt are imperatives for best irrigation practice, more especially so in hyper-arid and saline environments.

3.2. 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 Fig. 7.

Whereas the peak tree water-use in the S1 treatment was, in mid-summer, about 190 L d^{-1} (Fig. 4), for the S3 treatment the peak water use was just 130 L d^{-1} (Fig. 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.

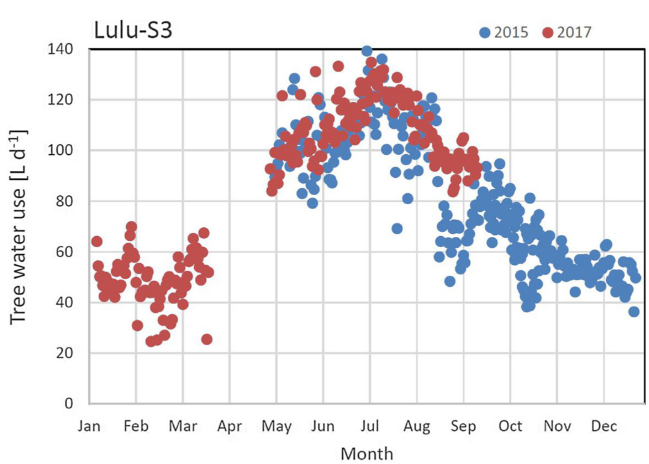

Fig. 7. The average daily tree water-use (ET_c, L d^{-1}) of the date palm trees (Trees 2 and 3: variety Lulu) at the International Center for Biosaline Agriculture (ICBA) near Dubai, UAE, as measured by the compensation heat-pulse method over the year 2015 (blue dots) and 2017 (red dots) for treatment 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. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

3.3. 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 ETc to one of the trees in each treatment. The CS655 probes were calibrated in the laboratory and the results for the four soil solution ECs and the three levels of soil-water content are shown in Fig. 8.

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. (2)),

$$EC = \frac{ECb + 0.829 - 2.964\,\theta - 6.953\,\theta^2}{0.087}. \tag{2}$$

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 Fig. 9.

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 corroborates our 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).

3.4. 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 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}.

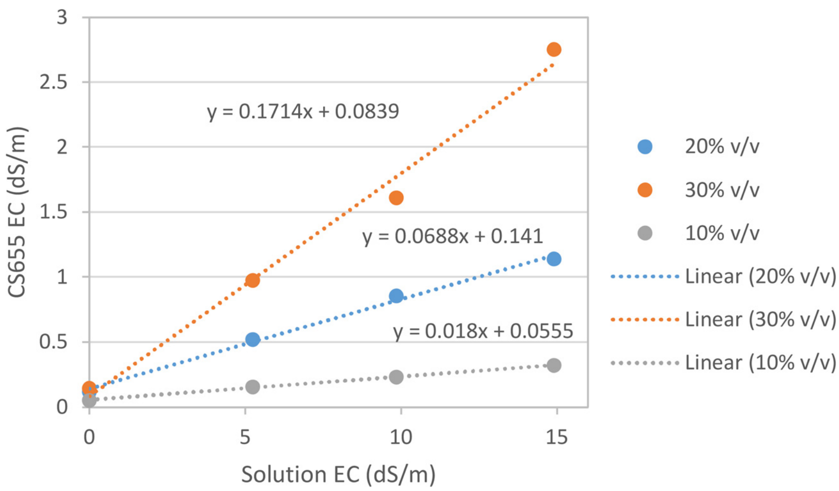

Fig. 8. Laboratory calibration data for the Campbell CS655 time domain reflectometer (TDR) probes. Sand from the field site was mixed with 4 different saline solutions (0, 5, 10 and 15 $dS\,m^{-1}$) and 3 different volumetric water contents (θ = 0.1, 0.2 and 0.3 $L\,L^{-1}$). The calibration for determining 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 contentθ.

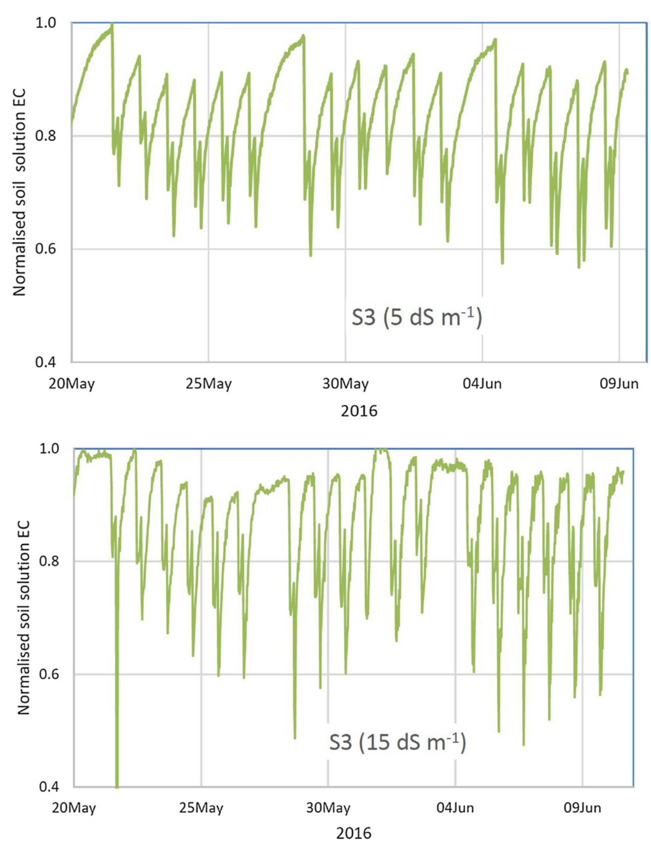

Fig. 9. Top. The normalised, soil-solution electrical conductivity EC (EC/EC_{max}) predicted from the water content (θ) and bulk soil electrical conductivity EC_b for a tree in the S1 (5 $dS\,m^{-1}$) treatment (top), and in the S3 treatment (15 $dS\,m^{-1}$) (bottom). These data was for a period during mid-May in 2016. The irrigation regimes, *I*, for both trees, were on weekly average $I = 1.5\,ET$c, 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 15–27 cm 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.

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 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 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

3.5. *Light stick and canopy light interception*

The results from the intensive use of the light stick on the 19th September 2015 are shown in Fig. 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 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

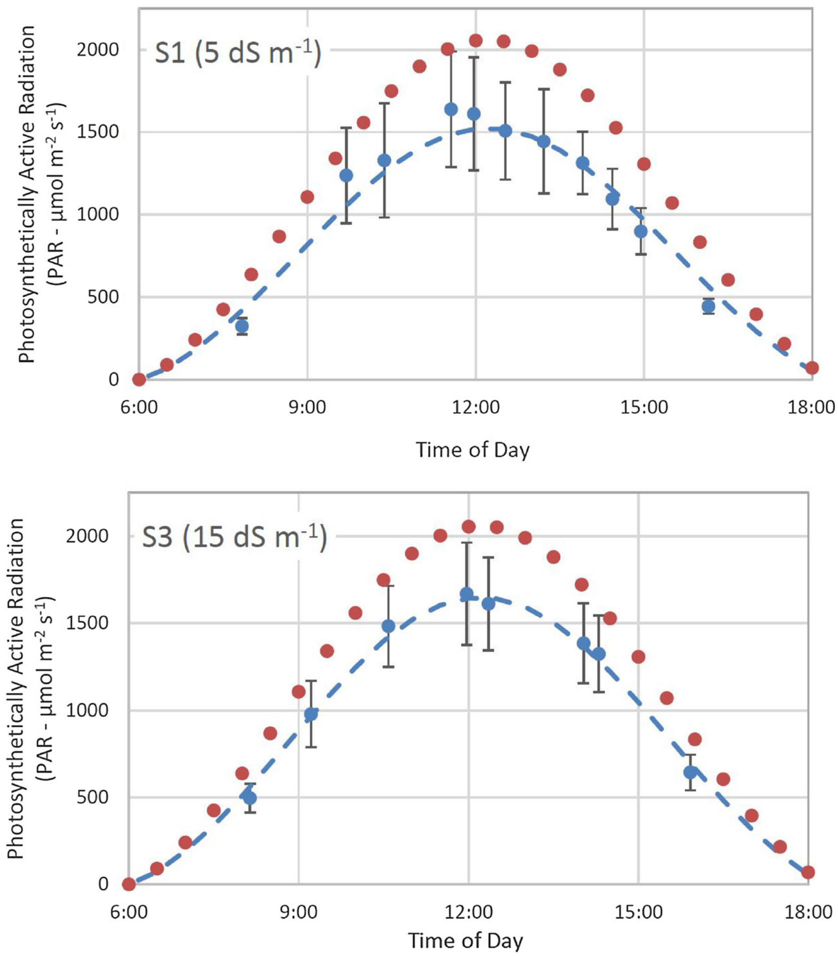

Fig. 10. The photosynthetically active (PAR, µmol m^{-2} s^{-1}) radiation from the sky over 19th September 2015 (Day of Year, DOY 262) (red dots), in relation to the PAR measured under the canopy using a light stick. Top: Measurements of the transmitted PAR under the canopies of the S1 trees during 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%. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

provides us with a good measure of the palm trees' canopy characteristics, and tree performance.

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 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 2
The average light interception (*LI*, %) values that we have measured with the light stick from Fig. 10, along with the crop coefficient *Kc* [-] 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 *Kc* 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

3.6. 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 *Kc* 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 3. In annual sum, the average daily water-use of the S1 trees is 140 L day^{-1}. Using the seasonally adjusted 1.5 ET_c allocation would

Table 3
The monthly average of the daily water use of date palms (ET_c) in L/day for irrigation with groundwater (GW) at 5 dS m^{-1}. This is taken from the 2016 envelope curve in Fig. 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 ETc of the S3 trees being 65% of those in S1. Current practice is to apply 275 L day^{-1} to all trees on every day of the year, except there is no irrigation on Fridays.

Month	Tree water use, ET_c L day^{-1}	Irrigation GW @ 5 dS m^{-1} L day^{-1}	Irrigation GW @ 15 dS m^{-1} L day^{-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

provide, on annual average, a daily application of 210 L day^{-1}, some 25% less than the current application of 275 L day^{-1}, and a saving of 25%. For the smaller S3 trees, the annually averaged daily water allocation need only be 137 L day^{-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 × 8 m, 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.

4. Conclusions

Currently saline groundwater is used in the UAE to irrigate date palms. The common practice is to irrigate each tree with 275 L day^{-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 day^{-1} in summer, and down to 80 L day^{-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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