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Is it true that the date palm tree consumes a lot of water? Evaluation of the date palm tree transpiration using Granier's sap flow method in a Tunisian Saharan oasis

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Abstract

To improve the irrigation water management in oasian context, evapotranspiration assessment is required. In Tunisian oases, date palm (*Phoenix dactylifera* L.) is the main crop and its water use is an essential evapotranspiration element. In this research, sap flow measurement was implemented to assess the date palm transpiration inside an irrigated-drained field within which the shallow-groundwater level and the water balance elements were continuously monitored. The site is a Tunisian Saharan oasis, stamped by waterlogging and salinity manifestation and by low-frequency and irregular flooding irrigation. The cropping system is two-storey palm/grass layered system. This paper focuses on one-year period sap flow measurements using a recalibrated Granier's TDP-method. Results showed that the instantly transpiration varied with the air temperature and was high related to the shallow water table nycthemeral fluctuation. The daily transpiration ranged between 0.5 and 3.5 mm d^{-1} with a clear seasonal variation. A water stress appearance according to water delivery frequency during the summer season was also revealed. The one-year-cumulated date palm transpiration was about 730 mm and represented almost 60% of the overall oasis deduced evapotranspiration. From this experiment case, it was noted that the date palm tree transpiration reflect a modest water consumption (35 to 45%) relatively to the surrounding high evaporative demand and it can be deduced that date palm tree, in itself, isn't a great water consumer in such cropping conditions. After more validation, these elucidations should be considered to rethink the date palm irrigation scheduling and the water management practices inside oasis schemes.

Keywords: Date-palm (*Phoenix dactylifera* L.), Sap flow, Transpiration, Saharan oasis, Tunisia

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Introduction

The irrigation water management and its rational use in arid and hyper-arid zones, such as oases context, requires an accurate quantification of the different water balance terms, including canopy transpiration reflecting the net crop water-consumption (Brunel et al., 2006). This knowledge is crucial to sustain a balanced functioning of a date palm oasian agro-system knowing a continuous enlargement in many hyper-arid regions of the world as in the North-African Saharan zone, posing thereby many challenge aspects, agro-socioeconomic and hydrological, very dependent on environmental, climatic and soil conditions (Sellami, 2008; Bouarfa et al., 2009; Mekki et al., 2013). Establishing exhaustive water balance and assessing evapotranspiration inside oasian schemes is thereby a key task to optimize the water use efficiency and to sustain water resources, especially if water is scarce, expensive and brackish as in most Tunisian Saharan oases (Sellami, 2008; Bouarfa et al., 2009; Mekki et al., 2013; Ben Aïssa et al., 2013; Hachicha and Ben Aïssa, 2014; Omrani, 2015).

The scientific efforts invested in this research topic are relatively recent for oasian context and, given their still too narrow analysis, spatially and temporally, haven't far served as an effective aid to decide on a more efficient water management inside date palm groves (Carr, 2013). Scientific research must, thus, invest in both ever more relevant methodological approaches and more useful modeling. Requiring deeply studies and research (Al-Muaini et al., 2019), it's clear that, depending of the biological aspects determining the date palm yield and the fruit quality, the transpiration constitutes an indispensable indicator to put in relation with the production factors and the local water quality and management constraints (Zhen et al., 2019).

Numerous methods and approaches are used to estimate crop evapotranspiration at different scales. For continuous-cover crops, the choice is so large. However, for sparse crops or row-cropped trees, like palm groves, orchards and forest

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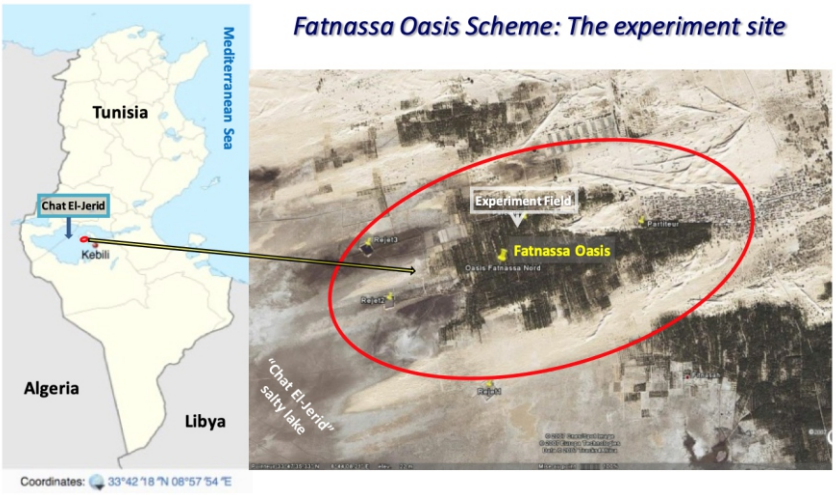
stands with sampling and representativeness problems, adequate methods are few (Granier, 1985). Among these methods, sap flow measurement is widely referenced for direct whole-tree transpiration assessment and several thermal methods are developed and used since some thirty years (Poyatos et al., 2016). The trunk sap flow measurement has been validated to monitor in situ trees' transpiration at different ecosystems such as savannahs (Do and Rocheteau, 2002b), forest stands (Granier, 1987; Köstner et al., 1998), fruit orchards (Cabibel et al., 1991b; Ben Aïssa et al, 2000), tropical palms (Dufrêne et al., 1992; Roupsard et al., 2006; Madurapperuma et al., 2009), date palm groves (Ringersma et al., 1996; Sellami and Sifaoui, 2003; Sperling et al., 2012; El-Khoumsi et al., 2017; Al-Muaini et al., 2019). It has the advantage to integrate roots and canopy heterogeneities through the trunk as a unique pathway of ascending water (xylem crude sap) respecting the soil-plant-atmosphere continuity.

As a contribution to these scientific investigations, we conducted this experiment aiming to apprehend the water balance inside an oasian cropping system with a particular focus on the date palm transpiration as a key component. In Fatnassa' date-palm grove, our oasian experiment site for several years (Ben Aïssa et al., 2005), we tried to assess and analyze the water balance, in connection with irrigation depth and frequency, inside an irrigated-drained field reflecting overall the water management complexity within the oasis (Ben Aïssa et al., 2013). In this paper, some results relating to the date palm sap flow magnitudes and variation are presented with the monitored water balance components (irrigation, drainage, water-table fluctuation, water salinity),. Among the several developed and used sap flow thermal methods, the Granier's thermal dissipation probe (TDP) technique, known for its simplicity and convenience for continuous measurements (Fuchs et al., 2017) was selected and applied for the experiment of this study.

Materials and Methods

Experiment site: context and specificity

The Fatnassa oasis scheme (33°,8N; 8°,7E), located in the north side of the Nefzawa Tunisian Saharan oases region, with about 150 hectares of irrigated area, was chosen as site to conduct this experiment (Picture1). This oasis, right-on the edge of a big salty lake called "Chat El-Jerid", is prone to waterlogging and salinity manifestations with a rather unfavorable water availability compared to many other oases in the region (Ben Aïssa, 2006; Hachicha and Ben Aïssa, 2014).



Picture 1. Geographic location of the experiment site
(Left: Map of Tunisia ; Right: satellite photo of the oasis from Google Earth on 2007)

The climate is continental Saharan, with high daily and seasonal thermal amplitudes and irregular yearly rainfall less than 100 mm. The mean potential evapotranspiration is about 1800 to 2000 mm yr^{-1} and the water deficit is continuously high overall the year (Floret and Pontanier, 1982). The soil inside the oasis is mostly gypsiferous or gypseous fine sand regenerated from eolian deposit of gypsic aridisoils active dunes. These soils, poor structured, are known by their instability, their rather high porosity and their weak water retention capacity. Some characteristics of the study site soil are presented thereafter (Table 1).

The experiment field consists of a 0.8 hectare plot containing 20-year-old "Deglet Nour" date palms planted in a 200 trees per hectare (7m per 7m) density. The average palm-trees height within this plot is ~8 m. The low canopy layer, underlying the palm-trees, consists mostly of sparse fodder and alfalfa crop almost renewed every 3 years (Picture 2).

As in most Tunisian oases, the irrigation water coming from deep fossil groundwaters is distributed in concreted channels and provided to farmers' plots in water turn. On the field, the water supply is carried out by total surface flooding. Its frequency in the experiment field, observed by continuous monitoring, is almost monthly with some turn irregularities, especially in summer season due to the high water demand and water scarcity (Ben Aïssa, 2006). At the approach of winter, the water turn is more regular; given the decrease of the crops water needs but also because of the farmers' voluntary irrigation reduction while the harvest season.

The drainage is deficiently assured by a subsurface PVC pipes system prone to mineral and root clogging (Ben Aïssa et al., 2013). The shallow saline water-table regenerated by irrigation with cyclic presence events near the soil surface is in close interactions with the soil, the crops and the different water and salinity management practices (irrigation, drainage, pumping etc.). The shallow groundwater table is thereby in a high dynamic and its fine-scale level monitoring

constitutes an important tool to apprehend the hydric functioning within a groundwater-soil-plant-atmosphere continuum (Ben Aïssa et al., 2013).

Moreover, the low soil water retention capacity and the low irrigation frequency confer a determining contribution of the shallow water-table in the water supply for the grown crops (date palm and fodder), well known for their developed root system and their salinity and gypsum tolerance (Ayers and Westcott, 1985). In such context, the practice of irrigation corresponds *de facto* to manage the shallow water table with high capillary rise than to maintain a weak useful reserve in a high macro-porous gypseous sandy soil.

Sap flow measurement and calculation

On-the field installation plan and handling

During this experimental work, on-the field sap flow measurement has been performed in accordance with Granier's heat dissipation method (Granier, 1985; 1987) recalibrated for tropical palms by Roupsard et al. (2006). Four neighboring fully-grown date palm trees (square mesh 7 x 7 m²) of the "Deglet Nour" variety were equipped with sap flow sensors. The locally-made sensors (TDP type) used in this experiment, having 20 mm in length and 2 mm in diameter, were manufactured according to Roupsard et al. (2006) prescriptions. As a result, the sensors are almost identical and accept the same calibration and calculation equations as that elaborated and validated by these authors. The heating voltages, provided by rechargeable battery, were regulated to have continuously a 200 mW constant power at each heated probe. Following a failure at one of the power-regulator output terminals, one of the singular sensors was left permanently without heating while recording its signal. The sensor signals were logged by a CR10x data logger via an AM416 multiplexer (*Campbell Scientific*) at one minute steps and averaged every 15 minutes. The data recovery was performed periodically using a laptop PC.

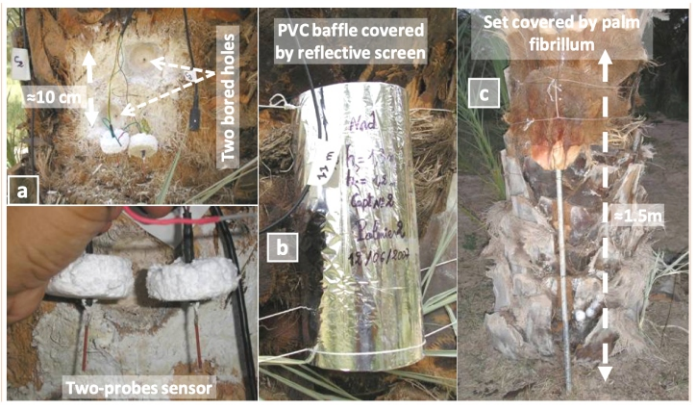
Given the date palm trunk thickness and hardness, some methodological adaptations about the installation and the insulation were however implemented compared to that prescribed by Roupsard et al. (2006) on Coconut palm. Indeed, on each palm tree, the sensor probes were installed at ~8 cm depth radially into the trunk North-direction side and at 1.5 m height above ground. Since we used 2 cm length probes, to reach the trunk sapwood, we performed 5 cm diameter and 6 to 8 cm depth holes using hole saw and wood chisel and without removing the old leaves pruned stubs traditionally left on the stem. At the bottom of each hole, it was drilled, using a 2 mm wick, 20 mm depth again to insert fitly the probes. After probes insertion, the wide bored holes were insidely masticated and then sealed with polystyrene cylinders to avoid sapwood desiccation (Picture 3, a). Each sensor was protected from direct sunshine by a PVC baffle covered by a reflective screen (Picture 3, b). For a better protection, the sensor set was finally well-covered with palm fibrillum to give the same color as the trunk. (Picture 3, c).

Table 1. Some soil characteristics in the studied field

Soil horizon (cm)	% Clay	% Silt	% Fine sand (0,05-0,2 mm)	% Medium sand (0,2-0,5 mm)	% Coarse sand (0,5-2 mm)	Gypsum (%)	Bulk density	Porosity (%)	θ_{fc} (%)	θ_{wp} (%)
0-20	4	6	72	13	5	70	1.13	32	15	5
20-40	5	6	71	14	4	67	1.15	28	16	5
40-60	5	7	72	12	4	62	1.18	25	15	6
60-80	6	8	73	11	2	55	1.21	22	13	5
80-100	6	8	76	10	0	52	1.25	20	13	6

(*) Horizons, deeper than 100 cm, are saturated in water because of the shallow water table level while sampling

Picture 2. Deglet Nour date palm trees inside the experiment field (Photo taken by I. BEN AISSA)



Picture 3. Details of the TDP Sap flow sensor installation on the date palm trunk with adopted insulation precautions (Photos taken by I. BEN AISSA)

Granier's TDP sap-flow calculation: a brief theory overview

The measurement principle is a convective cooling, due to the circulation of the sap, of a heated probe at constant power (Granier, 1985). The sensor consists of two cylindrical needles containing Cu/Cs thermocouples mounted in opposition. They are inserted radially into the stem sap-wood containing the xylem bundles ensuring the

crude-sap ascension. A gap of about 10 cm separates the heated needle (high) from the second needle (low) monitoring the reference trunk temperature below the heating point. The decrease in the temperature difference (ΔT) between the two needles is related to the flux density or sap velocity calculated by an empirical formula based on two sap flow conditions:

(i) at zero sap flow, we record a temperature difference called ΔT_{ref} or ΔT_{max} and

(ii) with non-zero sap flow, we record a temperature difference called ΔT

These thermal differences will be the basis for calculating the flux density () written as follows:

$$\phi = \alpha.(K)^{\beta} \quad (1)$$

where ϕ is the sap flux density ($m^3\ m^{-2}\ s^{-1}$) or also sap velocity ($m\ s^{-1}$), α and β are two calibration coefficients and K is a dimensionless term called the Flow Index and calculated as follows (whith, ΔT_{max} and ΔT_{ϕ} are the same parameters mentioned above):

$$K = \left[\frac{\Delta T_{max} - \Delta T_{\phi}}{\Delta T_{\phi}}\right] \quad (2)$$

Date-palm sap-flux density calculation

The sap flux density is calculated from an empirical model established for forest species (Granier, 1985, 1987) and fruit trees (Cabibel et al., 1991b). On palm trees (oil and coconut palms), Roupsard et al. (2006) recalculated α and β adjustment coefficients after a locally-made probes calibration in the laboratory and validated in a coconut palm field by comparison to the eddy covariance fluxes. The new adopted coefficients are 315.10^{-6} and 1.231 for α and β respectively, and we write:

$$\phi(m\ s^{-1}) = 315.10^{-6}.(K)^{1.231} \quad (3)$$

For this experiment, since we used the same locally-made probes as Roupsard et al. (2006) with the same heating power (200 mW), the same α and β equation coefficients were adopted (Formula 3) without further probes calibration. After a sensors installation tuning, in particular concerning the needles insertion depth and insulation, the preliminary recorded signals from the heated sensors evolve coherently with rather synchronous kinetics but, nevertheless, with differences in ΔT_{max} and ΔT_{ϕ} offsets and amplitudes. The ΔT_{max} values vary from day to day and differently for each sensor. Therefore, the consideration of a main ΔT_{max} on ten days envelope as mentioned by Granier (1987) seemed to be a supplemental source of error (Rabbel et al., 2016). Thus, to compute the flux index over a day we considered ΔT_{max} recorded during the two nocturnal periods, preceding and succeeding the diurnal period of the considered day.

Date-palm transpiration assessment from sap-flux density

From the above formula, the total sap flow (*Sf*) passing through the stem is estimated as follows (where *Sc* is the sap-conducting (sapwood) section area, estimated in m²):

$$Sf(m^3 s^{-1}) = \phi.Sc \quad (4)$$

For *Sc* calculation, an investigation has been conducted through observations of many fresh cuts made on date-palm stems in the oasis. This appreciation has been performed in other similar works on palm stems (Dufrêne et al., 1992; Ringersma et al., 1996; Sellami and Siffawi, 2003; Roupsard et al., 2006). For more accuracy, some recent studies (Sperling, 2012; Fathi, 2014) tried to differentiate a radial conduction variation inside the date-palm stem but the results are various. For our case, visual observations lead us to consider, in a simplification trend, that the whole white-colored sapwood section is uniformly sap conductive. A cut of a "Deglet Noor" palm trunk (having the same age and size as the studied trees) lead to estimate, through difference in color, that *Sc* is about 7 dm², representing ~52% of the total stem section area (Picture 4).

At a tree-scale, the measured sap-flow is expressed as:

- Hourly sap-flow ($L\ h^{-1}$); this expression is used to characterize and compare the actual and nycthemeral sap flow kinetics.
- Daily cumulated sap-flow ($L\ d^{-1}$); which corresponds to the daily transpiration expressed in ($mm\ d^{-1}$) on an area basis. For this, given the date palm plantation density within the experiment field, a relative occupation area of ~50 m² is allocated for each tree.

In order to extrapolate transpiration from tree-scale to field-scale, we have considered via simplification that the studied palms (equipped with sap-flow sensors) are representative of the whole field. The studied trees have nearly the same trunk perimeter of about 130±2 cm. From where, we estimate a daily transpiration (*Tp*), at the field-scale, by the following equation:

$$Tp\,(mm\ d^{-1}\ or\ kg\ m^{-2}d^{-1}) = \sum_{t=1}^{24h}(Sf.3600)\frac{N}{10000}.10^{-3} \quad (5)$$

where *Sf* is the single-tree sap flow ($m^3\ s^{-1}$) calculated by meaning measurements made on three palms, *N* is the number of palms per ha of field area ($N \approx 200$ trees per hectare).

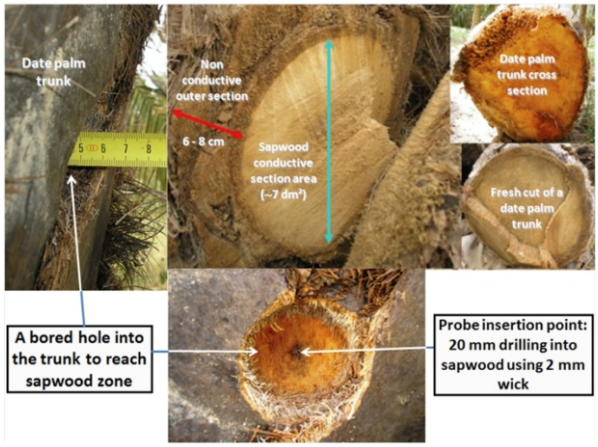
Climatic parameters

Given the lack of an in situ weather station, we tried to ensure an under-palm-canopy air temperature monitoring using a Cu/Cs thermocouple, lodged inside a ventilated box and logged by the same CR10x at the same time step as the sap flow. Moreover, the under-palm-canopy air temperature and relative humidity were also, but irregularly, half-hourly logged at 1.5 m height above ground using an EL-USB2 Lascar's sensor nearby the instrumented trees.

For above-canopy meteorological investigations, the daily climatic data, relating to the region in which the studied oasis is located, were furthermore collected from a governmental weather station located at Kébili city, about 20 km straight far from the experiment site.

Water table level, water and salt balances monitoring

The shallow water-table level was continuously monitored at two hand-augered observation wells dug between the field boundaries and the unique drain pipe crossing the field. A barometric-compensated pressure sensor is immersed, at each observation well, in the water table to monitor its level fluctuation. The details of all the devices installed in the field to monitor water table level, irrigation and drainage are well described by Ben Aïssa et al. (2013).



Picture 4. Cuts on date palm trunks to investigate the conductive sapwood area and to identify the Sf probes insertion depth (Photos taken by I. BEN AISSA)

Results and Discussion

Hourly sap flow variation with the under-canopy measured air temperature

The Figure 1 illustrates the hourly averages calculated from 14 days continuous measurement series related to air temperature; *Ta* (°C), and to sap flow; *Sf* (L h^{-1}) during the summer season (233 to 246 DOY). During this period, *Ta* varied from 25 to 48°C characterizing a high evaporative demand. From these hourly rates (averaged from 15min step records), we can perceive that *Sf* curves (of two presented palms) are fairly synchronous and very close during this period of measurement. The maximum hourly flow values, observed in the middle of the day, ranged between 12 and 17 L h^{-1} corresponding to 1.7 and 2.4 L dm^{-2} h^{-1} of flux densities. At this hourly time-scale, the figured courses shows a close relation between *Ta* and *Sf*. This concordance seems however less clear on a daily time-scale.

The comparison of the hourly averages during two days with contrasted weather conditions shows, that during the summer season (Figure 2, a), the air temperature is maximum two hours after the sap-flow reaches its maximum and it then decreases much less rapidly. This is can be explained by the fact that *Sf* (or transpiration) is a physiological phenomenon related also to the intercepted solar radiation, to the vapor pressure deficit and to the plant water status controlling together the stomata regulated opening and the water loss from leaves to the atmosphere. While *Ta*, pure physical, is influenced by the surrounding environment thermal inertia from where its evolution is slower than *Sf*. In winter season (Figure 2, b), the hourly kinetics are more synchronized or showing a small delay of the sap flow compared to the temperature with much lower maximum values than in summer. But, we have to indicate that *Ta* presented on these figures was measured under palm canopies and it can thereby be influenced by shading.

The day-night shallow water table fluctuation as related to the transpiration activity

On the figure 3, The curves of the instantaneous date-palm sap-flow and the fine-measured water table level evolving during 10 summer season consecutive days (236 to 245 DOY) succeeding an irrigation event, are presented. On the water table level curve, a day-night oscillation is clearly noticed during the groundwater table drawdown phase. This nycthemeral shallow groundwater level fluctuation is characterized by a faster diurnal drawdown than during nocturnal period. This fluctuation was assumed by many authors to be directly related to the phreatophytes evapotranspiration activity and magnitude (Loheide II et al, 2005). In our experiment field, the evapotranspiration outflow, occurring during the diurnal phase, is added to the drainage and downstream outflows, resulting thereby in a faster diurnal drawdown. During the nocturnal phase, evapotranspiration is almost zero and only drainage and downstream outflows which continue to drive the water table drawdown (Ben Aissa et al., 2013).

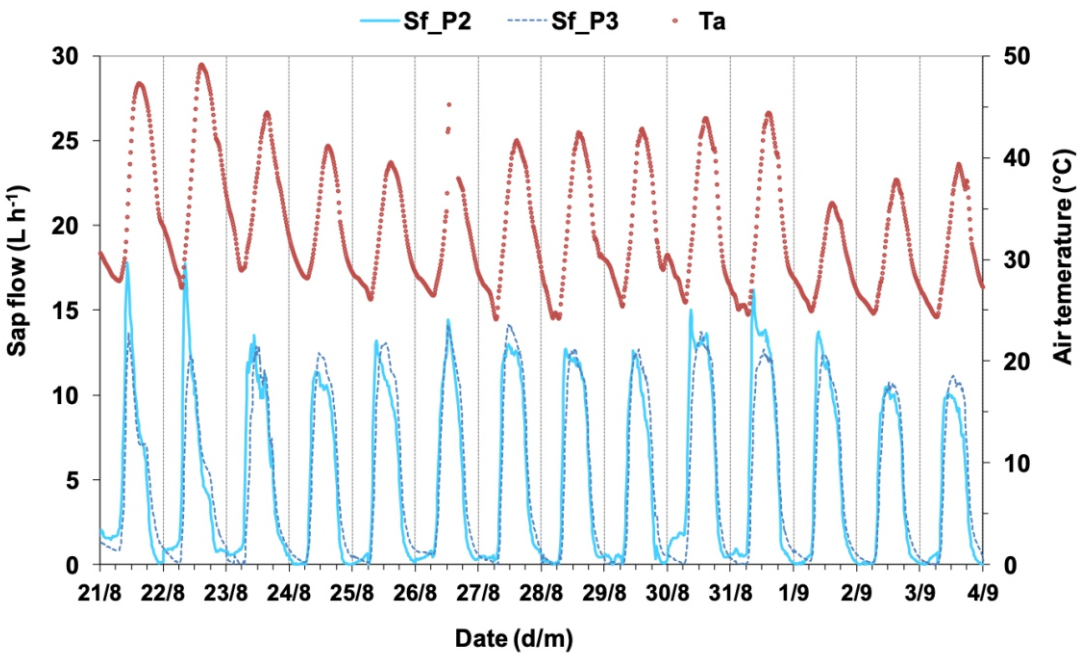


Figure 1. Daily courses of two neighboring palm trees (P2 and P3) sap flow (Sf) of and of the under-canopy air temperature (Ta): a series of 14 days measurement during summer season (233 to 246 DOY)

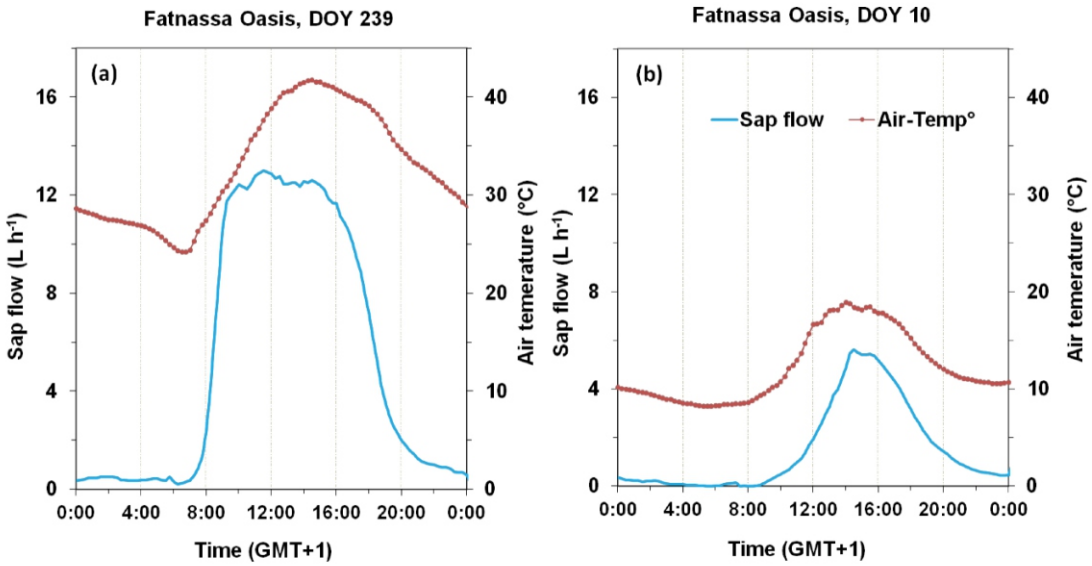


Figure 2. Daily courses of the date palm sap flow (L h^{-1}) and of the under-canopy measured air temperature (°C): A comparison between two evaporative demand contrasted sunny days; **(a)** DOY 239: Summer day with high evaporative demand, **(b)** DOY 10: Winter day with low evaporative demand

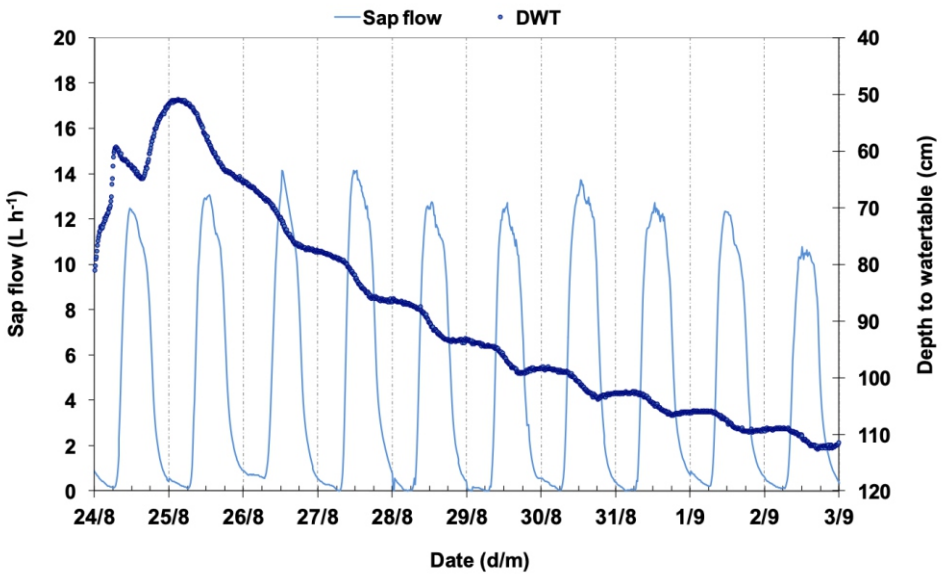


Figure 3. Temporal variation (236 to 245 DOY) of the date palm sap flow and of the depth to the shallow water table from the land surface (DWT) monitored inside the experiment field (10 min step values); (The irrigation event has occurred within DOY 235 and 236).

To demonstrate this relation between evapotranspiration outflow and the groundwater day-night oscillation, we superimposed the water table level and the instantaneous date-palm sap-flow courses. By curves observation, it can be seen clearly the synchronized evolving of the two phenomena. Indeed, after a nocturnal water table slow or zero drawdown phase, during which transpiration (sap flow) is almost zero, begin a more accelerated drawdown phase concomitant to the diurnal transpiration activity rise. It can be deduced here that the diurnal water table drawdown acceleration is, at least partially, driven by the date palm transpiration outflow. Similar results were found and discussed by Loheide II et al (2005) for some desert shrubs.

The concomitance of the drawdown acceleration course and the sap flow diurnal rise confers moreover, at least qualitatively, a more methodological strength to the date-palm transpiration assessment by sap flow measurement. The shallow water table nycthemeral fluctuation signal could therefore be valued to investigate the evapotranspiration flow of the total above-ground canopy inside the oasis scheme and to know more about the shallow groundwater contribution to this flow feeding.

Moreover, the hypothesis that date-palm behaves as a phreatophyte and can extract his water needs from the shallow groundwater seems to be demonstrated by this phenomena concomitance. In the literature, some authors mentioned that, being a tree of the desert, date palm requires sufficient soil moisture in their rooting zone (1.2 to 2 m depth) which is totally provided by a shallow (but non salty) water table or partially by regular adequate irrigation (Nixon, 1951; Munier, 1973, Liebenberg and Zaid, 2002; Chao and Krueger, 2007; El-Khoumsi et al., 2017).

Transpiration variation at daily time scale and with the irrigation frequency

Like at the hourly time-scale, sap flow averages show a high variability. Indeed, daily cumulated sap flow varied overall from 25 to 175 L d^{-1} $tree^{-1}$. Converted to mm d^{-1} unit (on the basis of planting density), daily transpiration varied thereby from 0.5 to 3.5 mm d^{-1} with an average of about 2 mm d^{-1} calculated over on the entire measurement period (between July and May of the following year). During monitoring summer season, (July-September), the daily palm transpiration averages ranged from 75 to 160 L d^{-1} $tree^{-1}$ which equivalent to 1.5 to 3.2 mm d^{-1} (Figure 4). During this critical water-need period, we received three monthly irrigation events of about 150±10 mm depth for each one. These three water deliveries are clearly differentiated through the consequent water table level raising (Figure 4).

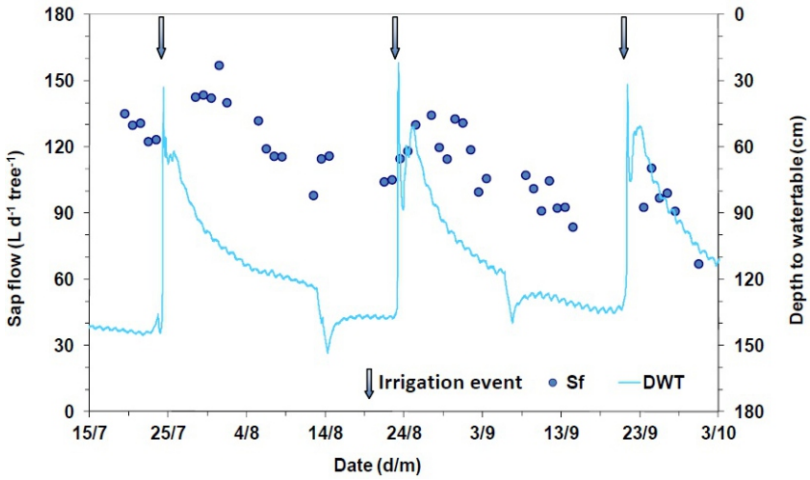


Figure 4. Temporal variation of the daily cumulated date-palm sap flow (L d^{-1} $tree^{-1}$) in relation to the irrigation events and the shallow groundwater depth (from DOY 196 to DOY 276).

It remains, however, an accurate evaluation of the low layer (forage crops and bare soil) contribution into the overall evapotranspiration. At the scheme scale it was deduced from salt and ionic balance (input-output) a yearly overall evapotranspiration of almost 1100 to 1200 mm yr^{-1} during a normal water supply functioning year (Marlet et al., 2007).

Noticed sources of error that may affect the date-palm sap flow measurement accuracy

In addition to the difficulty to localize the zero sap flow state and the derived ΔT_{max} determination inaccuracy described above, we distinguished, from the permanently unheated sensor signals or even from the other sensors when the power supplying battery is running out, a non-zero and repetitive temperature difference (ΔT) between the higher and lower sensor needles. The hypothesis of an equal temperature at the two needles insertion points under "without-heating" condition has a priori not been validated under field conditions (Cabibel et al., 1991a; Lu et al., 2004; Hölttä et al., 2015).

The temperature difference (Figure 6) is sharply negative (-0.2 to -0.6 °C) at the beginning of the day (between 7am and 11am, depending on the season) and gradually reversed the rest of the day to almost +0.3 °C with a daily and seasonal variation. This signal, common to all sensors under without-heating state, is then a not hazardous phenomenon, especially since it is repetitive with an observed effect of the daily solar and thermal cycle.

By superimposing the calculated flux density kinetics and the without-heating signal drawing(Figure 7), it has been noted that this offset can influence instantly flux density values, in particular by an early morning maximum appearance. Therefore, if we don't take this ΔT offset into account, we can be misled to explain this maximum by a greater morning transpiration activity. Consequently, we can even lose accuracy on the flux density calculation since the daily recorded amplitudes between maximum and minimum ΔT_{ϕ} were rather small (about 2.5 to 3 °C). This offset shouldn't be neglected since it can also induce an overestimation of ΔT_{max} whose consequences on the flux values can be significant (Peters et al., 2018).

The non-zero ΔT offset, recorded under without-heating condition, appears to have a significant effect on actual sap flow values which seem generally overestimated at the morning beginning (usually from sunrise to four hours later) and then underestimated towards the afternoon (Figure 7). However, this offset seems to have a less significant effect on the 24-hours cumulative flux since the afternoon underestimation will be compensated, ever partially, by the morning overestimation. The use of this without-heating ΔT offset to correct the under-heating sensor signal was tried to improve results accuracy (Figure 7). The corrected signal seem to be more coherent even concerning the daily evolving. However, since the unheated sensor was mounted on a distinct palm tree, we think that using its signal to correct the other trees' sensors signals is not much accurate.

Despite the thermal insulation precautions being taken during the installation, the observed non-zero ΔT offset, appears to be generated by thermal interferences related to external environment in particular to an air-soil temperature gradient which is rather variable during the day (Cabibel et al., 1991a ; Do and Rocheteau, 2002a). A better protection of the trunk base by shading-nets was attempted to attenuate the observed artifact peaks (Shackel et al., 1992; Roupsard et al., 2006). Regardless of the artifact origin, a signal correction and a measurement improvement should be implemented for a better measurement accuracy. There were some methodological attempts to skirt these temperature gradients by implementing cyclic heating (Do and Rocheteau, 2002b) or by appending in-opposition a cold sensor on the same trunk (Lu et al., 2004). A deeper investigation and research need to be performed to apprehend the artifact origin and to therefore suggest the reliable correction.

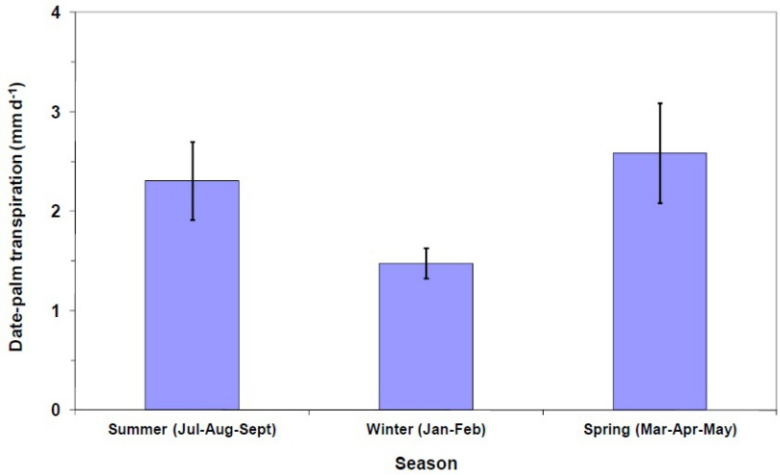


Figure 5. Seasonal means of the daily date palm transpiration (mm d^{-1}) inside the experiment field. Y bars represent ±Standard deviation

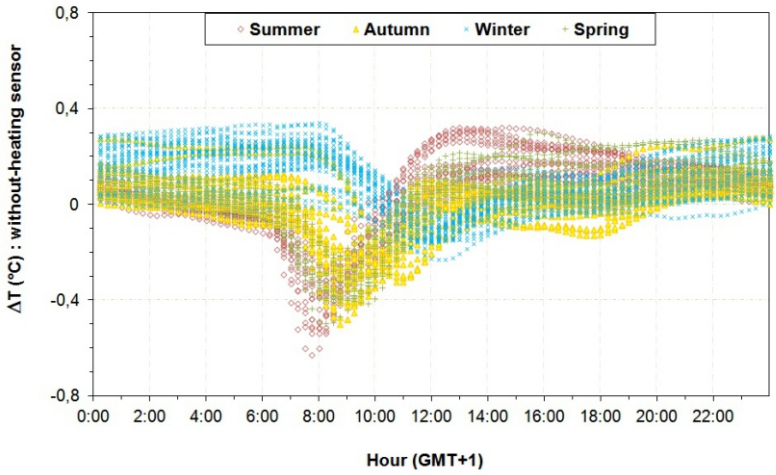


Figure 6. Seasonal variation of the ΔT signals recorded under without-heating state: highlighting of the non-zero thermal offset between the upper and lower needles of sap flow sensor. 15 days of the middle of each season are presented on this figure

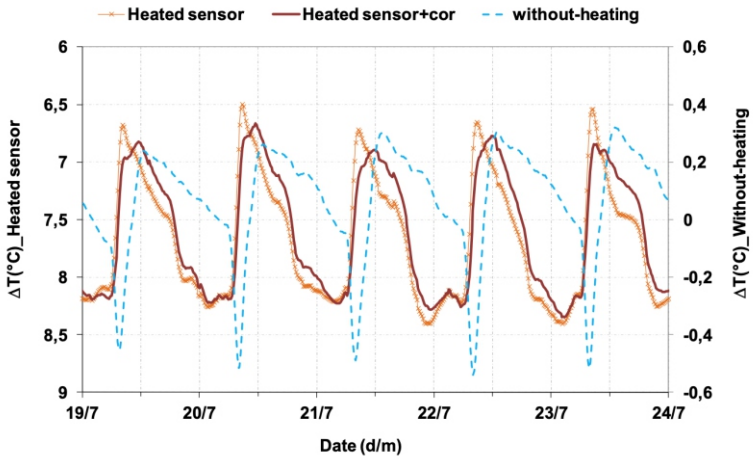


Figure 7. Comparison of the ΔT signals recorded under heating and without-heating state during five summer days: Approach to correct a heated sensor signal using a concomitant without-heating signal

Conclusion

This experiment tried to assess the date palm transpiration using the sapflow measurement and to investigate its hourly, daily and seasonal variation over one-year in relation to the main study site conditions (high evaporative demand, saline shallow water table, distant water supply deliveries)..

At the end of this work, the issued results showed that the instantly transpiration varied with the measured air temperature and was high-related to the monitored shallow water table nycthemeral fluctuation. The latter could therefore be valued to investigate the evapotranspiration flow of the total above-ground canopy and to know more about the shallow groundwater contribution to this flow feeding.

The daily transpiration rate, one-year-averaged at ~2 mm d^{-1}, ranged between 0.5 and 3.5 mm d^{-1} with a clear seasonal variation. Seasonal transpiration measured by this experiment ranged between 1.5 (winter season) and 2.6 mm d^{-1} (spring and summer seasons). During the summer hot season, a suspected-water-stress appearance according to water delivery frequency was also revealed. Indeed, the transpiration rate declined in few days after the irrigation events and could indicate a stress status related also to a detrimental salinity at the tree rhizosphere vicinity.

The one-year-cumulated transpiration was about 730 mm and represented almost 60% of the 1200 mm deduced-evapotranspiration for the overall oasis. From this experiment case, it was noted that the yearly date palm tree transpiration reflects a rather modest water consumption (35 to 45%) relatively to the surrounding Saharan high evaporative demand ranging between 1650 and 2000 mm yr^{-1}. It can therefore be deduced that the date palm tree, in itself, isn't a great water consumer in such cropping conditions. After more results validation, these quantitative elucidations should be considered to rethink the date palm irrigation scheduling and the water management practices inside oasis schemes.

Moreover, this work has revealed the existence of some uncertainties sources that can influence the sap flow measurements. All these issues should be considered in the future for a methodological improvement and more accurate results.

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References

Al-Muaini, A., Green, S., Dakheel, A., Abdullah, A., Abou Dahr, W.A., Dixon, S., Kemp, P., Clothier, B. (2019). Irrigation management with saline groundwater of a date palm cultivar in the hyper-arid United Arab Emirates. Agric. Water Manag., 211, 123-131. [Google Scholar] [CrossRef]

Ayers, R.S., Westcot, D.W. (1985). Water quality of agriculture. FAO Irrigation and Drainage Paper No. 29 (Rev. 1), Rome, 174 pp. [Google Scholar]

Ben Aïssa, I., (2006). Evaluation de la performance d'un réseau de drainage enterré au sein d'une oasis modernisée du sud tunisien : Cas de l'oasis de Fatnassa Nord à Kébili (Tunisie). Mémoire de Master Recherche "Eau et Environnement", AgroM-UM2, Montpellier, France, 119 pp.

Ben Aïssa, I., Bouarfa, S., Vincent, B., Chaumont, C., Perrier, A. (2013). Drainage performance assessment in a modernized oasis system. Irrig. & Drain., 62: 221-228. [Google Scholar] [CrossRef]

Ben Aïssa, I., Bouksila, F., Bahri, A., Bouarfa, S., Chaumont, C., Hichri, W. (2005). Gestion de l'eau et des sels au sein d'une oasis du Sud tunisien. Proc. Seminar "La Modernisation de l'Agriculture Irriguée", Project INCO-Wademed, Knowledge base on water demand management in the Mediterranean countries, 2004, Rabat. (Ed.) Hammani, A., Kuper, M. and Debbarh, A., pp. 312-322. [Google Scholar]

Ben Aïssa, I., Nasr, Z. & Ben Mechlia, N., (2000). Evaluation de la transpiration du Pommier en verger par la mesure thermique du flux de sève brute. Annales de l'INRGREF, num. spécial "Economie de l'eau en irrigation", Hammamet, 14-16 novembre 2000. INRGREF/Cemagref, 232 pp, ISSN:1737-0515, p155-167. [Google Scholar]

Bouarfa, S., Marlet, S., Douaoui, A., Hartani, T., Mekki, I., Ghazouani, W., Ben Aïssa, I., Vincent, B., Hassani, F., Kuper, M. (2009). Salinity patterns in irrigation systems, a threat to be demystified, a constraint to be managed: Field evidence from Algeria and Tunisia. Irrig. & Drain. 58(SI3):273-284. [Google Scholar] [CrossRef]

Brunel, J-P., Ihab, J., Droubi, A.M., Samaan, S. (2006). Energy budget and actual evapotranspiration of an arid oasis ecosystem: Palmyra (Syria). Agric. Water Manag. 84 (2006) 213-220. [Google Scholar] [CrossRef]

Cabibel, B., Do, F., Horoyan, J. (1991a). Mesures thermiques des flux de sève dans les troncs et les racines et fonctionnement hydrique des arbres. I. Analyse théorique des erreurs sur la mesure des flux et validation des mesures en présence de gradients thermiques extérieurs. Agronomie, 11, 669- 678. [Google Scholar] [CrossRef]

Cabibel, B., Do, F., Horoyan, J. (1991b). Mesures thermiques des flux de sève dans les troncs et les racines et fonctionnement hydrique des arbres. II. Évolution dans le temps des flux de sève et comportement hydrique des arbres en présence ou non d'une irrigation localisée. Agronomie, 11 (9), 757-766, doi:10.1051/agro:19910906. [Google Scholar] [CrossRef]

Carr, M.K.V. (2013). The water relations and irrigation requirements of the date palm (Phoenix dactylifera L.): a review. Exp. Agric. 49: 91–113. [Google Scholar] [CrossRef]

Chao, C.C.T., Krueger, R.R. (2007). The date palm (Phoenix dactylifera L.): overview of biology, uses, and cultivation. Hort. Science, 42:1077–1082 [Google Scholar] [CrossRef]

Clearwater, M.J., Meinzer, F.C., Andrale, J.L., Goldstein, G., Holbrook, N.M. (1999). Potential errors in measurement of non-uniform sap flow using heat dissipation probes. Tree Physiology, 19: 681–687. [Google Scholar] [CrossRef]

Do, F., Rocheteau, A. (2002a). Influence of natural temperature gradients on measurements of xylem sap flow with thermal dissipation probes. 1. Field observations and possible remedies. Tree Physiology, 22: 641–648. [Google Scholar] [CrossRef]

Do, F., Rocheteau, A. (2002b). Influence of natural temperature gradients on measurements of xylem sap flow with thermal dissipation probes. 2. Advantages and calibration of a noncontinuous heating system. Tree Physiology, 22: 649–654. [Google Scholar] [CrossRef]

Dufrêne, E., Dubos, B., Rey, H., Quencez, P., Saugier, B. (1992). Changes in evapotranspiration from an oil palm stand (Elaeis guineensis Jacq.) exposed to seasonal soil water deficit. Acta Oecol. 13 (3), 299–314. [Google Scholar]

El-Khoumsi, W., Hammani, A., Bouarfa, S., Bouaziz, A., Ben Aïssa, I. (2017). Contribution de la nappe phréatique à l'alimentation hydrique du palmier dattier (Phoenix dactylifera) dans les zones oasiennes. Cah. Agric. 26: 45005 [Google Scholar]

Fathi, L. (2014). Structural and mechanical properties of the wood from coconut palms, oil palms and date palms. PhD thesis, Faculty of Mathematics, Computer Science and Natural Sciences, University of Hamburg, Germany. 248 p. [Google Scholar]

Floret, C., Pontanier, R. (1982). L'aridité en Tunisie présaharienne: climat, sol, végétation et aménagement. Paris: ORSTOM, (150), 552 p. ISBN 2-7099-060-0 [Google Scholar]

Fuchs, S., Leuschner, C., Link, R., Coners, H., Schuldt, B. (2017). Calibration and comparison of thermal dissipation, heat ratio and heat field deformation sap flow probes for diffuse-porous trees. Agr. For. Meteorol. 244, 151–161. [Google Scholar] [CrossRef]

Granier, A. (1985). Une nouvelle méthode pour la mesure du flux de sève brute dans le tronc des arbres. Ann.Sci. For., 42, 193-200. [Google Scholar]

Granier, A. (1987). Evaluation of transpiration in a Douglas–fir stand by means of sap flow measurements. Tree Physiol. 3, 309–320. [Google Scholar] [CrossRef]

Hachicha, M., Ben Aïssa, I. (2014). Managing Salinity in Tunisian Oases. Journal of Life Sciences, ISSN 1934-7391, USA, Sept. 2014, Vol. 8, No. 9, 775-782. [Google Scholar]

Henia, L. (1993). Climat et bilan de l'eau en Tunisie. Essai de régionalisation climatique par les bilans hydriques. Thèse de Doctorat. Faculté des Sciences Humaines et Sociales de Tunis. 381 p. [Google Scholar]

Hölttä, T., Linkosalo, T., Riikonen, A., Sevanto, S., Nikinmaa, E. (2015). An analysis of Granier sap flow method, its sensitivity to heat storage and a new approach to improve its time dynamics. Agric. For. Meteorol. 211-212, 2-12, [Google Scholar] [CrossRef]

Köstner, B., Granier, A., Cermák, J. (1998). Sap flow measurements in forest stands: methods and uncertainties. Ann. For. Sci. 55 (1-2) 13-27. [Google Scholar] [CrossRef]

Liebenberg, P.J., Zaid, A., (2002). Date palm irrigation. In: Date palm cultivation, Zaid A. (ed.). FAO Plant production and protection paper 156, Rev. 1. FAO, Rome 2002. [Google Scholar]

Loheide II, S.P., Butler, Jr.J.J., Gorelick, S.M. (2005). Estimation of groundwater consumption by phreatophytes using diurnal water table fluctuations: A saturated-unsaturated flow assessment. Water Resour. Res., 41, W07030. [Google Scholar] [CrossRef]

Lu, P., Urban, L., Zhao, P. (2004). Granier's thermal dissipative probe (TDP) method for measuring sap flow in trees: theory and practice. Acta Bot. Sin. 46 (6), 631–646. [Google Scholar]

Madurapperuma, W.S., Bleby T.M., Burgess, S.S.O. (2009). Evaluation of sap flow methods to determine water use by cultivated palms. Env. Exp. Bot. 66:372–380. [Google Scholar] [CrossRef]

Marlet, S., Bouksila, F., Mekki, I., Ben Aïssa, I. (2007). Fonctionnement et qualité des eaux de la nappe de l'oasis de Fatnassa Nord - Arguments géochimiques. Actes du 3ème atelier régional scientifique et technique du Projet Sirma. 04-08 mai 2007, Nabeul, Tunisie. [Google Scholar]

Mekki, I., Jacob, F., Marlet, S., Ghazouani, W. (2013). Management of groundwater resources in relation to oasis sustainability: The case of the Nefzawa region in Tunisia. J. Env. Manag., 121:142-151. [Google Scholar] [CrossRef]

Munier P. (1973). Le Palmier dattier - Techniques agricoles et productions tropicales. Maison Neuve et Larose, 217pp; Paris.

Nixon, R.W. (1951). The Date Palm: "Tree of Life" in the Subtropical Deserts. Economic Botany, Vol. 5, No. 3 (Jul. - Sep., 1951), pp. 274-301. [Google Scholar]

Omrani, N. (2015). Verbesserung der Bewässerungseffizienz in den Oasen Südtunesiens-Fallstudie Nefzaoua Oasen. PhD thesis, Karlsruhe Institute of Technology (KIT), Germany. 129 pp. [Google Scholar]

Paudel, I., Kanety, T., Cohen, S. (2013). Inactive xylem can explain differences in calibration factors for thermal dissipation probe sap flow measurements. Tree Physiology, 33, Issue 9, 1 September 2013, Pages 986–1001. [Google Scholar]

Peters, R.L., Fonti, P., Frank, D.C., Poyatos, R., Pappas, C., Kahmen, A., Carraro, V., Prendin A.L., Schneider, L., Baltzer, J.L., Baron-Gafford, G.A., Dietrich, L., Heinrich, I., Minor, R.L., Sonnentag, O., Matheny, A.M., Wightman, M.G., Steppe, K. (2018). Quantification of uncertainties in conifer sap flow measured with the thermal dissipation method. New Phytologist, 4, [Google Scholar] [CrossRef]

Poyatos, R., Granda, V., Molowny-Horas, R., Mencuccini, M., Steppe, K., Martinez-Vilalta, J. (2016). SAPFLUXNET: towards a global database of sap flow measurements. Tree Physiol. 36, 1449–1455 [Google Scholar] [CrossRef]

Rabbel, I., Diekkrüger, B., Voigt, H., Neuwirth, B. (2016). Comparing T_{max} determination approaches for Granier-based sap flow estimations. Sensors, (16) 2042: 1-16. [Google Scholar] [CrossRef]

Ringersma, J., Mechergui, M., Pijnenburg, S. (1996). Transpiration measurements in Date Palm using the Granier method. In: Proc. Int. Conf. on Evapotranspiration and irrigation scheduling, Nov 3-6 1996, Texas American Society of Agricultural Engineers. [Google Scholar]

Roupsard, O., Bonnefond, J.M., Irvine, M., Berbigier, P., Nouvellon, Y., Dauzat, J., Tega, S., Hamel, O., Jourdan, C., Saint-Andre, L., Mialet-Serra, I., Labouisse, J.P., Epron, D., Joffre, R., Brconnier, S., Rouziere, A., Navarro, M., Bouillet, J.P. (2006). Partitioning energy and evapotranspiration above and below a tropical palm canopy. Agric. For. Meteorol., 139:252–268. [Google Scholar]

Sellami, M.H., Sifaoui, M.S. (2003). Estimating transpiration in an intercropping system: measuring sap-flow inside the oasis. Agric. Water Manage. 59 (3), 191–204. [Google Scholar] [CrossRef]

Sellami, M.H. (2008). A scientific guide for agricultural water management and biodiversity conservation inside the North African oasis. In: Agricultural Water Management Research Trends. 171-212. Magnus L. S. (ed.), ISBN 978-1-60456-159-3, Nova Sc. Pub., 2008. [Google Scholar]

Shackel, K.A., Johnson, R.S., Medawar, C.K., Phene, C.J. (1992). Substantial errors in estimates of sap flow using the heat balance technique on woody stems under field conditions. J. Amer. Soc. Hort. Sci., 117(2), 351-356. [Google Scholar] [CrossRef]

Sperling, O., Shapira. O., Cohen, S., Tripler, E., Schwartz, A., Lazarovitch, N. (2012). Estimating sap flux densities in date palm trees using the heat dissipation method and weighing lysimeters. Tree Physiol. 32, 1171–1178. [Google Scholar] [CrossRef]

Tomlinson, P.B. (2006). The uniqueness of palms. Botanical Journal of the Linnean Society, 151, 5-14. doi:10.1111/j.1095-8339.2006.00520.x [Google Scholar] [CrossRef]

Zhen, J., Tripler, E., Pevzner, Sh., Lazarovitch, N. (2019). Impact of fruiting on gas exchange, water fluxes and frond development in irrigated date palms. Scientia Horticulturae. 244, 234-241. [Google Scholar] [CrossRef]