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SUSTAINABLE IRRIGATION OF ARID FORESTS IN ABU DHABI USING GROUNDWATER AND TREATED SEWAGE EFFLUENT

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Abstract

In the early 1970s, the late Sheikh Zayed bin Sultan Al Nahyan, the founding father of the United Arab Emirates, embarked on a programme of 'greening' of the desert. The planted forests provide a variety of provisioning, regulating and cultural ecosystem services. However, the forests need to be irrigated. They are in a hyper-arid environment where annual evapotranspiration exceeds 1900 mm/y and rainfall is less than 60 mm/y. The source of the water for irrigation is currently groundwater. So low is the recharge of the aquifers that some of the groundwater currently extracted for irrigation comes directly from depletion of the groundwater reserves. And the groundwater supply is becoming more saline. Treated sewage effluent (TSE) is being considered as an alternative to groundwater (GW)

The first challenge is to establish how much water these arid-forest trees use when irrigated by GW, and to establish the minimum amount of water that is needed that will maintain a leaching fraction that will flush salts from the rootzone. The next challenge is to determine what level of the 'sweeter' TSE can be used to replace saltier GW.

In conjunction with New Zealand's Plant & Food Research and Maven Consultants, we have set up experimental plots at Madinat Zayed in the western desert of Abu Dhabi. Field experiments have already been going for over a year on Al Ghaf (*Prosopis cineraria*) and Sidr (*Ziziphus spina-christi*) trees. There are 12 trees in each plot, and six are being irrigated with GW and six with TSE. The GW has a salinity of around 8-10 dS/m, whereas the TSE is less than 1 dS/m.

We have installed heat-pulse devices to provide continuous monitoring of the trees' transpiration. Time domain reflectometry rods have been installed in the drip zone, and nearby, to monitor the soil's changing water content. Both Sidr and Al Ghaf have significantly deciduous behaviours and we have found this reduces their water requirements well below that a weather-based calculation based on *ET*o would suggest. In addition, the low salinity of the TSE is showing beneficial effects on the growth rates of both Sidr and Al Ghaf, especially so the Sidr. We are using the light stick we have developed to provide monitoring of the changing leaf area of the trees' canopies.

The goal is to develop a forest irrigation management tool to develop the most water-efficient irrigation practices possible by taking into account soil type, species, forest age, and climate.

Introduction

Arid forests are forests located in arid zones. The classification proposed by UNESCO divided arid zones into four categories, based on the ratio of the annual precipitation (P) to the annual potential evapotranspiration (PET). These are Hyper Arid Zone (P/PET ratio <0.03), Arid Zone ($0.03<P/PET<0.2$), Semi Arid zone ($0.2<P/PET<0.5$) and Semi Humid zone ($0.5<P/PET<0.75$) (De Pauw, et al., 2000).

In general, arid zones, or dry lands, have limited irregular rainfall, high temperatures and high evapotranspiration. Scarcity of water in arid zones is not the only factor which limits growth of natural forests, or makes the management of planted forests challenging. The soil in arid zones is another factor. It is mainly characterized by having fragile structure and low natural fertility, due to leaching of nutrients and weathering of minerals over a long time (FAO, 2010). Often these arid forests are located in desert regions. Due to these harsh environmental conditions, arid lands are more vulnerable to desertification. Thus forests in arid zones are important in preventing and combating desertification. Their protective functions, a regulating ecosystem service, in arid zones is more important than elsewhere. Arid forests have significant roles and deliver ecosystem services which are summarized as follows (FAO, 2010):

- Biodiversity conservation
- Habitat provision
- Soil stabilization
- Erosion and desertification control
- Climate change mitigation and adaptation
- Providing ecosystem goods such as fodder, wood, herbs and medicines
- Cultural services such a recreation and aesthetics.

Forests of Abu Dhabi

Currently, the Environment Agency - Abu Dhabi (EAD) manages 495 forest sites in the Abu Dhabi Emirate. More sites will be transferred to EAD management from the Abu Dhabi Municipalities by the end of 2016. The total area of these sites is 238,000 ha, and the total number of trees is around 19 million.

These forests are artificial and planted in the desert in late 1960s, mainly for their protective value from desertification and the "greening of the desert" which was the great initiative of our 'father', the first president of UAE Sheik Zayed. As well there are protected areas for different animal species. More than 90% of these forests depend on groundwater for irrigation, and in some areas they are being affected by shortages and the high salinity of the groundwaters.

Future Imperatives for Water Usage

Abu Dhabi's arid forests are currently imposing great pressures on groundwater quantity and quality. Moreover, some 7 forests managed by EAD are located within the groundwater "Red Zone". This is the zone in which the highest rates of ground water level decline have been recorded. In order to tackle this challenge, EAD has developed a comprehensive strategy for managing arid forests. The strategy is focused on managing the forests of Abu Dhabi in such a way to ensure their long-term environmental and financial viability so that they can deliver the ecosystem services sought from them. The main objectives in the strategy, which are related to water management and conservation, are as follows:

- When allocating water for forest irrigation, and where the infrastructure exists, or where it makes economic sense to develop the infrastructure, recycled water will be allocated first. Next will be desalinated water, and finally groundwater.
- All forestry activities - existing and future - should be as water efficient as possible
- Non-native tree species that require high volumes of water, or fresh water, should be identified and removed in a managed way.

Furthermore EAD has invoked many practical actions, and has proposed initiatives to ensure rapid implementation for these objectives. Some of these are:

- Assess the water need per plant for each of the plant species
- Assess the current opportunities for supplying the recycled water to forests
- Improve the irrigation infrastructure in order to reduce water loss.
- Update and verify the current status of the non-native trees
- Assess the financial resources required for removing non-native trees

Project Objectives

- Quantification of the irrigation needs of two important desert-forestry species: Al Ghaf and Sidr.
- Determine the impact of treated sewage effluent on Al Ghaf and Sidr using groundwater (GW; ≈ 10 dS/m) & treated sewage effluent (TSE; ≈ 1 dS/m).
- Assist with the development of a model for forestry irrigation and soil-salinity management in arid forests.

Materials and Methods

During the first year of this project, in early 2015, experiments were set up at Madinat Zayed in the western desert of Abu Dhabi. Field experiments have first been set up on Al Ghaf (*Prosopis cineraria*) and Sidr (*Ziziphus spina-christi*) trees. There are 12 trees in each plot, and 6 are being irrigated with GW and 6 with TSE. The GW has a salinity of around 8-10 dS/m, whereas the TSE is less than 1 dS/m.

The Treatments & Plans

Automatic irrigation systems have been installed at both experimental sites in the Khub AL Dahs Forest to control better and sustainably manage the irrigation. Two tanks of 5000 gallons (22,730 litres) are filled continuously with two types of water; GW with salinity of ~ 10 dS/m and TSE with salinity less than 1 dS/m. The water is then transferred into smaller tanks of 500 gallons (2,273 litres) to help with mixing water inside the tanks and reduce salinity variations. Each irrigation system is run for 6 hours daily, starting early in the morning. Filters were also installed to avoid sediment and residue accumulation. As well, flow meters record the actual amounts of irrigated water. Water is applied to trees using two pressure-compensated drippers per each tree, with each discharging at 4L/hr. Dykes were made around each dripper to help in retaining the irrigated water within the dripper zones.

The Soil's Physical Properties

The soil type in the experimental site is classified as Typic Torripsamments, mixed, hyperthermic (EAD, 2009). This type of soil is a deep, sandy soil with mixed mineralogy. The surface soil is usually loose and fine. It is excessively drained and its permeability is rapid, to very rapid (EAD, 2009).

For the purposes of managing the drip irrigation emitters, and understanding the pattern of wetting around and below the emitter, we measured the soil's hydraulic conductivity. As well, such knowledge will be important in the future for our modelling of the passage of water into, and through the soil, as well as for predicting the pattern of root-water uptake by the trees.

A mini-disk infiltrometer (Decagon Devices Inc., Pullman, Washington, USA) was used to measure the soil's near-saturated hydraulic conductivity, K (mm/hr). The 3-D flow of water from the fritted surface of the mini-disk of radius r_o quickly approaches a steady state Q_∞ ($m^3\ s^{-1}$). Wooding's equation (Wooding, 1968) conveniently describes this steady flow in relation to the disk's radius and the soil's hydraulic conductivity function – especially if it is of the form:

$$K(h) \quad = \quad K_s \exp(\alpha h),$$

where h is the soil-water pressure head (mm), K_s is the saturated hydraulic conductivity when h=0, and α is the slope of the exponential $K(h)$ relationship. From our measurements we found that the soil's saturated hydraulic conductivity is very high; K_s = 3 m/hr, and the capillarity is weak with an α of 0.02 m^{-1}. Thus gravity will dominate the water flow and the wetting pattern from the drippers will be vertically oriented.

Predicting Dripper Performance at Khub Al Dahs forest

Philip (1984) developed an analytical solution for travel times away from a surface point source discharging at rate Q (L/hr). His solution also assumed an exponential hydraulic conductivity function with a slope of α. The solution depends only on Q, α, and the soil's average water content θ.

This equation was used here to solve for the horizontal and vertical movement of the wet front under a dripper discharging at 4 L/hr at Khub Al Dahs. For a dripper discharging at Q=4L/hr, the wet front at the surface will expand to about a radial distance of 20 cm away from the dripper over about 3 hours. However the wet front directly below dripper will continue to proceed deeper into the soil, well beyond 500 mm over 3 hours, as gravity draws the water deeper over the irrigation period in this permeable soil. Given that the maximum surface extent of radial wetting is of the order 20 cm, it was decided to make a dyke of radius of 20 cm around each dripper to ensure that the wetting was contained to be circular and uniform, and so that we could obtain reliable measurements of soil water content change with our Time Domain Reflectometer (TDR) probes.

TDR Technology

Three-wire TDR rods of length 1.2 m have been installed in the drip zone, and nearby, to monitor the soil's changing water content. Because of the high salinity of the GW treatment, we had to sleeve the core rod to enable us to detect the 'echo' off the end of the rods. This 'echo' enables us to compute the soil's water content (θ). One sensor is in under the dripper, while the other sensor is 50 cm away.

Irrigation Performance

High resolution data from the TDR probes are obtained throughout the day every six hours. An example is shown in Figure 1 during March 2015 for a tree in the Al Ghaf site. These TDR data show rapid drainage and uptake of soil water from irrigation zone by the trees near to the dripper (red line), with slower changes in soil water content away from the drippers (blue line). There are no changes to soil water contents in the inter-row (green line). The "spikiness" of the dripper results are to be expected for a soil with such a high *K*s, and weak capillarity. This also means that the TDR probes just outside the drip zone remain very dry.

Usually there is no irrigation during Fridays, because it is a religious day. This occurs in most cases where irrigation is run manually. However the system here has now been shifted to an automated system at both the experimental sites. Nonetheless, especially early in the programme some issues have occurred and these resulted in some erratic irrigation patterns.

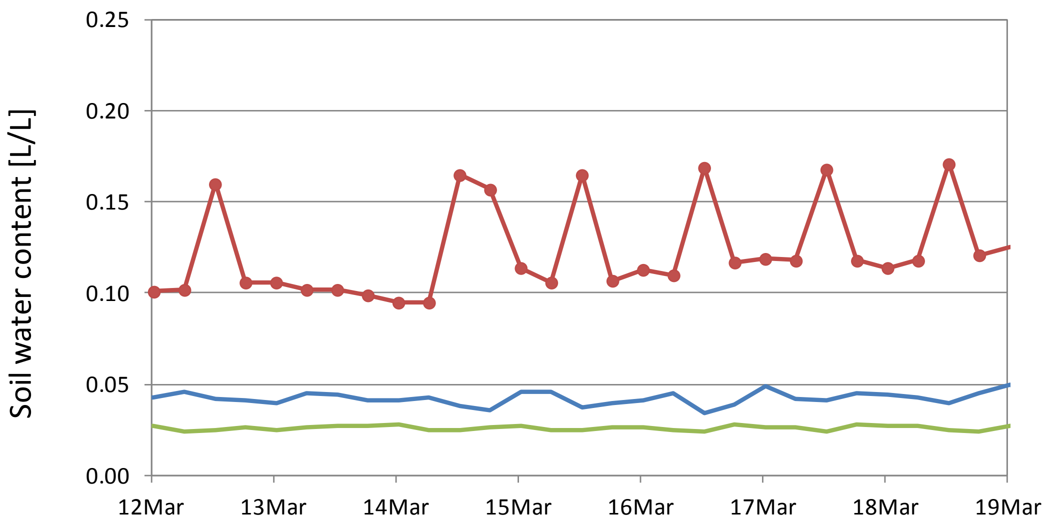

Figure 1. *The time domain reflectometry (TDR) measures of soil water content recorded every six hours at locations away from the dripper of an Al Ghaf tree.*

The Compensation Heat Pulse Velocity Method

We have installed heat-pulse devices in 8 trees per treatment to provide continuous monitoring of the trees' transpiration (*ET*c) using the compensation heat pulse velocity (CHPV) method. Two temperature probes and one heater probe were installed at various loactions in the trees. In Figure 2 can be seen the installed probes (left) and a diagrammatic representation of the CHPV method.

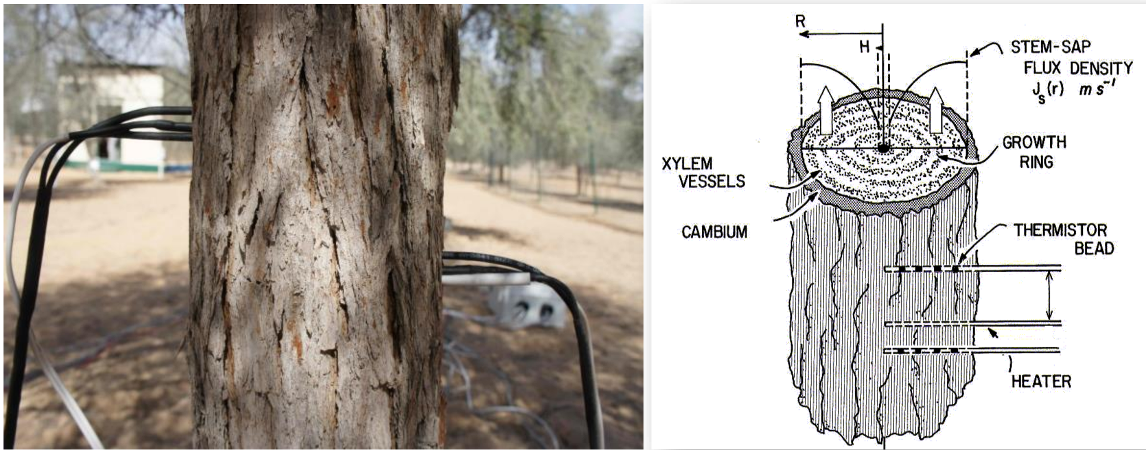

Figure 2. *The probes as installed into the Al Ghaf trunk in the experimental site in Khub AL Dahs forest (left). The diagram on the right shows how the Compensation Heat Pulse Velocity (CHPV) method can be used to infer the radial profile of sap velocity and the volumetric flow of transpiration.*

Every 30 minutes, the computer 'fires' a heat pulse so that the CHPV method can provide half-hourly measurements of tree transpiration during the day. This equipment has been running in the Al Ghaf trees since December 2014, and since February 2015 for the Sidr trees.

Results and Discussion

In order to know the amount of water required for irrigation, it is necessary to estimate two types of evapotranspiration. The first is the reference evapotranspiration, *ET*o, which is measured via the weather stations at the experimental sites. The other is the crop evapotranspiration, *ET*c, which is the quantity of water that is actually lost by transpiration from the trees. Tree transpiration, *ET*c, is measured by the sap-flow gear using the CHPV method. Because there is such a small area of soil wetted by the drippers, soil-water evaporation is ignored.

By knowing the relationship between the reference evapotranspiration, *ET*o, and trees' evapotranspiration, *ET*c, it is possible to infer the crop factor *K*c, where

$$ET\mathrm{c} = K\mathrm{c}\ ET\mathrm{o}\ .$$

This *K*c has a unique value of each tree species with different tree sizes and spacings. For an Al Ghaf tree, the *K*c found by the regression of *ET*c against *ET*o (Figure 3) gave a *K*c of 0.3.

Given this *K*c, it is then possible to predict the seasonal water use throughout the year as the daily pattern of *ET*o multiplied by *K*c. The seasonal pattern of *ET*c predicted from *K*c *ET*o for an Al Ghaf tree is shown as the blue dots in Figure 4. The predicted pattern of water use, using this singular *K*c, naturally follows the seasonal pattern of weather. Also shown in Figure 4 is the seasonal pattern of daily water use by the tree measured using the CHPV method. There is a distinct mismatch.

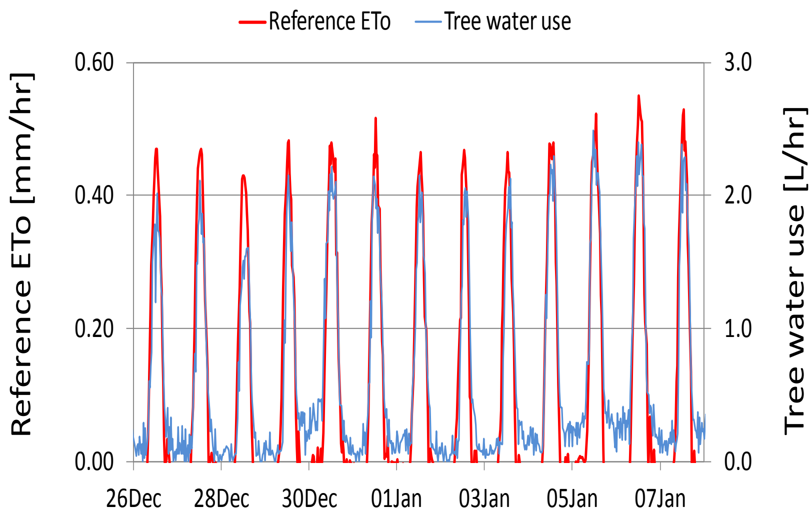

Figure 3. *Comparing sap-flow measured tree water-use in L/hr (blue line; right axis) with the reference evaporative demand ETo in mm/hr (red line; left axis) for a large Ghaf tree. Here this is just a comparison to show the parallel trends, for the axes have different units. This is discussed further in the text where the area per tree is taken into account through the crop factor Kc.*

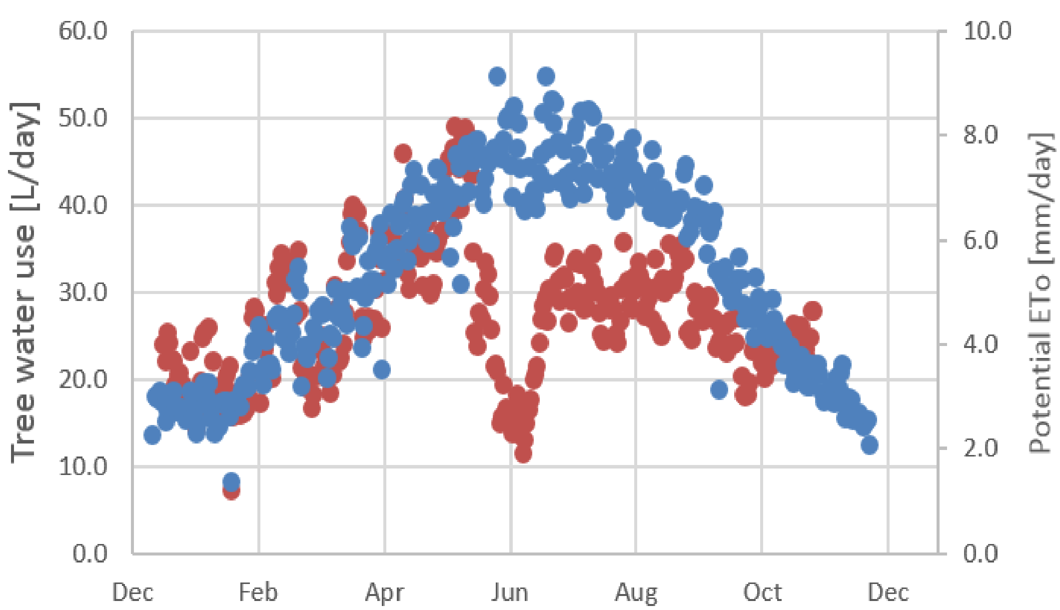

Figure 4. *The predicted seasonal variation in water use ETc for a large Ghaf Tree using Kc ETo (blue dots). Also shown is the seasonal pattern of ETc measured using the compensation heat pulse velocity (CHPV) method (red dots).*

In Figure 5 below, we show the measured daily pattern of sap flow in two Sidr trees, being the sum of the flows in the 4 instrumented stems of this multi-stemmed tree. The pattern of *ET*o over this winter to summer period would be that shown by the blue dots in Figure 4. Obviously there is a lack of coherence between our measured *ET*c and the weather controlled pattern of *ET*o. In other words, there is not a unique crop factor *K*c for Sidr either.

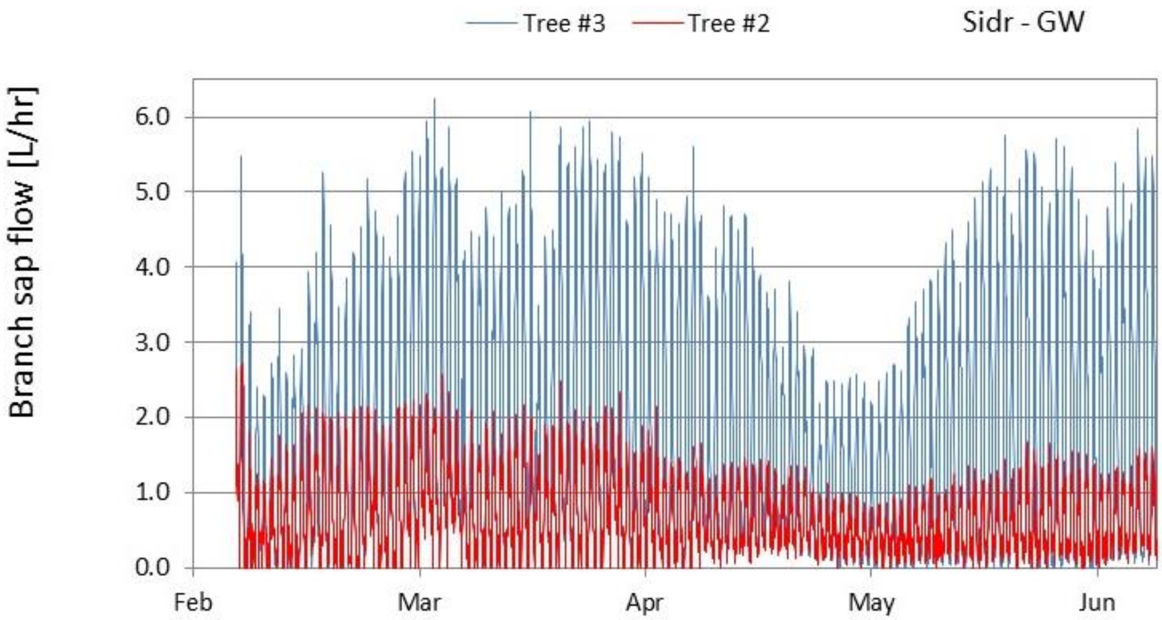

Figure 5. *The seasonal pattern of ETc measured in two Sidr trees of different sizes using the compensation heat pulse velocity (CHPV) method (red - tree #2, and blue - tree #3 lines).*

Figures 4 and 5 illustrate that both Al Ghaf and Sidr trees have different crop factors through different seasons, thereby indicating a complex seasonal pattern of water use. This is due to their natural life cycle of leaf growth, flowering and fruiting. Our field observations of tree phenology confirm this.

This seasonal pattern of leaf area means that *ET*c is decoupled from *ET*o, and so predicting *ET*c from *ET*o requires additional knowledge of the seasonal pattern of *K*c, which in turn is dependent on the canopy leaf area of the trees.

Whereas the current irrigation practice is to apply approximately 50 L/tree/day throughout the year, there will be substantial savings made possible when new practices are developed based on the findings of the variable *K*c that has been resolved here. Irrigation only need supply the pattern of the red dots in Figure 4.

Tree Water Use Results for Ghaf and Sidr

In the following sections the implications of this variable pattern of seasonal water use, and the implications for developing improved irrigation practices are discussed.

Al Ghaf

We have measured a complex seasonal pattern in tree water-use for Al Ghaf. This information are for assessing the amount of water which can be saved annually.

The peak water use is around 50 L/day, although it can be as low as 10 L/day

Currently these trees are irrigated throughout the year with approximately 50 L/day over 6 days per week. So the trees are each receiving 15,650 L/y.

However, because of deciduous behavior of the trees we find that the trees are only using 9,350 L/yr. This pattern of water use does not follow the reference *ET*o, since there is also strong season variation in the trees' leaf area (Figure 4).

So potentially, with this new knowledge, there is an irrigation saving of 6,300 L/tree/y, or some 40%. These substantial savings will be possible by matching daily irrigation amounts to take into account the seasonal pattern of *ET*o, and also accounting for the seasonal pattern in leaf area.

Due to the requirement to leach salts from the rootzone, it will not be possible to 'save' all of this water. It will depend on the salinity of the groundwater. But certainly savings can be made, and this will be the focus of future research in this programme. Of course, the salt leaching requirement does not apply to TSE. So those savings would be more realistic for TSE.

Sidr

The calculations for Sidr have yet to be completed, but the preliminary observations, based on Figure 5 suggest similar savings of the same order are possible. For the larger Sidr tree the water use in late spring is 50-60 L/day, but on May it drops to 20 L/day, before rising again as the new leaves develop.

The Impact of TSE on Sidr

The TSE treatment on both plots was initiated on May 2015. Whereas there have been no visual, or measured changes, observed for the Al Ghaf trees, the Sidr trees have shown a response to the 'sweeter' TSE (Figure 6).

Figure 6. *The impact of using irrigation with Treated Sewage Effluent (TSE-right hand side) on Sidr Trees. This response is just after applying TSE for seven months.*

The impact of TSE on the performance of the Sidr trees has been quite dramatic. Below in Figure 7 is shown a graph of the early-winter pattern of declining tree water use in Sidr trees #s 4 and 5 which are irrigated with GW. This decline is expected, as *ET*o is declining as winter approaches. Indeed, that declining pattern in *ET*o is shown as the green line in Figure 8. In Figure 8 is also shown the pattern of water use of Sidr tree #9 from the TSE treatment. For Tree #9, this tree's water use has gone from a daily peak-use of under 2 L/hr in September, up to peak use of over 3 L/hr in November (Figure 8, left-hand axis). This rise is dramatic, because over this period, with the approach of winter, the reference *ET*o has dropped from 2 mm/day down to 1 mm/day (Figure 8, right-hand axis). So despite the onset of winter and cooler conditions, Tree #9's water use has increased significantly. This increase is considered to be due to the growth of the tree's leaf area, brought about by the 'sweeter' TSE water whose salinity is about one tenth that of ground water. Our observations of the tree's leaf area, along with the others in the TSE treatment confirm this. This change in tree growth and leaf area will be monitored by the analysis of data obtained with the light-stick, as explained below.

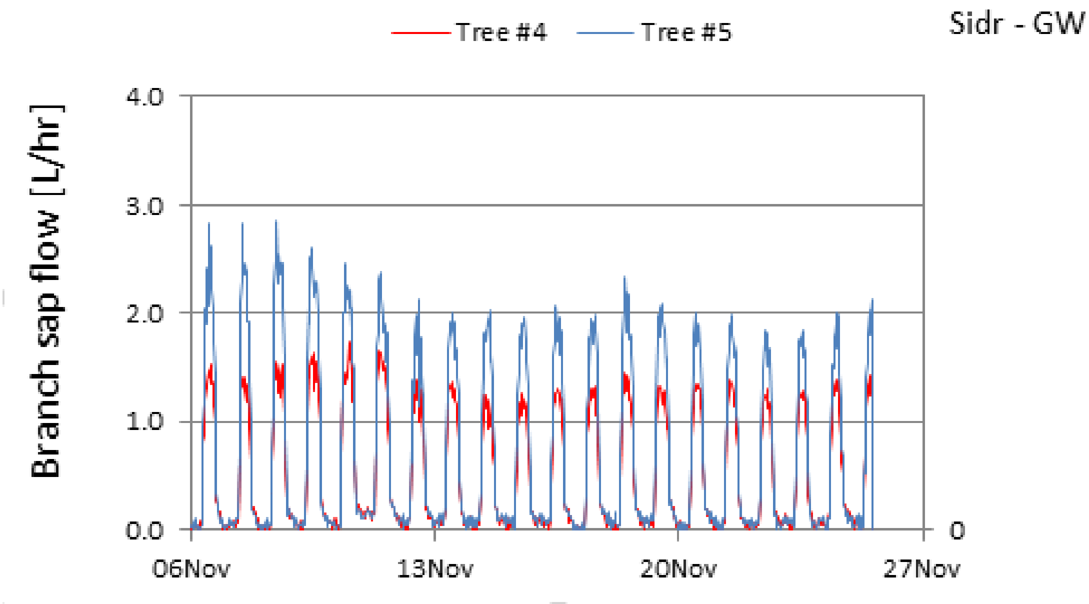

Figure 7. *Water use of Sidr trees #4 (red line) and #5 (blue line) from the groundwater treatment (GW).*

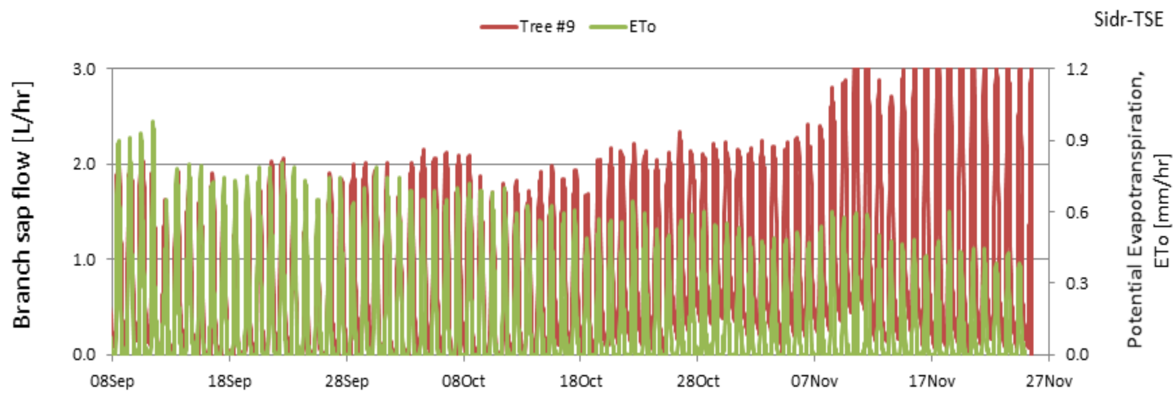

Figure 8. *Water use of Sidr tree #9 (red line, L/hr) from the Treated Sewage Effluent (TSE) treatment (left hand axis). Also shown on this graph is the declining pattern in the daily reference ETo (green line, right hand axis).*

Measuring Tree Leaf Area & Productivity

In order to interpret these tree water-use data, a 'light-stick' has been developed to monitor the changing patterns of total tree leaf area through measuring the shadow area cast by the tree.

From measurements of the tree's projected shadow area (PSA) it is possible to infer the tree's leaf area. And furthermore by using a simple measure of the tree's trunk cross-sectional area (TCA), by recording easily the tree's circumference, it will be possible to use measures of tree size in forest stands to predict the distribution of leaf areas of the trees. In this way the results can be up-scaled to a forest stand. Regular monitoring with this 'light stick' of the changing pattern of trees' leaf area will enable the building of a model of the link between prevailing weather and the trees' transpiration, *ET*c, since the tree's canopy area will be known and the crop factor, *K*c, can be inferred.

From all of these data, and the new knowledge it will be possible to develop a model of tree transpiration, the impact of the use of TSE, and need for a given leaching fraction to remove salts from the rootzone. This knowledge will all be incorporated into an irrigation management tool.

Conclusions

Arid forests in Abu Dhabi are mainly irrigated using groundwater, and this resource is both dwindling and becoming more saline. We have shown that irrigation can be reduced if the annual deciduous behaviour of the Al Ghaf and Sidr trees is taken into account. Savings up to 40% are considered possible.

The use of treated sewage effluent (TSE) has been found to have a beneficial impact on tree growth, especially for the Sidr trees. However, the 'sweeter' TSE has encouraged vigorous canopy growth, and so we will now explore ways of reducing TSE irrigation to achieve an acceptable pattern of tree growth.

A decision support tool is being developed to optimise irrigation for tree species, both for groundwater and treated sewage effluent.

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