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THE IMPACT OF USING TREATED SEWAGE EFFLUENT TO IRRIGATE ARID FORESTS IN THE HYPER-ARID DESERTS OF ABU DHABI

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Abstract

The arid forests of Abu Dhabi provide a variety of valuable provisioning, regulating and cultural ecosystem services. However, given the hyper-arid environment, they also require irrigating. The Secretary General of the Environment Agency - Abu Dhabi, Her Excellency Razan Khalifa Al Mubarak stated "*... our objective is to ensure that recycled water is used for irrigation while conserving groundwater resources.*" Law No. 5 of 2016, the regulation of groundwater in the Emirate of Abu Dhabi recently came into effect to achieve this.

Over the last two years we have carried out experiments at two desert locations, Madinat Zayed and Al Salamat, on four arid-forest species: Ghaf, Sidr, Arak and Samr. These experiments involved the use of both groundwater and treated sewage effluent (TSE) to irrigate the trees. Here we show new results from the work on Ghaf and Sidr trees. We highlight that for both species, the summer 'deciduous behaviour' determines tree water use and irrigation requirements. For the Sidr trees, the irrigation response with TSE continues to be significant, suggesting that by reducing TSE irrigation rates, greater value can be achieved with the same amount of TSE.

We also describe a new experimental set-up on Arak trees, using weighing lysimeters to monitor tree water-use, to overcome problems of using heat-pulse sap-flow monitoring with multi-stemmed trees. We also comment on the experimental set-up adopted for Samar trees, using heat-pulse probes inserted into the roots of several trees. These roots appear to be drawing water from beyond the small zone that is just wetted by the drippers.

Introduction

During the last decade, Environment Agency - Abu Dhabi (EAD) has managed the majority of government forests, along with some private forests in the Emirate of Abu Dhabi. The Agency took over management of these forests from different municipalities starting from the eastern region of the emirate in 2007, followed by the western region in 2009, and then the majority of remaining forests in 2014. All of these forests were established more than 35 years ago, and today they provide valuable services and benefits to the environment and community. The total number of these forest sites, as recorded in updated statistics in late 2016, is 486. These include desert forests, road belts, as well as nursery forests and other supporting planted forestry areas. The total planted area is 102,852 hectares and comprises more than 19 million trees (EAD, 2016a). Most of the forest trees are species native to the UAE, and well adapted to desert conditions.

Arid Forests in Abu Dhabi

Many of the native plant species in the desert forest are Ghaf, Sidr, Arak and Samar. These species were chosen to be our experimental trees because they are the most widely distributed native plant species in Abu Dhabi forests, covering around 78% of forest plants in the emirate (EAD, 2016a). Further details for each of these tree species is provided below.

Al Ghaf

Ghaf, or Al Ghaf, is the local Arabic name for *Prosopis cineraria*. Al Ghaf tree has a straight unbranched trunk for the first few metres (Figure 2). Then the branching starts. It is an indigenous species of the Arabian Desert. Al Ghaf is a drought-tolerant, evergreen, leguminous tree which can tolerate the harsh climate of the desert environment. Despite being evergreen, it does undergo cycles of leaf fall and renewal (Khan, 1999). The Ghaf tree can withstand high salinity levels up to 4,500 ppm, as reported by Dr Mohammed Ali in his detailed 1999 study about indigenous trees of the UAE. Al Ghaf trees can survive even when irrigated with high levels of salinity. Nevertheless, the high degree of salinity does affect their natural growth, health and colour.

Al Ghaf trees can be found growing naturally in the Abu Dhabi desert, either as individuals or in small clusters. They are also grown in large numbers in managed forests. Naturally occurring Al Ghaf trees depend mainly on the availability of groundwater, as well as any scarce rainfall. Their roots can grow as deep as 30 metres to access groundwater. However, with Al Ghaf trees in managed forests, this is not the case, as they are dependent upon irrigation for their water.

Sidr

Sidr, or Al Sidr, is the local Arabic name for the *Ziziphus spina-christi*. Al Sidr grows up to a height of approximately 10 metres, or so (Figure 4). The trunk may be undivided or divided near the base. The stem is then multi-branched. The Sidr is a widely distributed tree and can be found growing naturally, or as a cultivated forest. The reason behind its wide range distribution in UAE is because it can grow well in the sandy, gravelly or silty soils across the wadis and the plains. Also, it is tolerant to harsh conditions such as salt, drought, desert heat, and even heavy grazing by gazelles, oryx, and camels (Khan, 1999); (EAD, 2006).

Arak

Arak or Al Arak is the local Arabic name for *Salvadora persica*, also known as “toothbrush tree”. Arak has several forms, either as an overgrown shrub or straggly bush up to 10 metres high (Figure 5) or even as a small tree. It is commonly distributed in sandy areas, as well as on the lower slopes of mountains. It can withstand high winds and salinity, hence its use as a wind/sand break or ornamental hedge (Khan, 1999); (EAD, 2006).

Samar

Samar, or Al Samar, is the local Arabic name for *Acacia tortilis*. It occurs as either a large shrub or a small tree up to approximately 6 metres high (Figure 7). It has a characteristic flat-topped shape (EAD, 2006). It is a leguminous tree, well-adapted to the desert like Al Ghaf. However, unlike Al Ghaf, it has a shallow, but extensive root system, and thus is found growing naturally on hard soil or alluvial fans, and mostly depends on scavenging any winter rains (AAI, retrieved 2017). It is also planted in forestry blocks and is particularly common in the eastern parts of the emirate.

Groundwater resources in Abu Dhabi

Groundwater (GW) is the main natural water-resource in Abu Dhabi. It is mostly a non-renewable resource of water across the emirate, although there is some slow natural recharge from the Hajar Mountains that border the east of the emirate. Groundwater has been extensively extracted to meet Abu Dhabi's needs for water for different purposes. However, mainly it is to supply the agricultural sector. About 95 % of the total groundwater consumption is used by agriculture and forestry (EAD, 2016b). Over-abstraction of groundwater in the emirate compared to natural recharge rate has resulted in different challenges. Over-extraction threatens groundwater sustainability. Statistics from the major water and electricity authorities in the country showed that in 2000 and 2001, the emirate of Abu Dhabi was the largest user of groundwater, as compared to other emirates. However; it was a lower user in 2006. Recently, Abu Dhabi and the other emirates have managed to reduce their groundwater abstraction by depending on other non-conventional resources of water, such as desalinated water and treated sewage effluent (TSE). They are trying to meet the increased demands for water and avoid further deterioration of groundwater quantity and quality (Murad 2010).

EAD is the government entity mandated to protect and enhance groundwater resources in the Emirate of Abu Dhabi, as well as manage other environmental aspects. One of EAD's key priorities is to conserve groundwater and to actively contribute to integrated water management in Abu Dhabi. The target by 2020 is to reduce the total volume of groundwater extracted annually from 2.198 Mm^3 to 1.82 Mm^3 (EAD, 2016b). Also, one of the desired environmental outcomes is to increase the use of treated wastewater, or TSE, for agriculture and forestry.

Law Number Five

One of the key strategies for addressing Abu Dhabi's groundwater sustainability includes regulating for the responsible use of available groundwater. In 2017, during the International Water Summit (IWS), EAD announced the new Law No. 5, the Groundwater Organisation Law for Abu Dhabi Emirate, passed by HH Sheikh Khalifa bin Zayed Al Nahyan, President of the United Arab Emirates. This law clearly states that groundwater resources in the Emirate of Abu Dhabi are owned by Abu Dhabi Government. Also, under this law, groundwater abstraction and usage will be under EAD’s control. By this, Abu Dhabi is the first government in the Gulf region to state that it owns groundwater. The main objective of this new law is to ensure proper management of groundwater resources in the emirate. With the authorities and new responsibilities given to EAD, private sector entities and landowners will no longer be able to use the groundwater on their property without an EAD licence. The licence will be granted under regulations contained in Law No. 5. The goal is to conserve groundwater and to allow the resources to replenish (EAD, 2017).

EAD already started many initiatives to understand better the status and the pressure on the more than 100,000 groundwater wells in the emirate. These will enable EAD to improve groundwater management through the implementation of policies and by working together with other governmental and non-governmental organisations to support the implementation of the law’s objectives (EAD, 2017).

Finding alternative water resources

Abu Dhabi’s arid forests are currently imposing unsustainable pressures on both groundwater quantity and quality. Moreover, some 7 forests managed by EAD are located within the so-called “Red Zone”. This zone is where the highest rates in groundwater level decline have been recorded by EAD groundwater monitoring wells. To tackle this challenge, EAD has developed a comprehensive strategy for managing arid forests in the Abu Dhabi Emirate. The strategy is focused on managing the forests of Abu Dhabi in such a way so as to ensure their long-term environmental and financial viability so that they can deliver the ecosystem services sought from them. One of the forestry strategy's main objectives related to water management and conservation is 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 (Treated Sewage Effluent) will be allocated first. Next will be desalinated water and finally groundwater.

Currently, 60 % of Abu Dhabi’s TSE is re-used in different sectors, with the remainder being discharged into the sea or open desert. Re-use of TSE is increasing in the emirate, compared to several years ago when it was all dumped as waste. The challenge of fully reusing TSE has been the time and costs associated with building the needed infrastructure to transfer and distribute TSE to its final destination. Abu Dhabi has already started working towards re-using all its TSE for farms, amenity plantings, and forest irrigation. Implementation is planned for 2018 (EAD, 2017). A total of 90,707 m^3/d of TSE is scheduled to be transferred to forests (EAD, 2016c). Using TSE in agriculture will support both a reduction in the usage of groundwater, and enhance recharge through the ‘leakage’ of some fraction of the irrigation water, thereby allowing the opportunity for existing groundwater aquifers to replenish (EAD, 2011). Meanwhile, there will be better plant growth, healthier agriculture, and improved marine water quality by not dumping TSE into the sea. Air quality will also improve through stabilisation of the desert sands through enhanced forest health.

Forest Cancellation

Unsustainable use of groundwater and unsustainable water usage by forests are some of the significant environmental challenges facing Abu Dhabi, and they both require urgent intervention. As well as implementing Law No. 5, EAD has made additional decisions to enhance the future sustainability of forests.

EAD selected and cancelled some 105 forests in 2016. All operational activities, including irrigation, were stopped in these forests. Cancelled forests were selected under specified criteria and conditions agreed to by stakeholders and decision makers. The rest of the forests are still consuming significant amounts of water, and they mostly depend on groundwater for irrigation. The annual total water consumption by irrigation for the current forests is estimated to be 149, 076,998 m^3 (EAD, 2016a).

Objectives

The objectives of this research project are:

- Quantification of the irrigation needs of the four most important desert-forestry species: Ghaf, Sidr, Arak and Samar.
- Determine the impact of treated sewage effluent on forest growth and health across four species of forest trees using groundwater (GW; ≈ 10 dS/m; 6,400 ppm) and treated sewage effluent (TSE; ≈ 1 dS/m; 640 ppm).
- Assist with the development of a decision-support tool for forestry irrigation and soil salinity management in arid forests.

Here we report on how our experimental results can suggest that substantial water savings can be made by minimising GW irrigation to arid forests, and how TSE irrigation can be used most efficiently.

Materials and methods

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

Sap-flow sensors have, for the past two years (2015-2017), been operating in the trunks of four Ghaf trees and Sidr trees under both treatments of GW and TSE. These sensors monitor the instantaneous rates of sap flow. The sap-flow data provide a direct measure of the actual water use of the trees, which is expected to vary in response to weather, total leaf area and tree size, soil water availability, and irrigation salinity, amongst other factors. During the first two years of the experiments on Al Ghaf and Sidr, across both treatments, irrigation water was supplied at 50 L/tree/day. Beginning in January 2017, new water-saving treatments have been initiated. For GW, water is being applied on a daily basis of 1.5 ETc, the trees' actual water use, as measured during the first two years. This factor of 1.5 is for a 25 % factor-of-safety, and 25 % for a salt leaching fraction. For the sweeter TSE, the new schedule is just 1.25 ETc, as there is no need to leach salts from the root zone. These treatments represent savings of 40 % and
50 %, respectively, on current practice.

In December 2016, sap-flow measurement equipment was installed in the 6 experimental Samar trees. The irrigation treatments on Samar began during January 2017. By then, the trees has lost almost all of their leaves as part of their natural cycle of leaf loss and regrowth, and so the measured sap-flow rates were very low. The baseline irrigation rate of 50 L/tree/day is being applied to both treatments.

Arak trees were planted in lysimeters at the Al Salamat nursery of Barari, near Al Ain, during December 2015. Sap-flow devices could not be used for Arak, as the tree is multi-stemmed. A meteorological station has been erected, and load-cells under 16 trees have been installed to measure ETc by lysimetry. The trees' transpiration is calculated through weight changes. Also, a tipping spoon device has been attached at the exit point at the base so that drainage from the lysimeter can be measured. From these weight change data, the trees' transpiration can be inferred. Irrigation treatments with GW and TSE were applied recently during January 2017, using an ETc replacement schedule based on weight changes.

Results

Ghaf

Figure 1 shows the seasonal pattern of tree water use of the Ghaf trees in relation to the reference evapotranspiration (ETo) over two years. Although these trees exhibit summer deciduous leaf-fall, the timing and degree of defoliation vary between trees, such that on average the water use essentially tracks ETo, with a crop factor of around 0.2. Current practice is to apply about 50 L/tree/day throughout the year. Substantial savings are possible by accounting for the seasonal pattern of ETc. There has been no difference in tree performance as a result of the TSE irrigation (Figure 2).

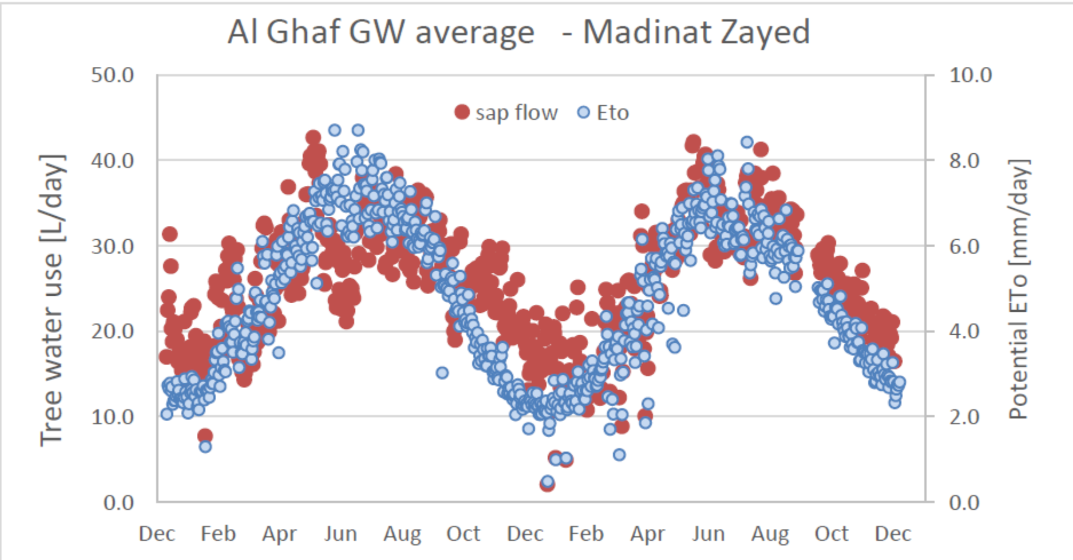

Figure 1. The measured water use of four Al Ghaf (*Prosopis cineraria*) trees (red dots) in relation to reference evapotranspiration (ETo) (blue circles), Abu Dhabi, 2015-16.

Figure 2. The experimental plot of Al Ghaf (*Prosopis cineraria*) trees, with the groundwater-irrigated trees on the left, and the sewage effluent-treated trees on the right, Abu Dhabi.

Sidr

The Sidr trees have a strongly deciduous pattern with severe defoliation in early summer, and again, to a lesser extent, in early winter. With the loss of leaves, the trees' water use (red and green dots) drops below that expected from the reference evapotranspiration, ETo (blue circles) (Figure 3). Thus the need for irrigation in summer and early winter is less than that which would be expected. Substantial savings are possible if the irrigation is based on ETc.

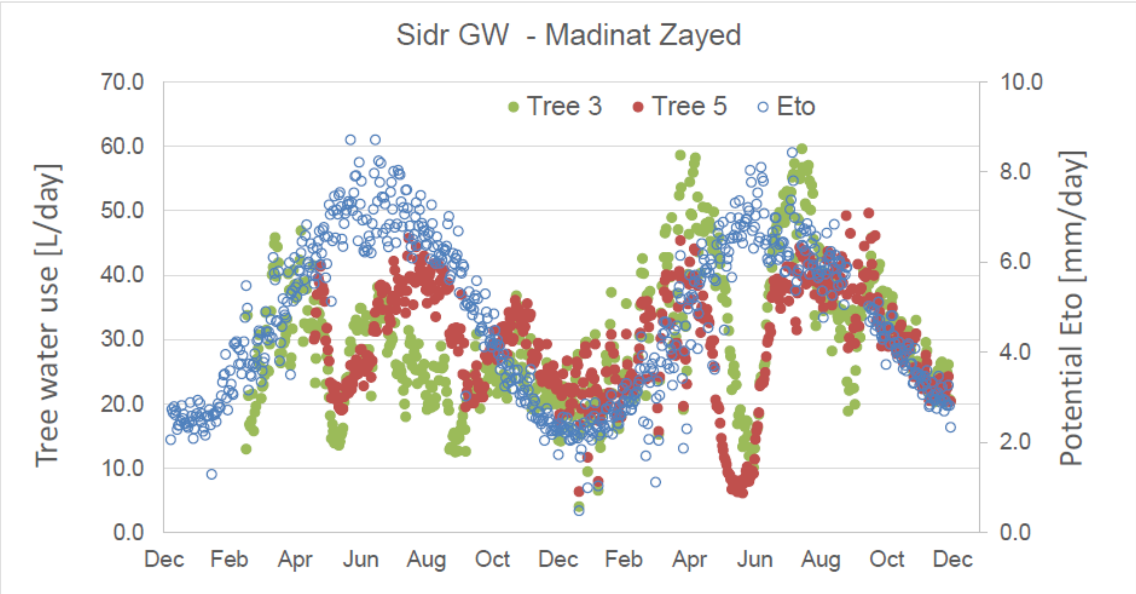

Figure 3. The measured water use of four Sidr (*Ziziphus lotus*) trees (red and green dots) in relation to reference evapotranspiration (ETo) (blue circles), Abu Dhabi, 2015-16.

For the Sidr trees, the impact of TSE irrigation has been very noticeable. Our initial assessments of nitrogen in both the irrigation waters, and in the soil around the drippers, reveal no difference in the levels of nitrogen. The TSE had an electrical conductivity (EC) of less than 1 dS/m, whereas GW was about 10 dS/m. We consider that it is the "sweeter" TSE that has resulted in a significant enhancement of tree growth and leaf area development (Figure 4).

Figure 4. The experimental plot of Sidr (*Ziziphus lotus*) trees, with the groundwater-irrigated trees on the left and the sewage effluent-treated trees on the right, Abu Dhabi.

Arak

Arak is a multi-stemmed tree ill-suited for the heat-pulse technique to measure sap-flow. We have therefore used small weighing lysimeters (Figure 5) to monitor tree water use.

Figure 5. The experimental plot of Arak (*Salvadora persica*) trees growing in weighing lysimeters, near Al Ain in Abu Dhabi.

Irrigation is applied manually, but the weight change, drainage by tipping spoon, and soil water content are logged electronically (Figure 6). The GW and TSE treatments started in January 2017.

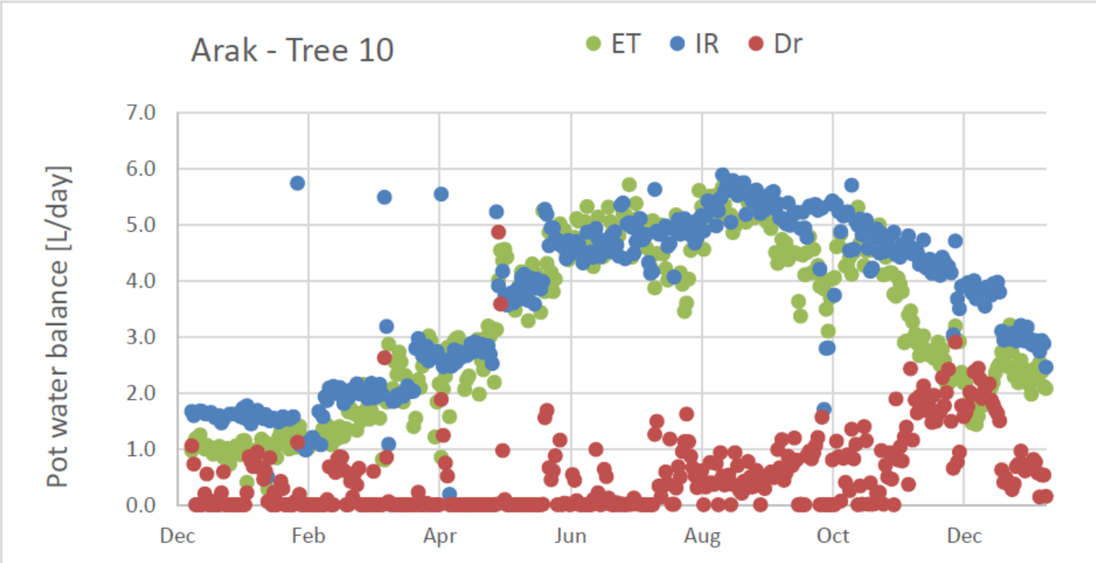

Figure 6. A plot of the annual water balance from one of the lysimeter pots (Arak tree #10) as represented by the total evapotranspiration (ET), irrigation (IR) and drainage (DR).

Samar

The final tree species in the study is Samar. The GW and TSE treatments began in January 2017 (Figure 7). The stems of 6 Samar trees, 3 with GW irrigation and 3 with TSE, have been instrumented with heat-pulse gear. In addition, heat-pulse equipment was installed into three surface roots, which appear to be drawing water laterally from beyond the zone wetted by irrigation. Analysis of these root sap-flow results will answer functional questions about why the form of the Samar root system is shallow with lateral spread. Are they scavenging rainwater stored in the interstitial spaces between the trees?

Figure 7. The experimental plot of Samar (*Vachellia tortilis*) trees near Madinat Zayed, Abu Dhabi. The inset shows a set of heat-pulse probes in a transverse surface root.

Conclusions

Our results suggest that substantial water savings of between 40-50 % are possible by minimising the irrigation to arid forests. The TSE has had no impact on the Ghaf trees, whereas there has been a very significant response to TSE shown by the Sidr trees. Applying TSE to Arak and Samar started in early 2017 and will continue until the end of the year. All of these results will be incorporated into a Decision Support Tool that can be used in the implementation by EAD of the recent Law No. 5 which seeks to protect the ground water resources of the emirate.

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