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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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ABSTRACT

Direct measurement of sap flow enabled determination of the seasonal pattern of water use, *ET*c, of three date (*Phoenix dactylifera* L.) varieties irrigated with groundwater at different salinities: S1 at 5 dS m^{-1} and S3 at 15 dS m^{-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 $Kc\ LI^{-1}$ 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. 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}. 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'. Analysis of the consumed water productivity, *CWP* (kg-dates kL^{-1}) provides insight into the impacts of salinity on date yield. 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.

1. 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 the less salt-tolerant crops of 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

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Table 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 dS m^{-1}	Trunk height m	Number branches	Branch length m $branch^{-1}$	Total branch length m $tree^{-1}$	Date Yield 2017 kg $tree^{-1}$	Date Yield 2012-15 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

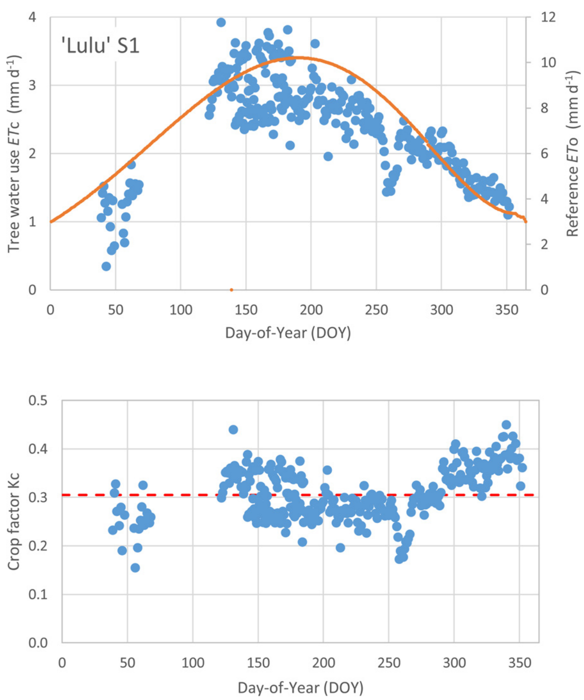

Fig. 1. Top. The 'Lulu' S1 treatment (5 dS m^{-1}) tree water-use, *ETc* (mm d^{-1}), as measured using sap-flow monitoring (blue dots, left axis). The data are presented in relation to day-of-year (DOY) and comprise measurements over 2.2 years from 20/5/2015 through until 4/7/2017. These data extend 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, *ETo*, from the FAO-56 method is shown as the redline (right axis). Bottom. The seasonal pattern throughout the year in the crop factor, *Kc* (= *ETc* / *ETo*), derived from the data above, with the red-dotted line being the annual average *Kc*. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

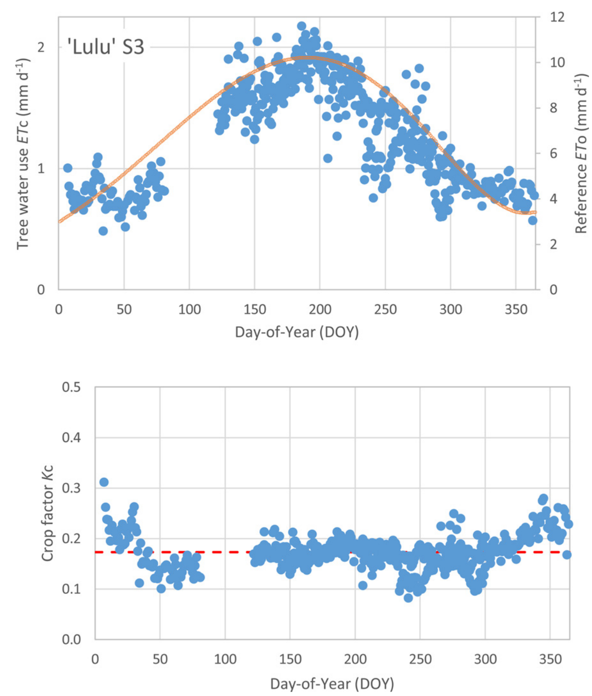

Fig. 2. Top. The 'Lulu' S3 treatment (15 dS m^{-1}) tree water-use, *ETc* (mm d^{-1}), as measured using sap-flow monitoring (blue dots, left axis). The data are presented in relation to day-of-year (DOY) and comprises measurements over 1.7 years from 4/5/2015 through until 19/1/2017. These data extend 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, *ETo*, from the FAO-56 method is shown as the red line (right axis). Bottom. The seasonal pattern throughout the year in the crop factor, *Kc* (= *ETc* / *ETo*), derived from the data above, with the red dotted line being the annual average *Kc*. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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). Groundwater 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 (Ministry of Environment and water (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'. Richards (1954) asserted that date palms are the most salt tolerant of any fruit crop. However, 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, *ETc* (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

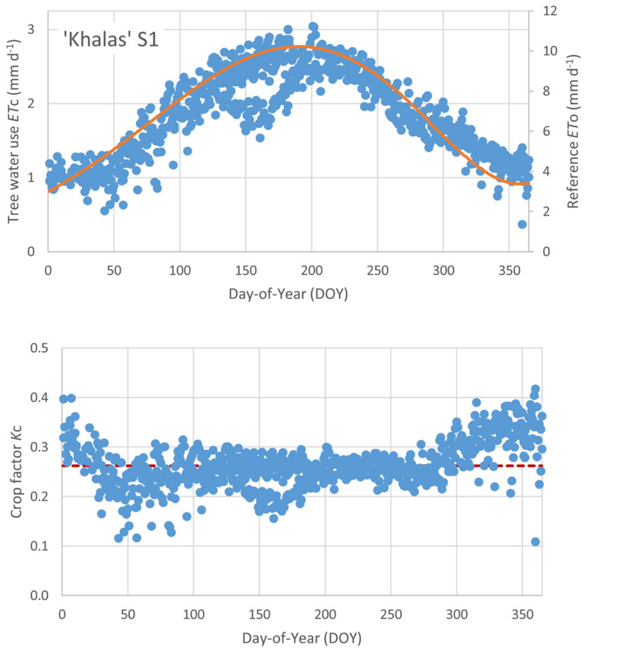

Fig. 3. Top. The 'Khalas' S1 treatment (5 dS m^{-1}) tree water-use, *ET*c (mm d^{-1}), as measured using sap-flow monitoring (blue dots, left axis). The data are presented in relation to day-of-year (DOY) and comprise measurements over 2.3 years from 4/5/2015 through until 16/9/2017. The conversion 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. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

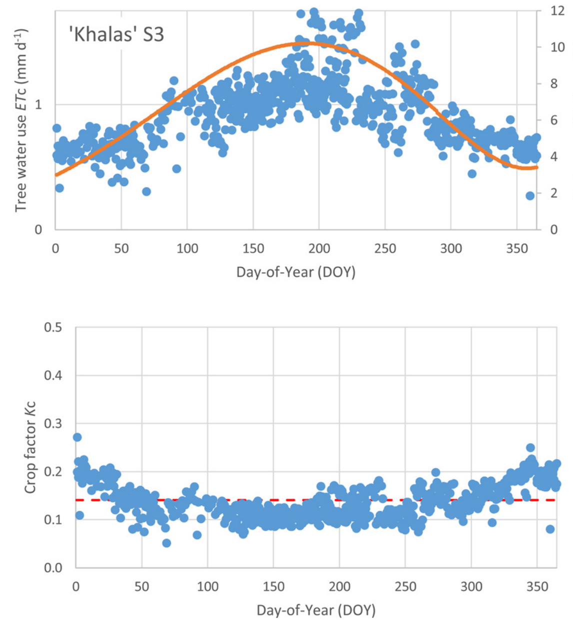

Fig. 4. Top. The 'Khalas' S3 treatment (15 dS m^{-1}) tree water-use, *ET*c (mm d^{-1}), as measured using sap-flow monitoring (blue dots, left axis). The data are presented in relation to day-of-year (DOY) and comprise measurements over 2.3 years from 4/5/2015 through until 16/9/2017. The conversion 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. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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 over-watering 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 only the two rates of irrigation water salinity of 5 (S1) and 15 (S3) 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*, using the approach of Goodwin et al. (2015).
- 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.

2. 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.

2.1. Study site

Our experiments were carried out over the years 2015–2017 at the International Centre for Biosaline Agriculture (ICBA) (25.09 °N;

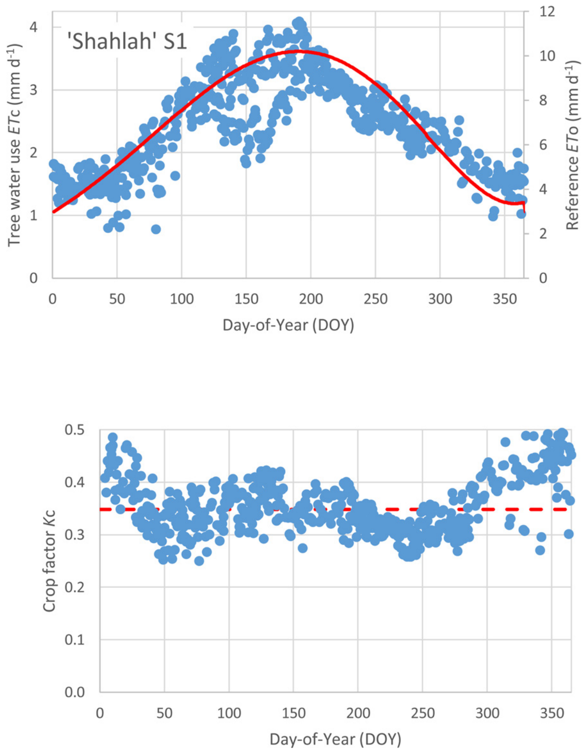

Fig. 5. Top. The 'Shahlah' S1 treatment (5 dS m^{-1}) tree water-use, *ET*c (mm d^{-1}), as measured using sap-flow monitoring (blue dots, left axis). The data are presented in relation to day-of-year (DOY) and comprise measurements over 2.3 years from 4/5/2015 through until 16/9/2017. The conversion 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. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

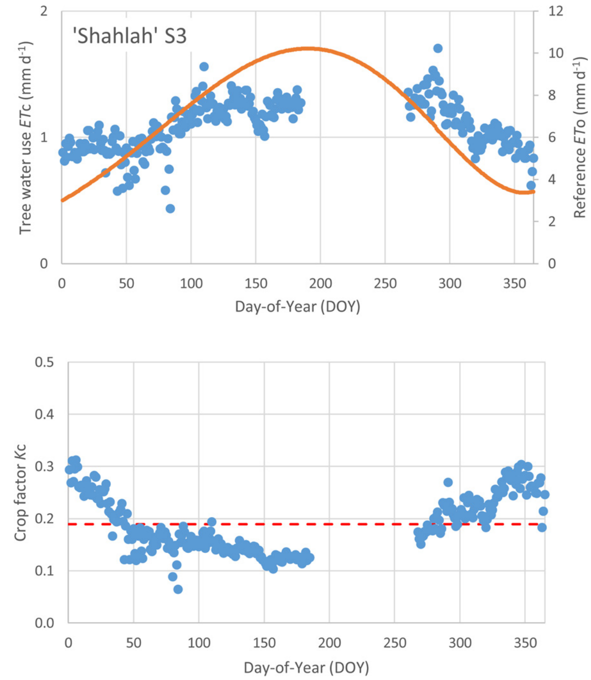

Fig. 6. Top. The 'Shahlah' S3 treatment (15 dS m^{-1}) tree water-use, *ET*c (mm d^{-1}), as measured using sap-flow monitoring (blue dots, left axis). The data are presented in relation to day-of-year (DOY) and comprise measurements over 2.2 years from 4/5/2015 through until 4/7/2017. The conversion 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. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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}. Over several years, the hourly pattern of *ET*c 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 (*ET*o) 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. (1)):

$$ETc = Kc * ETo, \tag{1}$$

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 *ET*o. Here we used our measurements of *ET*c and *ET*o to compute the daily pattern of *K*c over several years for the three varieties and the two rates of irrigation-water salinity.

2.2. 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 2012–2015 inclusive.

2.3. Light stick

A hand-held light stick (Al-Muaini et al., 2019a) was used to record proximally the percentage of visible light being transmitted through the canopy via a series of understory transits. The percentage of light intercepted at just above the surface of the desert sand, 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.

2.4. Water productivity

To gain insights into the differing salt tolerances of the three

Table 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 Figs. 1–6, 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 Figs. 7 and 8 for the other two date varieties.

Variety and Salt Tolerance	Irrigation Salinity dS m^{-1}	Annual *ET*c kL y^{-1} $tree^{-1}$	Leaf Area m^2 $tree^{-1}$	Light Interception *LI* [-]	Crop Factor, Kc [-]	Ratio *Kc* LI^{-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

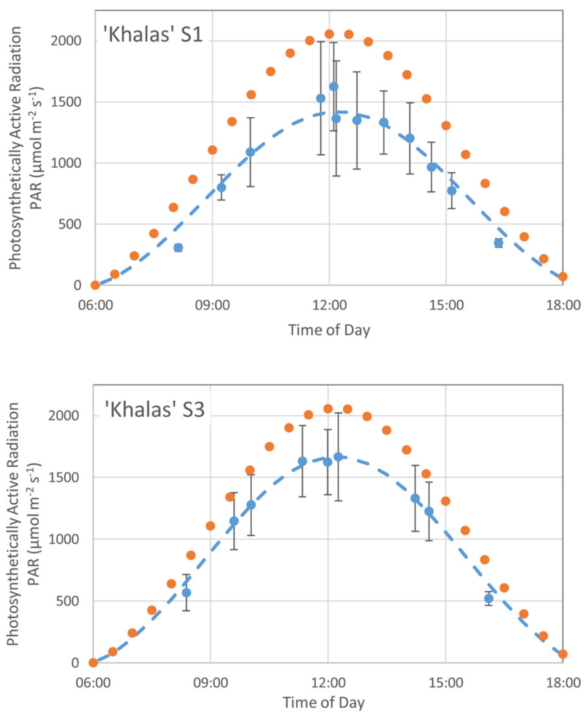

Fig. 7. Top. The photosynthetically active (PAR, μmol m^{-2} s^{-1}) radiation from the sky over 19 September 2015 (Day of Year, DOY 262) (red dots), in relation to the PAR measured under the canopy of the 'Khalas' S1 treatment (5 dS m^{-1}) using a light stick (blue dots). The light interception, *LI*, 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. The vertical bars are the standard deviations in the instantaneous measurements of PAR measured during each transit. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

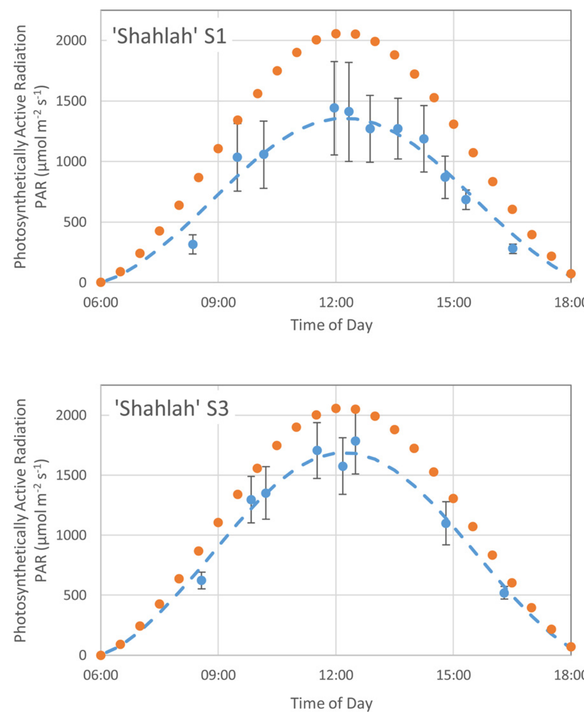

Fig. 8. Top. The photosynthetically active (PAR, μmol m^{-2} s^{-1}) radiation from the sky over 19 September 2015 (Day of Year, DOY 262) (red dots), in relation to the PAR measured under the canopy of the 'Shahlah' S1 treatment (5 dS m^{-1}) using a light stick (blue dots). The light interception, *LI*, 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 vertical bars are the standard deviations in the instantaneous measurements of PAR measured during each transit. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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 definitions and 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, since soil-water evaporation can be ignored in this hyper-arid desert. 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 (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.

Table 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 1, and the annually consumed water-use ETc comes from Table 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 kg tree^{-1}	Consumed Water Use, ETc kL tree^{-1}	Consumed Water Productivity, CWP kg kL^{-1}	Salinity Ratio (S3/S1) of CWP [-]
'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

3. 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 Kc values for the varieties. We then show it is possible to predict Kc 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.

3.1. 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 1). There were similar reductions in the other canopy characteristics of the palm trees, as listed in Table 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.

3.2. 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 results for the daily values of ETc and Kc in Figs. 1–6 on single graphs using day-of-year (DOY) as the abscissa. There are some gaps in our daily ETc 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 ETc (Figs. 1–6), 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 ETc and ETo, so the left-hand ordinate axis is scaled for each graph to show how ETc tracked the seasonal pattern in ETo. 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 ETc peaked at over 4 mm d^{-1}, and the smallest was for 'Khalas' S3 where the peak ETc was just 1.75 mm d^{-1}.

The data for the graphs of Kc used the quotient of measured ETc / ETo, and all the ordinate axes range from 0 to 0.5.

3.2.1. 'Lulu'

The patterns of ETc and Kc for the salt-tolerant 'Lulu' S1 treatment are shown in Fig. 1. Whereas the peak ETo was about 12 mm d^{-1}, the peak ETc 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 ETc. The trace of Kc in Fig. 1 revealed a slight rise in Kc late in the year, which we consider to be due to a seasonal growth of leaf area in autumn. The average daily Kc for 'Lulu' S1 was 0.31 (± 0.05) (Table 2).

The ETc and Kc results for 'Lulu' S3 are shown in Fig. 2, and the rates of water use were just under about half of those of the S1 treatment, with the average Kc being 0.17 (± 0.03) (Table 2). Again there was a rise in Kc in late October, and now a drop in Kc 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 Kc 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 2), a drop of 43%.

3.2.2. 'Khalas'

The 'Khalas' trees are smaller (Table 1) and have a lower leaf area (Table 2) than the equivalent 'Lulu' trees. Their rates of ETc were correspondingly less (Figs. 3 and 4). Within the variability resulting from difficulties with irrigation management the rates of ETc tracked ETo. The annual average Kc 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 Kc 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 2).

3.2.3. 'Shahlah'

The salt-intolerant 'Shahlah' S1 trees had the largest leaf area per tree (Table 2), whereas the S3 trees had the smallest leaf area per tree of all trees. The seasonal patterns of ETc and Kc were similar to those of the other two varieties (Fig. 5 and 6). The S1 Kc was 0.35 (± 0.05), the largest of all treatments, whereas the Kc of the S3 treatment was 0.19 (± 0.05) (Table 2).

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

3.3. 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, Kc, was close to the annual average value (Figs. 1–4). 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 2). Here, in Figs. 7 and 8, we present the results for 'Khalas' and 'Shahlah' at the two salinities.

The transits with the light stick shown in Figs. 7 and 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 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 Kc LI^{-1} for 'Khalas' and 'Shahlah' were very similar (Table 2). On average for all varieties and salinity treatments, the mean Kc LI^{-1} was 0.95. That this value is not too dissimilar to 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 $Kc\ LI^{-1}$ being 0.4-0.6. Al-Yamani et al. (2019b). They found $Kc\ LI^{-1}$ to be just 0.1 for the hardy and woody xerophytic Al Samr tree (*Acacia tortilis*).

The values of $Kc\ LI^{-1}$ 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 $Kc\ LI^{-1}$ 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.

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.

3.4. 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 3, along with the respective date yields, *Y*. The computed *CWP* revealed an interesting pattern with salinity by variety (Table 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 $dS\ m^{-1}$.

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. One UAE Dhs is currently worth US $0.27 (February 2019). This analysis provides an economic 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 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).

4. 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 $Kc\ LI^{-1}$ 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 ($\approx$ 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.

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