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The impact of replacing groundwater by treated sewage effluent on the irrigation requirements of Al Ghaf (*Prosopis cineraria*) and Al Sidr (*Ziziphus spina-christi*) forests in the hyper-arid deserts of Abu Dhabi

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ABSTRACT

The arid forests of Abu Dhabi are valuable but they require irrigating. Currently groundwater (GW) is the source of this water, but these subterranean reserves are being over-exploited. Law No 5 of 2016 on the regulation of GW has been passed by the Government of Abu Dhabi to reduce GW abstraction. Abu Dhabi has a supply of tertiary-treated sewage effluent (TSE) that could be used as an alternative for irrigation. We set up experiments near Madinat Zayed in the Al Dhafra region of Abu Dhabi on two arid-forest species: Al Ghaf (*Prosopis cineraria*) and Al Sidr (*Ziziphus spina-christi*). The trees were planted at 8 m x 8 m spacing. The TSE is significantly 'sweeter' than GW, as its electrical conductivity is < 1 dS m^{-1}, whereas GW is 8–10 dS m^{-1}. The GW in this region is very high in nitrates (38.4 ± 9.2 mg-NO$_3$ L^{-1}), and this was not significantly different from the TSE (53.7 ± 11.8 mg-NO$_3$ L^{-1}). We monitored the actual tree water-use (*ETc*, L h^{-1}) via heat-pulse devices in both the GW and TSE-irrigated trees. We quantified the differences in the *ETc* patterns for both the GW and TSE-irrigated trees of both species over 3 years. Both species showed positive growth-responses to TSE, relative to the GW, and we consider this to be due to the lower electrical conductivity of the TSE water. Because of this growth response the *ETc* of the TSE by the Ghaf trees was, on annual average 17% higher than GW, and for the Sidr it was 39%. Our results were corroborated by leaf conductance and leaf-area inferences. But for TSE there is no need for a salt-leaching fraction. Furthermore, to achieve the same tree-health outcome as with the GW, even less TSE need be applied. Irrigation requirements for TSE were at least 25% less than for GW.

1. Introduction

Abu Dhabi's arid forests are located in a hyper-arid desert, where annual precipitation is less than 50 mm, and annual potential evapotranspiration exceeds 2000 mm. Despite these harsh desert conditions, the first president of the United Arab Emirates (UAE), H.H Sheikh Zayed Al Nahyan sought to establish many forests to realise the valuable ecosystem services delivered by the trees. This 'greening of the desert' began in the 1970s. Abu Dhabi's forests now cover about 3.5% of the Emirate. The total number of trees is around 20 million trees, and thanks to irrigation with groundwater (GW), some 80% of these forests are classified in good condition.

The annual GW consumption for irrigation of the current forests is estimated to be about one quarter of total GW extractions. Meanwhile, conserving GW is imperative for food security, cultural heritage, and the environment of Abu Dhabi. In November 2016, the General Secretariat of the Executive Council of the Abu Dhabi Government issued Law No. 5, officially declaring that the Emirate of Abu Dhabi owns the GW reserves, and that its extraction and use would be governed by the rules, standards and conditions set out by Environment Agency – Abu Dhabi (EAD). Law No.5 will help to manage the demand for GW and ensure reserves into the future (EAD, 2017).

In an earlier paper (Al-Yamani et al., 2018) we described our experiments on the irrigation of Al Ghaf and Al Sidr by saline GW with an electrical conductivity (EC) of 8–10 dS m^{-1}. From our results and analyses we provided EAD with new GW irrigation allocations for Law 5 based on direct measurements of tree water use (*ETc*), plus a factor-of-safety of 25%, and a salt-leaching fraction of 25% (Al-Yamani et al.,

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2018). Adoption of this allocation regime will result in GW savings of up to 40% in forest irrigation.

1.1. Treated sewage effluent

However, even greater savings are required to protect GW reserves, so the Abu Dhabi government has recently started new initiatives to understand better the status and the pressure on the more than 100,000 groundwater wells in the Emirate. This strategic assessment now involves seeking ways to reduce pressure on GW by finding alternative sources for irrigation. The UAE has been collecting and treating sewage since 1973, and this tertiary-treated TSE is derived from desalinated water. Across the hyper-arid states of the Gulf Cooperation Council (GCC) there is an emerging interest in using TSE for irrigation in agriculture, and for its use in watering amenity plantings (Al-A'ama and Nakhla, 1995; Al-Zubari, 1998). Treated sewage effluent is 'sweeter' than GW, in the sense of salt. The EC of TSE is generally $< 1\ \mathrm{dS\,m^{-1}}$, some tenfold lower than GW. The TSE comes from residential and municipal sources, trade water-use, plus some storm-water runoff and rainfall. There are more than 60 wastewater treatment plants in the UAE, and the majority of these are in Abu Dhabi. Most of these treatment plants use advanced technologies to treat the sewage water to a tertiary level. Currently some TSE is used for irrigation of amenity vegetation, but still a significant volume of TSE is disposed of into the Arabian Gulf. The Government has a plan to achieve full usage of TSE for irrigation.

1.2. Objectives

The goal of the work outlined here was to provide EAD with guidelines to aid in the implementation of Law 5 in terms of irrigation requirements, impacts on tree health, and GW savings, through the use of TSE to irrigate two major species of arid forest: Al Ghaf (*Prosopis cineraria*) and Al Sidr (*Ziziphus spina-christi*). The research objective was to quantify the water-use ET_c (L d^{-1}, or mm d^{-1}) of Al Ghaf and Al Sidr trees irrigated with TSE, so that new allocation guidelines can be developed for Law 5 for this alternative water source. The ET_c of the TSE-irrigated trees is compared to that of those GW trees previously described in Al-Yamani et al. (2018). We also sought to determine what controls the differences in the ET_c between the GW and TSE-irrigated trees, and to quantify the impact of TSE on both tree performance and soil health. In Al-Yamani et al. (2018) we provided irrigation allowances that would minimise the use of GW to irrigate the trees, and here we sought to do the same for TSE so that maximum benefit can be made of this valuable alternative source of water. Furthermore, we describe the use of our 'light stick' to infer the fractional light interception (*LI*) of the GW and TSE trees. This *LI* enables their crop factor, K_c, to be estimated, so that the FAO-56 model (Allen et al., 1998) can be used to predict the tree's *ET*c simply from the reference evapotranspiration ET_o using $K_c\ ET_o$.

2. Materials & methods

The major native species of the hyper-arid forests of the Abu Dhabi desert are the Ghaf, Sidr, Arak and Samr. Here we discuss irrigation experiments on mature plots of Al Ghaf and Al Sidr trees. Both tree species in our experimental plots were irrigated either with GW or TSE.

2.1. Research site

This research was carried out within the Khub Al Dahs forest (23.51 °N, 53.75 °E) near Madinat Zayed in the Al Dhafra region of the western desert of Abu Dhabi. Al-Yamani et al. (2018) have provided a complete description of the site and the experimental set-up, so only salient details are repeated here. The soil is a Typic Torripsamment, mixed, hyperthermic (Soil AD158) (EAD, 2009; Shahid et al., 2014). It is a deep, sandy soil that is widely distributed across 75% of the UAE. A large proportion of the managed forests in the UAE are on this type of soil.

Two experimental sites were established. One site consisted of 12 Al Ghaf trees and the other 12 Al Sidr trees. Within each plot, six trees in a single row were irrigated with GW, and in the neighbouring row six trees were irrigated with TSE. The botanical details of the Ghaf and Sidr trees are provided in Al-Yamani et al. (2018). Also, as described in Al-Yamani et al. (2018), sapflow sensors were installed in four trees of each treatment to provide a continuous record of the trees' transpiration ET_c (L d^{-1}) using the compensation heat pulse velocity method (Green et al., 2003). The sapflow devices were installed in the Ghaf trees in December 2014, and during February 2015 for the Sidr trees. The TSE treatments on both tree species began on 18 May 2015.

Automated irrigation systems were used at both experimental sites to control the irrigation using GW and TSE. Two tanks, each of 22,730 litres, were located at both the Ghaf and Sidr sites. One tank at both sites was continuously filled with GW having a salinity of 8–10 dS m^{-1}. The other tank at both sites were filled every month with TSE provided by the Abu Dhabi Sewerage Services Company. The source of the TSE was domestic TSE from the city of Madinat Zayed, which has a population of 30,000. The EC of the TSE water was always much less than 1 dS m^{-1}. The water from both of these large header tanks was then transferred separately to smaller tanks each of 2273 litres to help with the mixing of the water to reduce salinity variations. Each system was operated daily for 6 h, beginning early in the morning. Flow meters were used to monitor the applied aliquots of water. Pressure-compensated drippers were used with two 4 L h^{-1} drippers per tree. Thus, each tree received about 60 L d^{-1}, on each day throughout the year. The irrigation strategy was however changed in the last year of the experiment, 2017, as we discuss later.

2.2. Weather monitoring

Khub Al Dahs forest has a meteorological station that records high-frequency weather data including global shortwave radiation (LI-COR 1200, LI-COR Inc., Lincoln, Nebraska 68504-5000, USA), air temperature and relative humidity (Vaisala HMP 45C, HMP 45C, F1-00421 Helsinki, Finland), wind speed at 3 m (Maximum 3-cup anemometer), and rainfall (Pronamic 101, 6950 Ringkobing, Denmark).

These weather data were used to compute the hourly and daily values of the reference evaporation (ET_o, mm hr^{-1}, or mm d^{-1}) using the FAO-56 approach of Allen et al. (1998). The transpiration rate of the trees (ET_c, mm hr^{-1}, or mm d^{-1}), as measured by the sapflow sensors, was then related to ET_O via the crop-factor, K_C [-] using

$$ET_c = K_c.\ ET_o. \tag{1}$$

2.3. Soil, water, and leaf analyses

Samples of the irrigation water, soil, and the leaves were collected from both the GW and TSE trees at appropriate times. Chemical and microbiological analyses on the soil and water sampled were carried out by the commercial company Exova Ltd in Dubai (www.exova.com). Leaf samples were analysed by United Arab Emirates University in Al Ain.

2.3.1. GW and TSE water analyses

There are more than 40 wells in Khub Al Dahs forest. The GW in Al Ghaf experimental site is pumped from a different well than the one in Al Sidr experimental site.

Water samples were collected directly from dripper outlets while the irrigation was on. Two water samples were collected from both the GW and TSE lines at the Al Ghaf and Al Sidr sites in 2015 at the initiation of the TSE application, and a second sampling was done at the end of 2017.

2.3.2. Soil analyses

The first soil samples, labelled as the reference, were taken in February 2015. These were taken inside the same forest, and close to, but just outside of the experimental plots. We collected a total of six soil samples, three of them were taken directly under the dripper at depths of 10, 20 and 40 cm, and the other three samples were taken on the edge of the wet zone around the dripper.

Soil samples were collected three more times during the experiments: in December 2015; December 2016; and finally in December 2017. These soil samples were also collected from directly under the dripper and at the edge of the wetted zone. They were taken from around two guard trees located at the respective ends of the experimental rows, so as to avoid disturbing the soil around the experimental trees. The guard trees were under the same irrigation regime as the experimental trees.

2.3.2.1. Chemical analyses. After examining the results of the soil chemistry obtained between the guard trees, and between the edge of the drip-zone and directly under it, we decided to group the results as there were no differences between these groupings.

2.3.2.2. Microbiological analyses. Laboratory analyses were carried out on these soil samples for Enterococci (CFU 100 m L^{-1}), faecal coliforms (CFU 100 m L^{-1}), and helminth eggs (eggs L^{-1}) to assess the risks of the use of TSE on human health.

2.3.3. Leaf analyses

Leaf samples from Al Ghaf and Al Sidr were collected from the experimental trees. We took a random selection of leaves, about 10–20 from each tree, from around each quadrant of each tree. Leaf sampling was done at four times: in 2015, 2016, 2017 during the period of April-June, and the final group of samples were taken on December 2017.

2.4. Leaf Conductance

A diurnal sequence of leaf conductance, g_c (mmol m^{-2} s^{-1}), was carried out of the Sidr trees on the 26 September 2017, as this was the time at which trees' leaf area was near its maximum. The measurements were made from mid-morning through to mid-afternoon using a steady-state porometer (LI-1600, LI-COR Inc., Lincoln, Nebraska 68504-5000, USA) to measure the g_c. Because of the small and pinnate nature of the leaves of Al Ghaf, it was not possible to measure the g_c of those leaves. The coriaceous Sidr leaves are hypostomatous, with the stomata present only on the lower surface of the leaves

2.5. The light stick

Given the lower EC, we anticipated that the TSE would most likely have a beneficial impact on tree growth and tree health. Our measurements of tree water-use, ET_c, would, we hypothesised, reflect this change in tree performance. However, we also sought a simpler means of inferring this response, and one that would have greater utility by measuring the tree canopy characteristics that might be affected by TSE. This would also extend to assess the impact of GWs of different salinities.

Lang (1987) developed a method of using the transmittance of the sun's beam through a tree's canopy to infer the canopy leaf area. Canopy radiation interception can be estimated from static, or mobile, arrays of quantum sensors using Beer's Law. Extending the method of Lang and McMurtrie (1992), we have developed a small, hand-held 'light stick' that can be used in an understory transit to record the percentage of light being transmitted through the canopy. The light-intercepted fraction (LI) from these light stick measurements provides a measure of the canopy size and leaf area density. The small light stick (Tranzflo NZ Ltd, Palmerston North, NZ) is 200 mm long, with 4 equi-spaced quantum sensors that are sensitive to photosynthetically active radiation (PAR). The light stick was held horizontally just above the sand surface, and then in a 'sweeping' motion the interior of each of the tree's shadow area was traversed completely so that the light transmittance could be determined. The length and breadth of the perimeter of each tree's shadow area were measured at the same time. From time-of-day, the zenith and azimuth angles of the sun are known, and it is then possible to compute the effective tree-shadow area (Lang and McMurtrie, 1992). From the light stick's measure of transmittance, and given the tree spacing, we thus can infer the *LI* fraction by the leaves and woody structures that have intercepted the incoming radiation. Both the TSE and GW trees were measured for both species and this was carried out April, May, September, and December. These dates would enable us to capture the changing leaf areas of the trees at the beginning of leaf-fall, the maximum defoliation, and the maximum leaf area, respectively.

The light stick was used here to determine the impact of TSE on the changed growth habit of the Ghaf and Sidr trees that had previously been irrigated with GW. Also the *LI* is linked here to the crop factor, *K*c, we inferred directly from the sap flow measurements.

3. Results and discussion

3.1. Water, soil and leaf results

3.1.1. Water

The main differences between GW and TSE waters lay in their salt chemistries. The electrical conductivity of the TSE was less than 10% of that of the GW. The anion and cation chemistries reflected the high content of salts in the GW (Table 1).

Interestingly, especially from the perspective of plant growth, there is no significant difference between the nitrate contents in the GW and TSE. Both were very high, and well in excess of health guidelines for potable water. Fragaszy and McDonnell (2016) reported that high levels of nitrate occur naturally in the groundwater around Liwa, due to the low rates of plant uptake, high leaching, and the accumulation of precipitation-derived evaporites.

3.1.2. Soil

3.1.2.1. Chemistry. The key results for the salt chemistry found on

Table 1
The average properties of both the groundwater (GW) and treated sewage effluent (TSE) used for the irrigation of the Al Ghaf and Al Sidr trees. Samples were collected from the irrigation lines in both in 2015 and again in 2017. Using a t-test, here ns is statistically 'not significant' ($P > 0.05$) and *** is high significance ($P < 0.001$).

Al Ghaf and Al Sidr Water Analyses		Groundwater	Treated Sewage Effluent	
	Units	Mean and Standard Deviation		
Inorganic Parameters				
Conductivity	mS/cm	7.5 (0.9)	0.8 (0.04)	***
pH Value @ 20 °C	pH units	7.9 (0.1)	7.9 (0.3)	ns
Anions				
Bicarbonate	mg/L	67.1 (4.7)	73.2 (4.0)	ns
Carbonate	mg/L	5.0 (0.1)	2.2 (0.3)	***
Nitrate	mg/L	38.4 (9.2)	53.7 (11.8)	ns
Sulphate	mg/L	778.3 (38.7)	65.3 (19.5)	***
Chloride	mg/L	1972.5 (372.1)	126.0 (13.1)	***
Phosphorus	mg/L	–	2.6 (0.2)	
Cations				
Calcium	mg/L	189.5 (29.5)	31.8 (4.6)	***
Magnesium	mg/L	77.0 (14.8)	4.5 (0.6)	***
Sodium	mg/L	1272.0 (189.4)	95.9 (3.7)	***
Potassium	mg/L	48.2 (7.5)	12.0 (1.2)	***
SAR		19.8 (3.4)	4.8 (0.9)	***

Table 2
The salt chemistry for the soil samples under the drippers of the groundwater (GW) and treated sewage effluent (TSE) irrigated Al Ghaf and Al Sidr trees. Here ECe is the electrical conductivity of the saturated paste extract, and SAR is the sodium adsorption ratio. Using a t-test, here ns is statistically 'not significant' ($P > 0.05$), * is low significance ($P < 0.05$), ** is medium significance ($P < 0.01$), and *** is high significance ($P < 0.001$).

		pH		ECe (dS/m)		SAR	
Al Ghaf	**GW**	7.6 (0.2)	ns	6.3 (3.7)	***	10.9 (3.6)	**
	TSE	7.5 (0.3)		2.4 (2.6)		5.4 (7.5)	
Al Sidr	**GW**	7.9 (0.3)	*	8.4 (9.4)	**	16.1 (14.6)	***
	TSE	7.7 (0.3)		1.9 (1.4)		4.4 (2.8)	

saturated paste extracts are given in Table 2.

The salinity and the sodicity (Sodium Adsorption Ratio, SAR) values for soil samples taken under Al Ghaf and Al Sidr trees are higher in the soil irrigated with GW, than in the soil irrigated with TSE. This is to be expected because of the different salt chemistries of the two irrigation sources (Table 1). An interesting finding from the soil salinity values is that there is no build-up of salinity in the soil around the drippers. This confirms the in situ findings using EC probes we described in Al-Yamani et al. (2018). The salt leaching fraction of 25%, with a factor-of-safety of 25%, appeared effective at leaching the salts from the dripzones of the GW-irrigated trees.

In addition to this salt chemistry, we determined the total nitrogen content of the soil wetted by the respective irrigation waters (Table 3). There were no differences in soil nitrogen content between the GW-irrigated soil, and the TSE-irrigated soil, and this was the same for both the Al Ghaf and Al Sidr trees. The high amounts of soil nitrogen reflect the high concentrations of nitrate in both the GW and the TSE waters, and the similarity in the nitrate concentration between these two irrigation sources. Thus it is not possible to attribute any differences in plant growth and performance to nitrogen nutrition.

We also carried out analyses of the soil concentrations of heavy metals and metalloids (Table 4). The results were equivocal. The only differences between the GW and TSE soil concentrations for the Ghaf were for zinc, chromium and fluoride, and all were highly statistically significant. The only differences between the soils at the Sidr site were for chromium (low significance) and fluoride (medium significance). In all cases, the GW-irrigated soil that had the higher concentrations.

3.1.2.2. *Soil microbiology*. No helminth eggs were found in the wetted soil of either treatment. Enterococci and faecal coliforms were found in virtually all samples from both treatments. There were no significant differences between the concentrations of either the Enterococci and faecal coliforms between the GW and TSE treatments. Thus, it would seem that the Enterococci and faecal coliforms are naturally occurring, and not derived from human sources via just the TSE. This forest is home to herds of desert gazelles, and there is abundant bird-life. These would seem to be the origin of these microbes. However, both plots had been fenced off for three years. So it would seem that the communities of these microbes are now living autonomously in the soil, as has been found elsewhere (Byappanahalli and Fujioka, 1998). Hartz et al. (2008)

Table 3
The total nitrogen content of the soil measured on saturated paste extracts for the wetted soil under the groundwater (GW) and treated sewage effluent (TSE) irrigated Al Ghaf and Al Sidr trees. Here ns is statistically 'not significant' ($P > 0.05$).

	Total Nitrogen (mg/kg)		
Al Ghaf	**GW**	443 (189)	ns
	TSE	495 (389)	
Al Sidr	**GW**	326 (141)	ns
	TSE	334 (127)	

Table 4
The soil concentration (mg kg^{-1}) of various metals and metalloids in the groundwater (GW) irrigated soil, and the treated sewage effluent (TSE) irrigated soil under both the Al Ghaf trees and Al Sidr trees. Using a t-test, here ns is statistically 'not significant' ($P > 0.05$), * is low significance ($P < 0.05$), ** is medium significance ($P < 0.01$), and *** is high significance ($P < 0.001$).

Element (mg/ kg)		Zn		V		Mn		Pb		Cu		Co		Cr		As		F		Fe		Al		Ni	
Al Ghaf	**GW**	30.8 (17.8)	***	10.2 (2.2)	ns	112.4 (21.8)	ns	2.0 (0.4)	ns	5.6 (2.3)	ns	2.0 (0.3)	ns	21.0 (7.4)	***	1.4 (0.3)	ns	2.3 (1.1)	***	3238.0 (579.3)	ns	2703.5 (423.0)	ns	11.3 (1.9)	ns
	TSE	15.0 (8.9)		9.5 (1.5)		110.5 (16.1)		2.5 (2.3)		4.6 (2.8)		1.9 (0.2)		14.3 (4.3)		1.3 (0.2)		1.1 (0.3)		3177.5 (447.2)		2630.0 (370.8)		11.5 (1.9)	
Al Sidr	**GW**	15.6 (7.0)	ns	9.7 (1.8)	ns	110.5 (21.6)	ns	1.7 (0.2)	ns	4.2 (1.4)	ns	2.0 (0.3)	ns	15.7 (2.7)	*	1.2 (0.2)	ns	1.3 (0.9)	**	3207.0 (514.4)	ns	2644.5 (350.0)	ns	10.9 (1.7)	ns
	TSE	14.9 (8.5)		8.9 (2.1)		107.1 (23.7)		1.6 (0.3)		3.5 (0.8)		1.8 (0.4)		13.2 (4.2)		1.3 (0.2)		0.7 (0.2)		2994.0 (562.1)		2429.5 (420.2)		10.3 (1.8)	

Table 5

Analysis of the nutrient status of leaves sampled from both Al Ghaf and Al Sidr trees irrigated with either groundwater (GW) and treated sewage effluent (TSE). Using a t-test, here ns is statistically 'not significant' ($P > 0.05$), and * is low significance ($P < 0.05$).

		Al Ghaf			Al Sidr		
		Groundwater	Treated Sewage Effluent		Groundwater	Treated Sewage Effluent	
Leaf Nutrients	Units	Mean and Standard Deviation					
Nitrogen	mg/kg	1.9 (0.3)	1.9 (0.3)	ns	2.4 (0.3)	2.1 (0.5)	*
Phosphorus	mg/kg	1056 (304)	1129 (268)	ns	1056 (244)	1121 (252)	ns
Potassium	mg/kg	6396 (1388)	6937.8 (1485.5)	ns	7317 (1972)	8030 (1753)	ns

reported on the survival potential of Enterococci and faecal coliforms in sub-tropical beach sand. From our results, it now seems that they can also survive in the drip-zones of irrigated desert sands. The use TSE for irrigation of amenity forests would therefore seem not to pose a risk to human health.

3.1.3. *Leaf*

The bulked results in relation to the leaf macro-nutrients are given in Table 5.

There were no significant differences in P and K values between the irrigation treatments for both Al Ghaf and Al Sidr. There was a difference of low statistical significance between the leaf N concentrations in Al Sidr trees. But it was the GW-irrigated trees that had the higher N amounts. Thus we conclude that any differences that we observed between the TSE and GW irrigated trees were not due to the amounts of nutrients in the TSE-irrigated trees.

3.2. Al Ghaf transpiration – GW and TSE

Sap flow data for the four GW irrigated Ghaf trees began on 12 December 2014, and continued over three years through until early 2018 (Fig. 1). The daily measured tree water use values, *ET*c (L d^{-1}), are presented along with the daily values of the reference evapotranspiration, *ET*o (mm d^{-1}) The first two years of these data were presented by Al-Yamani et al. (2018), and we present the extended three-year data set here for completeness to enable comparison with the TSE values (Fig. 2). The TSE treatment began on 18th May 2015.

Over the last 7 months of 2015, despite the TSE being applied to the treatment trees, there was no difference in their *ET*c relative to that of the GW trees. Both the GW and TSE patterns of *ET*c tracked *ET*o. However, during the early months of 2016, the TSE trees' *ET*c increased relative to previous tracking with *ET*o, and became relatively greater than the *ET*c of the GW trees. This divergence became clearer when we calculated and compared the crop factors, *K*c, for the GW and TSE trees. In Fig. 3 is shown the annual variation in the *K*c of the GW trees and this data set comprises over 3 years of daily measurements, which is one more year than the equivalent data set previously presented by Al-Yamani et al. (2018). There was a muted seasonal pattern due to the asynchrony of the deciduous behaviours of the various trees. Peak leaf area occurred in December-January, and there was leaf fall in February. Over the 3 years the annual average *K*c for the GW trees was 0.110 (± 0.03, n = 1127).

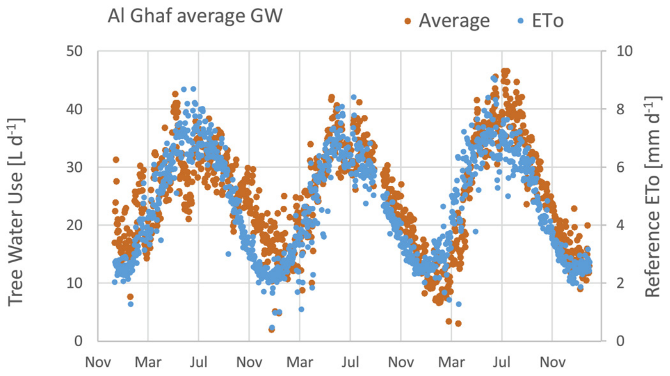

Fig. 1. The seasonal pattern from 2015 to early 2018 of the average of the daily water-use *ET*c (red dots, left axis in L d^{-1}) from measurements made every 30 min on all four groundwater (GW) irrigated Al Ghaf trees in relation to the reference evapotranspiration *ET*o (blue circles, right axis in mm d^{-1}). This GW water-use data extends by the year the results presented by Al-Yamani et al. (2018) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

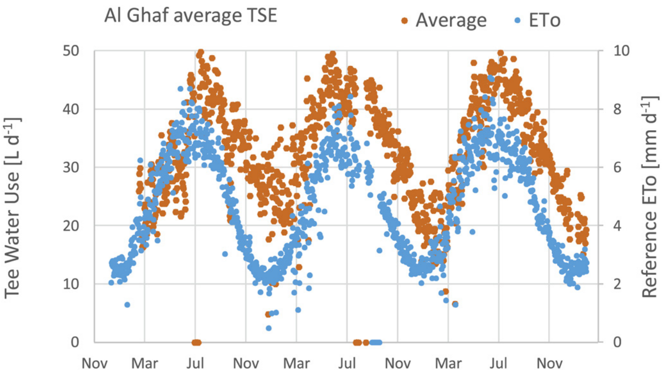

Fig. 2. The seasonal pattern from 2015 to early 2018 of the average of the daily water-use *ET*c (red dots, left axis in L d^{-1}) from measurement made every 30 min on all four treated sewage effluent (TSE) irrigated Al Ghaf trees in relation to the reference evapotranspiration *ET*o (blue circles, right axis in mm d^{-1}). The TSE treatment began on 18th May, 2015 (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

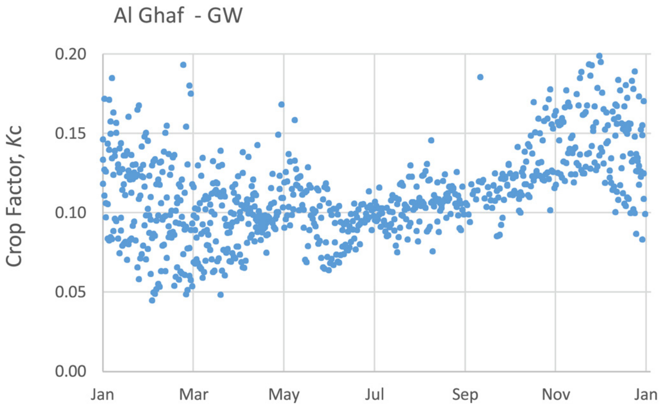

Fig. 3. The average daily crop-factor, *K*c (=*ET*c/*ET*o), for the Ghaf trees irrigated with groundwater (GW) over the three years of 2015 through to early 2018. These *K*c data include an extra year's results from those presented by Al-Yamani et al. (2018).

The annual seasonal patterns in the *K*c values for the TSE trees are shown in Fig. 4 for the calendar years of 2015, 2016 and 2017. Unlike

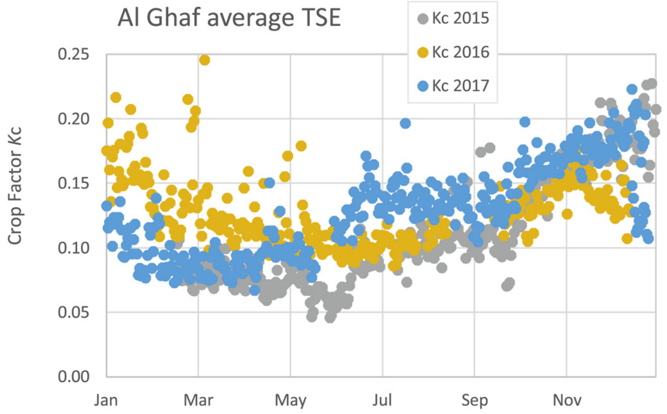

Fig. 4. The average daily crop-factor, *K*c (=*ET*c/*ET*o), for the Ghaf trees irrigated with treated sewage effluent (TSE) over each of the years 2015 (grey dots), 2016 (yellow dots), and 2017-early 2018 (blue dots). The TSE irrigation began on 18th May 2015, and previously the trees had been irrigated with groundwater (GW) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

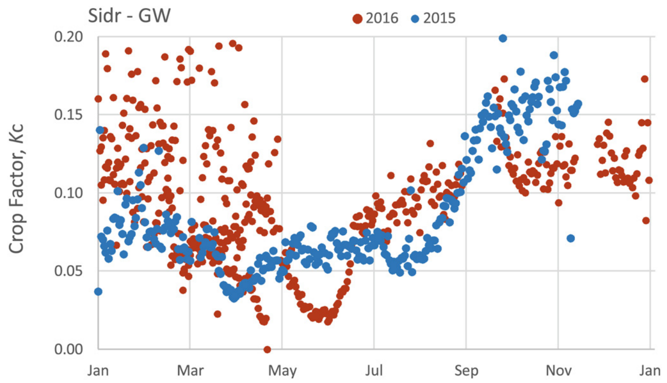

Fig. 5. The average daily crop-factor, *K*c (=*ET*c/*ET*o), for the Sidr trees irrigated with groundwater (GW) over each of the years 2015 (blue dots), and 2016 (red dots). These 2015–2016 data were presented by Al-Yamani et al. (2018) without separating the years. Here we have separated the years 2015 and 2016 to show the difference in the *K*c during an 'on' year for vegetative vigour (2016) and an 'off' year for vegetative vigour (2015) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

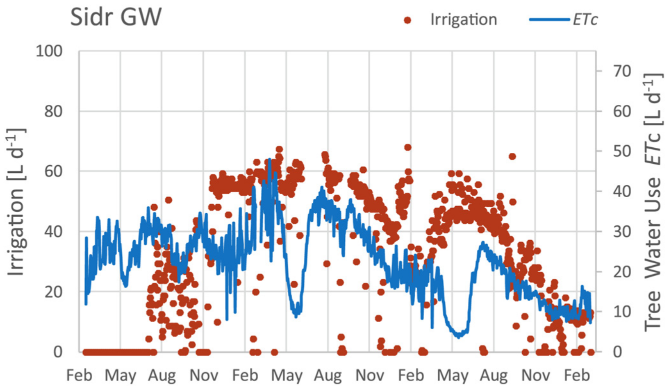

Fig. 6. The daily average water-use of the groundwater (GW) irrigated Sidr trees, *ET*c (blue line, L d^{-1}), from measurements every 30 min made over the years 2015 until early 2018. Also shown is the amount of water applied on average to each of the trees (red dots) as measured using an in-line flowmeter. A zero reading here often indicates a flowmeter malfunction rather than an absence of irrigation (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

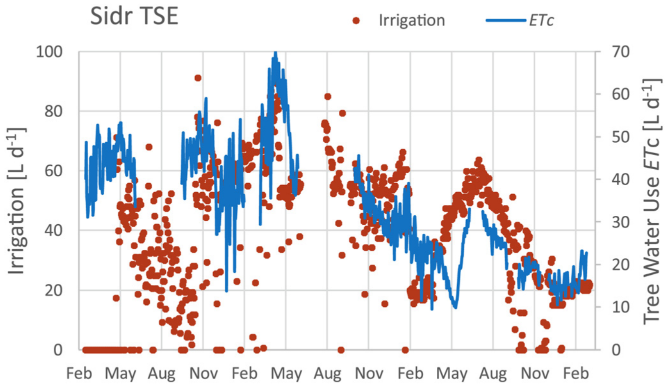

Fig. 7. The daily average water-use of the treated sewage effluent (TSE) irrigated Sidr trees, *ET*c (blue line, L d^{-1}), from measurements every 30 min made over the years 2015 until early 2018. Also shown is the amount of water applied on average to each of the trees (red dots) as measured using an in-line flowmeter. A zero reading here often indicates a flowmeter malfunction rather than an absence of irrigation. The TSE irrigation began in May 2015, and previously the trees had been irrigated with groundwater (GW) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

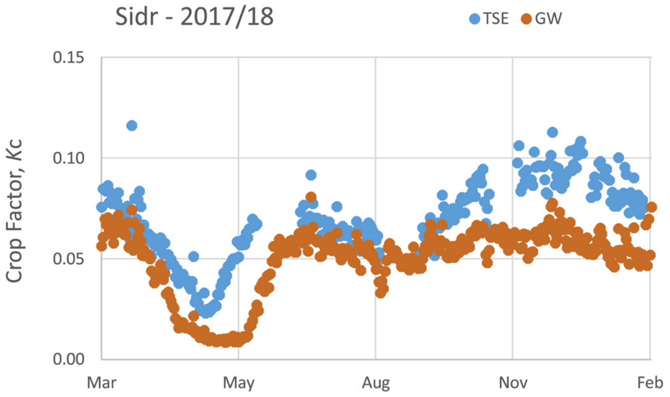

Fig. 8. The average daily crop-factor, *K*c (=*ET*c/*ET*o), for the Sidr trees irrigated with groundwater (GW - orange dots) and treated sewage effluent (TSE – blue dots) over of the years 2015, 2016, and 2017-early 2018. The TSE irrigation began in May 2015, and previously the trees had been irrigated with GW. During the year 2017-18, irrigation was restricted to 1.5 *ET*c (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

for the GW trees (Fig. 3) there was a separation in behaviours between years for the TSE trees (Fig. 4). The annual average *K*c for 2015 for the TSE trees was 0.112 (± 0.03, n = 309), which was no different from that of the GW trees. However, in the year after beginning TSE irrigation there was greater vegetative vigour, and less defoliation, especially during January-May 2016. The 2016 annual average *K*c was 0.127 (± 0.027, n = 310) which was significantly ($P < 0.001$) higher than the 2015 average value. For 2017, the annual average *K*c was 0.129 (± 0.035, n-358), which was not significantly different from the 2016 value.

Thus our sap-flow measurements have revealed that TSE increased the trees' leaf growth such that the *K*c of the TSE trees became 17% higher than that of the GW trees. We were not able to discern any visual differences between the treatment trees, and this difference was made detectable only through our sap-flow measurements.

3.3. Al Sidr transpiration – GW and TSE

Our measured *ET*c for each of the four multi-stemmed Sidr trees was

Fig. 9. Left. Al Sidr Tree 5 that is groundwater irrigated (GW). Right. Al Sidr Tree 8 which is treated sewage effluent irrigated (TSE). These photographs were taken on 26th April 2017 at a time of maximum deciduous leaf fall.

computed using our baseline measurements of sapflow in the four monitored trees of each treatment. Before we began to analyse the impact of TSE on the water use of the Sidr trees, we re-visited the crop-factor results of Al-Yamani et al. (2018) for the GW-irrigated trees. Al-Yamani et al. (2018) presented the 2015 and 2016 *K*c data as one; here we have split the two years to show the difference in the vegetative vigour between the years (Fig. 5). It can be seen that January to April 2015 was an ‘on’ fruiting year, with low vegetative vigour, whereas 2016 was an ‘off’ fruiting year, with high vegetative vigour. The fruit, when they drop to the ground, provide food for the desert gazelles. The ‘on-off’ year behaviour in 2015 and 2016 affected the comparison we wished to make with the TSE trees immediately upon commencement of the treatment.

In Figs. 6 and 7 we present the actual average tree water uses, *ET*c (L d^{-1}), of the GW and TSE Sidr trees, Also shown in these figures are the actual daily amounts of irrigation applied to each of the trees, noting that a zero value does not always mean ‘no irrigation’ because sometimes there was a flowmeter malfunction. By comparison of Figs. 6 and 7, it can be seen that in early 2015 the *ET*c of the TSE trees was already greater than that of the GW trees before the TSE treatment was commenced on 18th May. This difference was due to the lower vegetative vigour of the GW trees in the ‘off’ fruiting year of 2015 (Fig. 5).

During 2016, we provided EAD with advice that considered the sustainable irrigation of arid forest trees would be at the rate of 1.5 *ET*c, allowing for a factor-of-safety of 25%, and a salt-leaching fraction of 25%. We decided to test this schedule experimentally on the Sidr trees in 2017. Figs. 6 and 7 shows the reduced rates of irrigation with a summer peak rate of irrigation dropping to about 45 L d^{-1}.

Thus the 2017 data provide us with a good comparison of the impact of TSE on Al Sidr tree water use. Over the year from 1 March 2017 to 1 March 2018, we applied an average of 30 L d^{-1} of irrigation to the GW trees, and 33 L d^{-1} to the TSE trees. So within our ability to manage the irrigation, we essentially applied the same amount of water to both treatments of around 30 L d^{-1}, being half of what is current practice of 60 L d^{-1}. Over that year, the GW trees transpired on annual average 14.4 (± 3.0) L d^{-1}, whereas the TSE trees transpired on average 20.0 (± 7.2) L d^{-1}, a rate that was 39% higher. Therefore, TSE irrigation could be even further reduced below 30 L d^{-1}, to achieve a similar ‘tree-health’ outcome as the GW trees.

In Fig. 8, we show the seasonal trend in the respective crop factors over 2017-18 for the GW and TSE-irrigated trees. As expected the *K*c for the TSE trees was always higher than that of the GW trees. Furthermore, the deciduous loss of leaves in early April was not as severe for the TSE trees, and the re-emergent leaf growth occurs sooner, and more vigorously, in May. Under this reduced-irrigation regime, the annual average *K*c for the GW trees was 0.056, whereas it was 0.070 for the TSE trees.

In Fig. 9, we show the comparison between two trees and their maximum deciduous defoliation. Tree 5 (left) is a GW-irrigated tree, and Tree 8 (right) is TSE irrigated. There were more viable and greener leaves on the TSE tree at this time. In Fig. 10, we show these same two trees at a time when they were approaching their maximum leaf area in late September. The greater leaf area of the TSE tree is obvious, and we draw attention to the differing sizes and light ‘densities’ of the respective tree shadows.

3.4. *Leaf Conductance, gc*

During mid-morning to mid-afternoon on the 25 September 2017 we carried out measurements of g_c on the GW and TSE Sidr trees. For the TSE trees we found the average g_c to be 17.7 mmol m^{-2} s^{-1} (SE ± 2.2, n = 19) and that for the GW trees was 8.1 mmol m^{-2} s^{-1} (SE ± 1.5, n = 17). The difference was significant ($P < 0.05$). The GW trees had a lower g_c, presumably as a result of their lower and more negative osmotic water potential resulting from the irrigation with

Fig. 10. Left. Al Sidr Tree 5 that is groundwater irrigated (GW). Right. Al Sidr Tree 8 which is treated sewage effluent irrigated (TSE). These photographs were taken on 26th September 2017 at a time of maximum canopy leafiness.

more saline groundwater. This difference in g_c would explain the different tree productivities (Figs. 9 and 10). Both these conductance values are very low, as befits a xerophytic halophyte like Al Sidr (*Ziziphus*) growing under conditions of high temperatures combined with very low atmospheric humidity. The relative humidity was around 10% at noon and the air temperatures were > 45C. Arndt et al. (2011) reported low g_c values for *Ziziphus rotundafolia* growing under controlled conditions in pots. For their severe water-stress treatment water was withheld, and the leaf water potential dropped to -2 MPa after 20 days, at which time the osmotic potential was -2.3 MPa. Between 15 and 28 days, they measured the leaf conductance of these stressed *Ziziphus* trees to be between 5–15 mmol m^{-2} s^{-1}. Although our leaf conductance measurements were carried out only over a single day, they do indicate that the GW trees were under greater water stress than the TSE trees that were irrigated with lower salinity water. This difference in stomatal conductance would seem to account for the greater productivity of the TSE trees.

3.5. Light stick and the crop factor

The *LI* results are presented in Table 6. For the GW-irrigated Ghaf trees the *LI* was at its lowest of 0.26-0.28 during leaf-fall in April-May, and rose to 0.30 in December at the time of maximum leafiness. There was also a seasonal change in the TSE-irrigated Ghaf trees, albeit somewhat muted. The TSE trees had a significantly greater ($P < 0.05$) *LI* than the GW trees by 11%.

A similar seasonal pattern in *LI* was found the Sidr trees for both treatments (Table 6). The *LI* for the TSE trees was twice that of the GW trees, and this difference was significant ($P < 0.0001$).

The light stick clearly picked up the leaf-growth responses to TSE by both species through measuring *LI*. However, the seasonal changes in *LI* were less than anticipated from our visual observations of the changing leafiness (Figs. 9 and 10). This is due to the characteristic canopy architecture of both species. The leaves of Al Ghaf and Al Sidr (Figs. 9 and 10) are small and numerous on the many structural branches of the trees. So even during leaf fall there was a substantial degree of light interception by the woody branches of the tree (Fig. 9, left). This woodiness explains the muted seasonal response in the measured *LI* despite the changing leaf area.

Studies have linked the easily-measured value of *LI* to the crop factor *K*c in order to predict tree water-use, *ETc*, using the inferred *K*c in the formula: $ETc = Kc\ ETo$. The ratio $Kc\ LI^{-1}$ has been found to be in the range of 1–1.2 for well-watered horticultural trees (Goodwin et al., 2006; O'Connell et al., 2008; Goodwin et al., 2015; Al-Muaini et al., 2018).

The annual average *K*c values of the Ghaf trees in 2017 were 0.110 and 0.129 for the GW and TSE treatments respectively. So the $Kc\ LI^{-1}$ values are 0.39 and 0.42, much less than the 1–1.2 that has been reported. For the Sidr trees the *K*c values were 0.056 and 0.07 for the GW and TSE treatments. Their $Kc\ LI^{-1}$ values are therefore 0.62 and 0.37, which are again much less than those already reported.

We consider there are two reasons why these $Kc\ LI^{-1}$ values are less than half of those reported by others. Firstly, as noted above, there was a significant contribution of the woody branches of these arid-forest species in the measured *LI*. This woody infrastructure does not contribute to transpiration, and is not reflected in the *K*c. Secondly, both Al Ghaf and Sidr are xerophytic halophytes, and would have been under salt stress under our treatments. We measured very low leaf conductances for Al Sidr, which we considered to be typical of *Ziziphus* trees at low water potentials ($\approx$ -2 MPa) and low osmotic potentials ($\approx$ -2 MPa) (Arndt et al., 2001). Thus the ratio $Kc\ LI^{-1}$ is much lower for our arid-forest trees than the well-watered value of 1–1.2 for horticultural trees, because of water stress resulting in a lower *K*c, and because our *LI* value was higher though the influence of non-leaf

Table 6

Calculations of the trees' shadow areas from length and breadth measurements in mid-morning, and the fractional light interception (*LI*) obtained using the light-stick at various times during 2016 and 2017. These measurements are the average for the four treatment trees of each treatment for the Ghaf and Sidr experiments. The effective tree-shadow area (m^2) would be the product of the two right-hand columns.

Al Ghaf: Groundwater

Date	Shadow area (m^2)	Light interception fraction, *LI*
25 April 2017	22	0.26
26 April 2017	22	0.28
25 May 2016	22	0.27
25 September 2017	22	0.30
26 September 2017	22	0.30
9 December 2017	22	0.28
Average (± SD)		0.28 (± 0.02)

Al Ghaf: Treated Sewage Effluent

Date	Shadow area (m^2)	Light interception Fraction, *LI*
26 April 2017	23	0.30
25 May 2016	23	0.30
25 September 2017	23	0.31
26 September 2017	23	0.31
9 December 2017	23	0.31
Average (± SD)		0.31 (± 0.01)

Al Sidr: Groundwater

Date	Shadow area (m^2)	Light interception fraction, *LI*
26 April 2017	8	0.08
25 May 2016	8	0.09
25 September 2017	8	0.10
26 September 2017	8	0.09
27 September 2017	8	0.10
10 December 2017	8	0.10
Average (± SD)		0.09 (± 0.01)

Al Sidr: Treated Sewage Effluent

Date	Shadow area (m^2)	Light interception fraction, *LI*
26 April 2017	14	0.18
25 September 2017	14	0.18
26 September 2017	14	0.18
27 September 2017	14	0.19
10 December 2017	14	0.19
Average (± SD)		0.19 (± 0.004)

interception of light by the woody parts of the trees.

Nonetheless, the consistent values of $Kc\ LI^{-1} \approx 0.4\text{-}0.6$ for these arid-forest species does appear provide a simple basis for using the light-stick measurements to infer the crop factor. We are examining this further for another arid-forest species, Al Samr.

3.6. Irrigation requirements

Current practice at Khub Al Dhas forest is to irrigate both the Ghaf and Sidr trees with 60 L d^{-1} of groundwater. Implementation of Abu Dhabi's Law 5 requires that irrigation be allocated at the minimum amount required to achieve the desired goal. In Al-Yamani et al. (2018) we provided an irrigation allocation schedule for GW to both the Ghaf and Sidr trees which suggested a monthly schedule of 1.5 ETc, and this was based on 25% factor-of-safety, and a 25% salt-leaching fraction. Our results here show that with TSE, the 25% requirement for a salt-leaching fraction could be dispensed with. So for TSE the suggested schedule now becomes the 1.25 ETc column in Table 1 of Al-Yamani et al. (2018). That means that on an annual average basis, the Al Ghaf trees only need 34.9 L d^{-1} of TSE, and the Sidr trees only need 29.3 L d^{-1}. Furthermore, if the desire were to use TSE to achieve the same tree productivity as for the GW trees (Figs. 9 and 10), then this rate of TSE could be even reduced further because of the beneficial impact of the 'sweeter' TSE.

4. Conclusions

The arid forests in the hyper-arid deserts of Abu Dhabi require irrigating. Saline groundwater is the predominant source for the irrigation water, and the current practice is to irrigate Al Ghaf and Al Sidr trees using 60 L of groundwater every day of the year. In Al-Yamani et al. (2018) we proposed an allocation schedule for irrigation using saline GW which was based on 1.5 ETc, accounting for a 25% factor-of-safety and a 25% salt leaching fraction.

We now update these recommendations for TSE. These irrigated arid forests require considerably less water than current practices for both GW and TSE. The low salt content of the TSE means that far less extra water is required when using TSE instead of GW, to achieve similar plant growth to that achieved with current irrigation. These changes represent a 50–60% reduction in water application from current practices. In addition, using an alternative water source like TSE will reduce the drawing down of the finite groundwater reserves and protect the remaining aquifer stocks of water.

References

Al-A'ama, M.S., Nakhla, G.F., 1995. Wastewater resue in Jubail, Saudi Arabia. Water Res. 29, 1579–1584.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration. Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56, FAO, Rome.

Al-Muaini, Ahmed, Green, Steve, Dakheel, Abdullah, Abdullah, Al-Hareth, Abou Dahr, Wasel Abdelwahid, Dixon, Steve, Kemp, Peter, Clothier, Brent, 2018. Irrigation management with saline groundwater of a date palm cultivar in the hyper-arid United Arab Emirates. Agric. Water Manag. 211, 123–131.

Al-Yamani, Wafa, Steve Green, Pangilinan, Rommel, Dixon, Steve, Shahid, Shabbir, Kemp, Peter, Clothier, Brent, 2018. Water Use of Al Ghaf and Al Sidr Forests Irrigated With Saline Groundwater in the Hyper-Arid Deserts of Abu Dhabi. Agric. Water Manag. 203, 105–114.

Al-Zubari, W.K., 1998. Towards the establishment of a total water cycle management and re-use program in the GCC countries. Deslination 120, 3–14.

Arndt, S.K., Clifford, S.C., Wanek, W., Jones, H.G., Popp, M., 2001. Physiological and morphological adaptations of the fruit tree *Ziziphus rotundifolia* in response to progressive drought stress. Tree Physiol. 21, 705–715.

Byappanahalli, M.N., Fujioka, R.S., 1998. Evidence that tropical soil can support the growth of Escherichia coli. Water Sci. Tech. 38 (12), 171–174.

EAD, 2009. *Soil* Survey of Abu Dhabi Emirate (Vol. I. Extensive Survey). Environment Agency - Abu Dhabi, Abu Dhabi, UAE.

EAD, 2017. Water. Environment Agency – Abu Dhabi, Abu Dhabi, UAE.

Fragaszy, S., McDonnell, R., 2016. Oasis at a Crossroads: Agricultural and Groundwater in Liwa, United Arab Emirates. IWMI Project Report 15: Groundwater governance in the Arab World, pp. 72.

Goodwin, I., Whitfield, D.M., Connor, D.J., 2006. Effects of tree size on water use of peach (Prunus persica L. Batsch). Irrig. Sci. 24, 59.

Goodwin, I., Cornwall, D., Green, S.R., 2015. Transpiration of pear trees and implications for irrigation scheduling. Acta Hort. 1094, 317–324.

Green, S., Clothier, B., Jardine, B., 2003. Theory and practical application of heat pulse to measure sap flow. Agron. J. 95 (6), 1371–1379.

Hartz, A., Cuvelier, M., Nowosielski, K., Bonilla, T.D., Green, M., Esiobu, N., McCorquodale, D.S., Rogerson, A., 2008. Survival potential of Escherichia coli and enterococci in subtropical beach sand: implications for water quality managers. J. Environ. Qual. 37, 898–905. https://doi.org/10.2134/jeq2007.0312.

Lang, A.R.G., 1987. Simplified estimate of leaf area index from transmittance of the Sun's beam. Agric. For. Meteor. 41, 179–186.

Lang, A.R.G., McMurtrie, R.E., 1992. Total leaf areas of single trees of *Eucalyptus grandis* estimated from transmittances of the Sun's beam. Agric. Forest Meteor 58, 79–92.

O'Connell, M.G., Goodwin, I., Wheaton, A.D., 2008. Response of pink lady apple to irrigation estimated from effective area of shade. Acta Hort. 792, 495–502.

Shahid, S.A., Abdelfattah, M.A., Wilson, M.A., Kelley, J.A., Chiaretti, J.A., 2014. United Arab Emirates Keys to Soil Taxonomy. Springer, pp. 108.