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Research paper

Estimating sap flux densities in date palm trees using the heat dissipation method and weighing lysimeters

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In a world of diminishing water reservoirs and a rising demand for food, the practice and development of water stress indicators and sensors are in rapid progress. The heat dissipation method, originally established by Granier, is herein applied and modified to enable sap flow measurements in date palm trees in the southern Arava desert of Israel. A long and tough sensor was constructed to withstand insertion into the date palm's hard exterior stem. This stem is wide and fibrous, surrounded by an even tougher external non-conducting layer of dead leaf bases. Furthermore, being a monocot species, water flow does not necessarily occur through the outer part of the palm's stem, as in most trees. Therefore, it is highly important to investigate the variations of the sap flux densities and determine the preferable location for sap flow sensing within the stem. Once installed into fully grown date palm trees stationed on weighing lysimeters, sap flow as measured by the modified sensors was compared with the actual transpiration. Sap flow was found to be well correlated with transpiration, especially when using a recent calibration equation rather than the original Granier equation. Furthermore, inducing the axial variability of the sap flux densities was found to be highly important for accurate assessments of transpiration by sap flow measurements. The sensors indicated no transpiration at night, a high increase of transpiration from 06:00 to 09:00, maximum transpiration at 12:00, followed by a moderate reduction until 08:00; when transpiration ceased. These results were reinforced by the lysimeters' output. Reduced sap flux densities were detected at the stem's mantle when compared with its center. These results were reinforced by mechanistic measurements of the stem's specific hydraulic conductivity. Variance on the vertical axis was also observed, indicating an accelerated flow towards the upper parts of the tree and raising a hypothesis concerning dehydrating mechanisms of the date palm tree. Finally, the sensors indicated reduction in flow almost immediately after irrigation of field-grown trees was withheld, at a time when no climatic or phenological conditions could have led to reduction in transpiration.

Keywords: evapotranspiration, irrigation scheduling, sap flow, sap flux density.

Introduction

Being a monocot species, the vascular system arrangement in the stem of date palm trees differs significantly from that of the majority of commercially grown dicotyledonous fruit trees. Palm trees do not have cambium and their stem lacks secondary xylem vessels. The date palm's stem is comprised of primary vascular bundles embedded in a parenchymatous tissue and surrounded by a wide external layer, the leaf bases of previous years. The diameters of the vascular bundles vary between 1 and 3 mm, depending on their location within the stem

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(Parthasarathy and Klotz 1976, Tomlinson 1990). The surrounding tissue could be several centimeters wide, providing thermal insulation and mechanical support. For the duration of its life time, the tree is dependent on the primary vascular tissues of its stem, rendering the tree vulnerable to hydraulic disruptions (Zimmermann and Sperry 1983). Vascular bundles are more abundant in the peripheral area than in the stem's inner cylinder (Parthasarathy and Klotz 1976). However, the increased abundance of vascular bundles in the outer parts of the stem does not necessarily suggest increased water movement, since the latter is dependent on the direction of the vessels (i.e., towards the crown of the tree or sideways to the leaves), bundle diameter and the ratio between protoxylem and metaxylem. Finally, as water flow takes place within the same vessels throughout the life span of the plant, while its hydraulic structure and properties vary little, the date palm tree is an attractive candidate for adequate and representative long-term sap flow measurements.

Since water use in plants varies both seasonally and diurnally, continuous monitoring of water consumption is essential for optimizing irrigation scheduling, both for irrigation frequency and amounts. In these tall trees, growing up to 20 m in height, it is very difficult to perform scheduled irrigation based on physiological parameters that are usually measured in the canopy (e.g., leaf water potential, stomatal conductance, the rate of carbon fixation or chlorophyll *a* fluorescence; Ford et al. 2004). Therefore, it is crucial to be able to assess water use in an accessible and representative tree organ, such as the stem.

Sap flow measurements are widely used in agricultural research. Common sap flow measurement methods include the heat pulse, the heat dissipation and the heat balance methods (Swanson 1994). When deploying sensors deep into fibrous stems such as the palm's, the simplicity of installation (Do and Rocheteau 2002) makes the heat dissipation method favorable. Heat dissipation sensors have previously been used in various plantations. The sensors have been successfully applied for tracking sap flux density (Fd) in banana trees, with correspondence to gravimetric measurements of transpiration (Lu et al. 2002, 2008). As for date palms, sap flow has been evaluated and presented as a function of global and net radiation values (Sellami and Sifaoui 2003). Furthermore, Renninger et al. (2010) had calibrated the heat dissipation method for Amazonian palms while investigating transpiration changes between the wet and dry seasons. The notion of longer sensor probes for reaching deeper into the stem was also addressed in previous works; Lu et al. (2000) worked on matured orchard-grown mango trees with sensors as long as 20 cm, Sellami and Sifaoui (2003) used 6-cm-long probes for sap flow measurements in palm trees grown in an oasis and Roupsard et al. (2006) used 12-cm-long probes for sap flow assessments in tropical palms. Nevertheless, none of those sensors were long enough for conducting research on fully grown date palm trees. Furthermore, extra-strong probes, forced or even hammered into the tree and therefore leaving no spaces between the probe and the conducting tissue, can allow long-term sap flow measurements.

Granier's equation for calibrating the heat dissipation method is based on an empirical relationship between three measured species (Granier 1985, Lu et al. 2004). Hence, in species for which physical investigation of heat transfer in the stem is lacking, it was advised by Smith and Allen (1996) to calibrate this technique. The transient properties of the sap flux densities along the radial and vertical axes of the stem should be addressed as well. For the heat dissipation sensor to supply a representative value of the total water passing through the stem it is crucial to understand the pattern of the flow within the tree's stem. Clearwater et al. (1999) claimed that the matter of variance in sap flow along a single probe has not been addressed, after inserting long probes into deep sapwood. Their research pointed to an underestimation of the sap flow made by Granier's equation due to contact between the sensor and the inactive xylem, and promoted the use of multiple short probes for true description of the sap flux density.

The objectives of the present study were: (i) to develop a heat dissipation sensor specifically for date palm trees; long enough to reach the stem's inner core, tough enough to penetrate the outer fibrous layers and sensitive enough to the range of the palm's sap flux densities. (ii) To compare between the measured transpiration (T) and the sap flow (F) on both hourly and daily resolutions. (iii) To attain an empirical correction factor for the original Granier equation.

Materials and methods

The experimental site and trees

Fully grown date palm trees (*Phoenix dactylifera* L., cv. Medjool), grown in massive weighing lysimeters in Israel's southern Arava R&D Yotvata station (29°53N, 35°04E) were used for this study. The lysimeter tanks (10 m^3 in volume) are made of PVC equipped with a bottom layer of highly conductive porous media and filled with local soil. The lysimeter's weight was recorded every 5 min; irrigation and drainage events were recorded correspondingly. Lysimeters were equipped with four load cells (H8C-N5-10K-6YB, Zemic Inc., Santa Fe Springs, CA, USA) with an accuracy of ±55 g and a maximum weight capacity of 36 tons. T (kg) was calculated from the mass balance as: $T = I - D - \Delta W$, where I is irrigation, D is drainage, and ΔW is the change in lysimeter mass. Further information concerning the lysimeter installation can be found in the work of Ben-Gal and Shani (2002), Tripler et al. (2007, 2011).

Three fully grown palm trees were examined for sap flux density during this study. Trees were 10 years old; with stem heights of >10 m and diameters of 60 cm. Stem diameter

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remained constant all the way from bottom to top due to an appropriate irrigation regime throughout the years of growth. Despite having a 30-cm stem radius, clearing the dry leaf basis surrounding the fibrous tissues, showed that the first 7 cm are made of non-conducting vessels; these vessels supplied older leaves with water in previous years. These leaves have been cut and therefore such vessels no longer exist. Hence, for future references the assumed conductive sapwood would have a radius of 23 cm. The region is hyper-arid, reaching maximum temperatures of 42 °C, with low relative humidity (15%), and <25 mm average annual precipitation; thus, although some measurements were made during the autumn season, the trees still encountered significant water loss through transpiration. Irrigation water was pumped to tanks stationed at a height of 4 m, after which it flowed gravimetrically through 8 l h^{-1} drippers (Netafim, Tel Aviv, Israel). Irrigation amounts were calculated according to previous drainage collection, thus sustaining a constant leaching factor of 0.3 (i.e., daily ratio between drainage and irrigation quantities) and avoiding water stresses. Depending on climatic conditions irrigation was divided to five events a day, thus avoiding runoff and assuring infiltration of water inside the tank.

Sensor construction

The heat dissipation sensors were constructed to meet the date palm stem sap flow measuring requirements (Figure 1). The probes are extra long and tough, thus enabling sap flow measurements as deep as the stem's center. The sensor head is crafted from stainless steel while the rest of the pipe is made of Perspex tube. The pipe is 30 cm long with a radius of 0.5 cm and is filled with an epoxy (EP 169 & EPC 140/9; Polymer Gvulot, Halutza, Israel) casting. A 470-Ω metal film resistor (IRC, Corpus Christi, TX, USA) was placed in the center of the steel head, alongside a copper–constantan thermocouple (T type) while the rest of the space was filled with epoxy as well. This resistor was chosen especially for the sensor's requirements; its resistance tolerance is down to 0.05%, it has low noise and a negligible voltage coefficient, thus assuring minimum variance in the heat supply. The probe's steel tip is 2 cm long and has a radius of 0.5 cm; the tip's whole outer surface is thermally active at passing heat into the stem from the power-supplied resistor packed into it. When powered by a constant regulated voltage of 12 V, the power output of the sensor was ~300 mW. Power was supplied by a rechargeable battery. The battery was constantly connected to a charger, and regulated by a voltage regulator, hence maintaining constant power supply. The heat dissipation sensor requires two probes to be inserted at the measured site; hence it is referred to as a 'dual probe' sensor. There is always one probe which does not receive power supply, and thus will measure the reference temperature, while another probe is supplied by electric power and records the heated stem temperature. By making sure that the reference probe is located ~10 cm upstream from the heated probe, heating of the reference probe is avoided. In our study both reference and heating probes were constructed in exactly the same way, where the only difference was that when installed, the reference probe was not connected to the power supply. Thermocouples and resistors were connected to the datalogger and battery, respectively. Inside the tree the wires run through the epoxy-filled Perspex pipe, thus protecting all inner parts from mechanical or chemical damages.

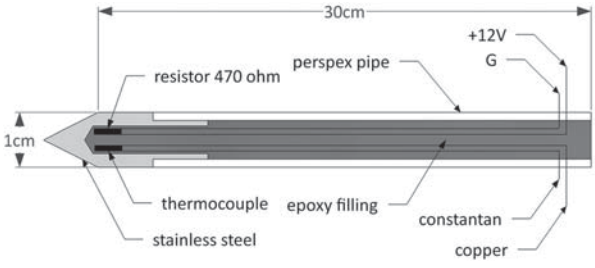

Figure 1. A date palm tree adapted heat dissipation probe. The probe is 30 cm long and has a radius of 0.5 cm. Its extra length enables measurements at the stem's center. The tip of the probe is made of stainless steel and it was sharpened to allow maximum penetration; its length from tip to base is 2 cm. A 470 Ω resistor and a copper constantan thermocouple were stationed at the probe tip, thus allowing both heating and tracking temperature variations.

Sensor installation and allocation

A total of four sensors were inserted into each tree, at 1 and 10 m heights from the ground surface. For each height there were two depths, 30 cm deep (the stem's center) and 24 cm deep, see Figure 2. A pre-drill with an 8 mm driller was

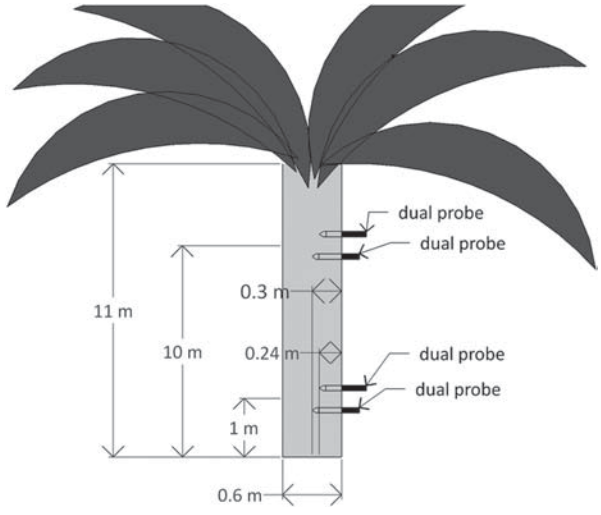

Figure 2. An illustration of a date palm tree and the sensors connected to it. The date palm tree is 11 m tall, with a radius of 0.3 m. Four sensors are installed along the tree's stem; each sensor contains two probes, a heated one and a non-heated one that is used for the reference temperature. Two heights (1 and 10 m from surface) and two depths (30 and 24 cm) are examined.

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performed before inserting the probes. The probe was pushed inside the tree, and hammered to reach the final depth and maximum contact with the stem's inner tissues. For each sensor the two probes were connected to one another by the constantan wires. The copper wires on the other hand run all the way from the probes to the datalogger (CR1000, Campbell Scientific, Logan, UT, USA), thus attaining temperature differential readings. Readings were taken every 10 s, and the data were averaged and stored every 5 min. Finally, the data were processed with the MATLAB software. The heat dissipation index, k, was calculated according to Granier's equation: $k = (\Delta T_{max} - \Delta T)/\Delta T$ where ΔT is the temperature difference between a heated and a non-heated location, and ΔT_{max} is the maximum temperature difference obtained when sap flow was assumed to be zero. Finally, by inserting an independent reference probe at each height, the stem's inner temperature was measured. These thermocouples were connected directly to the datalogger via both copper and constantan wires.

Measuring the hydraulic conductivity

A set of mechanistic measurements was made to detect the specific hydraulic conductivity (hc) for a cross section of the stem. A 5-m-tall tree was cut down in a cultivated date palm plantation. Sapwood samples were extracted from 20-cm-thick cuttings of the stem. An increment borer with a core diameter of 5 mm (Haglof, Langsele, Sweden) was used to withdraw a 2.5-cm-long axial stem (i.e., vertical to the cutting) core samples. Six depths were sampled: 8 cm (slightly into the depth of the stem, skipping all the dry bark tissue), 10, 12, 14, 16 and 18 cm (near the stem's center). All core samples were kept saturated in a 10 mM KCl solution until tested for hc. The samples were pushed into Tygon tubing, thus sealing all peripheral open vessels and connected to a water tank by additional Tygon tubing. Finally, the outcoming water discharge rate was constantly measured gravimetrically. Under these laboratory settings, the specific hydraulic conductivity was calculated according to: $hc = QL/A\Delta P$ where Q is the measured discharge rate (g s^{-1}), ΔP is the applied pressure (10 kPa), L is the sample length (2.5 cm), A is the sample section area (0.2 cm^2) and hc is the specific hydraulic conductivity (kg m^{-1} s^{-1} MPa^{-1}).

Irrigation field experiment

Finally, a field irrigation experiment was conducted in a neighboring cultivated plantation in the Arava. Three sensors were inserted into a single tree and the sap flux density at the stem's center was followed up over the months of July and August 2011. The tree was regularly irrigated with drip irrigation as was the rest of the plantation. Irrigation was suspended, for 2 weeks from 8 August by removing the drip lateral away from the tree's vicinity; thus, the tree was deprived of irrigation water at the peak transpiration period of the year. All sensors were connected to a datalogger and the temperature differences were stored continuously. The tree was 6 m tall and had a radius of 25 cm. The whole installation process was performed in the exact same manner as that for the calibration experiment conducted on the lysimeter trees.

Results and discussion

Axial variations in sap flux densities and specific hydraulic conductivities

Sap flux density (Fd), as measured at two depths (i) for three consecutive days, exhibited explicit spatial variations. Fd was calculated according to the original Granier (1985) calibration ($Fd = 188.99k^{1.231}$), where k is the heat dissipation index (see Materials and methods for equation). Sensors were placed at two depths, 30 cm deep (i.e., the stem's center) and at 24 cm deep (Figure 3) 1 m above ground. The peak flux was reduced by half, from 25 to 12 g m^{-2} s^{-1}, at the outer stem's tissue. Such findings highlight the significance of measuring the sap flux densities at the stem's center, being the location where stable, massive flow occurs. Moreover, these variations raise the importance of attaining hydraulic spatial description for the conductive area. Differences in sap flux densities were also found by Sellami and Sifaoui (2003). Their work presented clear differences between two depths of the stem, and for most of the hours of the day the inner flow exceeded the outer flow. Nevertheless, in their study the sensor was not inserted all the way into the stem's center where the massive flow is assumed to occur. Conversely, in their study of coconut palms, Roupsard et al. (2006) found a constant Fd pattern throughout the stem's radius; again, their sensor did not reach the center of the stem and an extrapolation was made.

The radial variability of the stem's hydraulic properties was evaluated by mechanistic measurements. The specific hydraulic conductivity (hc) for six different depths of the stem is presented in Figure 4. Depths of 8, 10, 12, 14, 16 and 18 cm into the stem were evaluated. The stem's first 7 cm was comprised of dry tissues known as the fibrous sheath; these are dried leaf

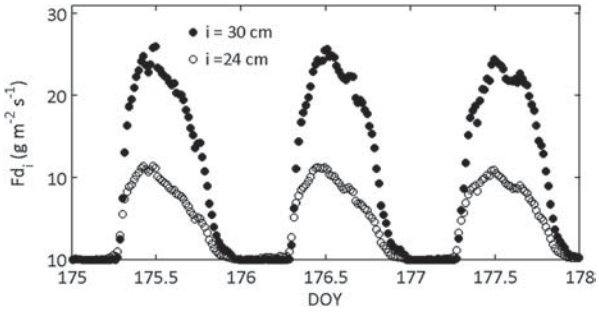

Figure 3. The flux density (Fd) variations at two different depths (i) during three consecutive days. Two sensors were installed 1 m above ground; on at the depth of 24 cm (empty circles) and the second at 30 cm (full circles).

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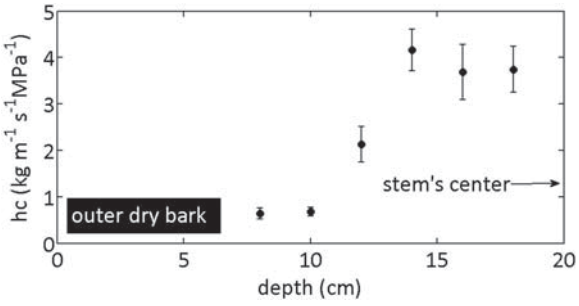

Figure 4. Specific hydraulic conductivity (hc) values for axial stem samples. Cores were collected at 2 cm intervals from the center of the stem and outwards at five different stem sections. The samples were checked for hydraulic conductivity under a water column pressure of 10 kPa. Samples were 2.5 cm long and had a radius of 0.25 cm. The whole stem profile had a radius of 20 cm, and the outer 7 cm were dry fibrous non-conducting tissue. Each data point represents five stem cores from the same radial position and their standard error.

bases and vessels that supplied the leaves with water in the past. In accordance, no flow was detected in this region (data not shown). Very low hc was detected in the peripheral zones of the stem followed by an increase in hc with depth toward the center of the stem. Unlike dicots the peripheral area of the stem conducts very little water; then half way into the stem's center hc doubles and at the inner 5 cm the hc is doubled again. Vessel distribution and functionality of the stem cross section support the results of hc, as most axial flow occurs in the center of the stem while the relative abundance of small vessels in the periphery is responsible for radial flow to the leaves (Tomlinson 1990). Furthermore, the specific hydraulic conductivity reduction at the peripheral parts of the stem corresponds to the reduced Fd once moving away from the stem's inner core.

Sensor evaluation

Figure 5a presents the actual transpiration measured by the lysimeters versus the palm's sap flow as detected by the modified sensors. Sap flow is calculated from Fd as detected at the inner sensors (i.e., stem's center), using the original Granier (1985) calibration, and assuming homogeneous radial hydraulic properties. The supposed conductive area was 0.17 m^2, having a stem radius of 30 cm yet neglecting the outer 7 cm, being absolutely non-conductive. The Granier equation presents high correlation to the modified sensor's outputs, attaining a high r^2 of 0.9. Nevertheless, there is a 40% underestimation of the total flow assessed by the sensors (i.e., slope value of 1.4). Such underestimation of the flow could be caused by inappropriate calibration parameters and the need of local correction factors for our case study.

As previously discussed, the radial profile of both hydraulic properties and sap flux densities is not homogeneous; this could be a major reason for the sensors' underestimation of the flow as well. Furthermore, a recent study conducted over palms

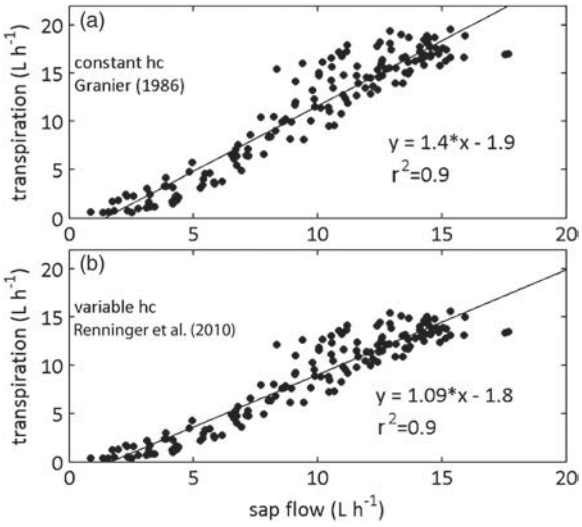

Figure 5. Water flow as measured by the modified sensors versus the actual transpiration (full circles). (a) Total flow was calculated according to Granier's (1985) original equation, flux densities were measured at the stem's center and homogeneous radial flow was assumed. A linear regression line is presented for the evaluation of the required correction factor. (b) Total flow is calculated according to Renninger et al.'s (2010) equation, flux densities are measured at two depths (i.e., 24 and 30 cm), and a non-homogeneous radial flow profile is assumed.

produced a modified calibration for sap flow (Renninger et al. 2010), and should be more appropriate for this research. Thus, using Renninger et al.'s (2010) calibration ($Fd = 192.3k^{1.3}$), and assuming varying hydraulic conductance, results in a better fit between sap flow and transpiration (Figure 5b). Sap flow in this case is calculated for sensors at both depths (i.e., 24 and 30 cm); the inner 6 cm are represented by the inner sensors, while the surrounding 17 cm are represented by the outer sensors. This is by no means an adequate description of the axial variance of fluxes. Nevertheless, Figure 5b clearly exhibits an improvement of the sap flow measurements. The correlation is still high ($r^2 = 0.9$) and the slope value is now only 1.09 (9% underestimation of the total flow). Therefore, sap flow calculations henceforth will be according to Renninger et al.'s (2010) equation.

The sensor's reaction to Fd changes was not immediate, a time factor was inserted into the data. It was found that by referring the sensors' output to Fd of the previous hour, maximum correlation was attained, as r^2 values increased from 0.75 to the presented 0.9. Such time delay of the sensor could be a result of natural time differences between transpiration and sap flow due to the stem's water capacitance. However, time delays in the sensing tip could also be a result of the probes' thermal properties, although laboratory tests proved the sensor's reaction was almost immediate.

As the Granier method requires the comparison between momentary heat dissipation and zero flux heat dissipation values (assumed to occur at night) we had to evaluate the 'zero

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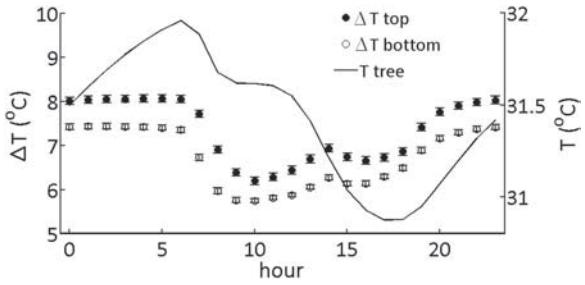

Figure 6. Temperature differences, ΔT, between the reference and the heated probes for two sensors. Both sensors are located in the tree's center but at different heights (1 and 10 m, empty and full circles, respectively). The data were collected and averaged for the whole month of August. Single reference probes located correspondingly at the stem's center exhibited the stem's internal temperature (line).

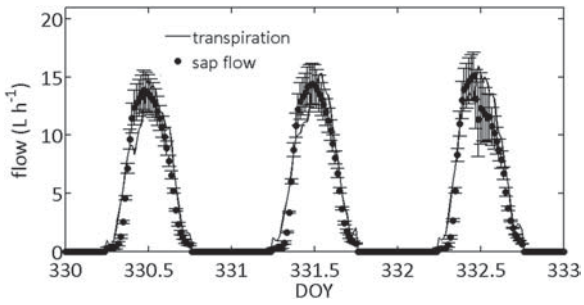

Figure 7. Sap flow as measured in two trees over three consecutive days by both the heat dissipation sensor (dots with error bars) and the weighing lysimeters (line). Sap flow was calculated according to Renninger et al.'s (2010) calibration.

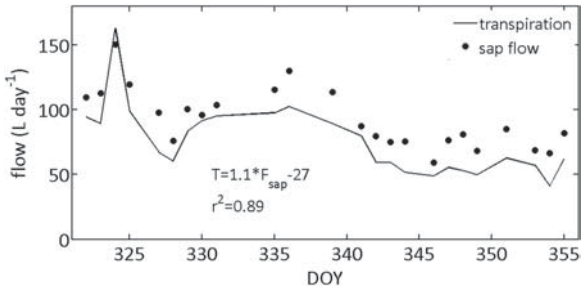

Figure 8. Sap flow at the upper part of the tree (full circles) and transpiration (line) values of >30 consecutive days as measured by the heat dissipation sensor and the weighing lysimeters. A linear regression was calculated, exhibiting the required correction factors.

night flux assumption'. In Figure 6, temperature differences between the heated and the reference probes are presented at hourly bases as averaged for the whole month of August. These data are from two sensors located at the center of a single tree, at two heights (1 and 10 m, empty and full circles, respectively). Stable values were attained throughout the night hours, from 22:00 to 6:00. Therefore, after proving minimum variations for the night hours, and attaining very similar values throughout the month, the daytime ΔT values could safely be calculated against the night values. The daily temperatures (line) at the center part of the tree (measured by single reference probes) are also presented in Figure 6. Variance of the internal temperatures was found to be extremely low, ranging between 31 and 32 °C, and independent from climatic conditions, e.g., the day's sun hours or outside temperatures, due to the thickness of the stem and the outer dry insulation tissues. As the daily inner temperature pattern does not fit the ΔT cycle either, there seems to be no influence of stem temperature on the sensor's reading. Furthermore, such low daily temperature fluctuations, of ~1 °C, are not expected to influence the probes' materials which are specially constructed to meet higher temperature variations.

Results of the sap flow at the upper part of the tree and transpiration are presented in Figure 7, for three consecutive days. This figure acts as an authentication for the modified sensor readings as it exhibits values with very high correspondence to the transpiration. There are almost perfect matches during the moderate flux periods of the day, i.e., morning and afternoon. However, for the peak transpiration period in the middle of the day less agreement is found between the different sensors, hence the larger error bars. The sensors also attain values somewhat different than the ones measured by the lysimeter at these noon hours; yet, maximum flow is fairly evaluated. Again, differences could be caused by physiological tree conditions or technical issues related to the sensors; yet probably are a combination of both. Both sensor and lysimeter exhibited the repetitive daily flow pattern; predawn values are low, ascend through the morning, reach maximum values at midday, descend through the afternoon, and reach minimum values again at night.

A daily integral of both sap flow and transpiration is presented in Figure 8. When daily values are presented there is no time delay in the sensor's reaction, and the parameters' correspondence is naturally clearer. The modified sensors still underestimate flow by ~10% when compared with transpiration as measured by the lysimeters; thus, future calculations require a corresponding correction factor. As the research aim is to improve future irrigation practices in agriculture, focusing on the daily scale may be sufficient and will suit future research.

Flux densities at the stem's center were found to be larger in the upper part of the tree (at 10 m) in comparison with the lower part (1 m height), as shown in Figure 9. The Fd values during night hours (00:00–06:00) were low at both heights; the early-morning increase was similar, but later on sap flux density differed between the sensors. While the bottom sensor measurements stabilized at around 10:00, the sap flux density measured by the upper sensor continued to increase until noon. Furthermore, the upper sensor exhibited a smoother curve, while the lower one was more 'noisy'. Finally, the upper sensor exhibited higher values until midnight as compared with

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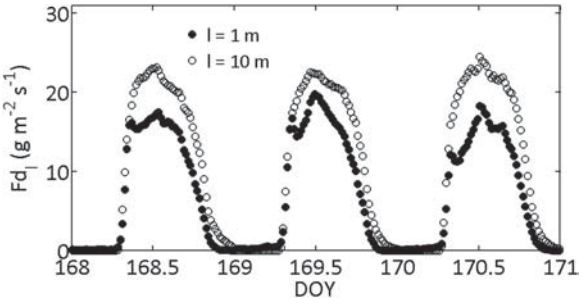

Figure 9. Flux density (Fd) variations with height (*l*) during three consecutive days. Sensors were installed at the stem's center at the heights of 1 and 10 m above ground (full circles and empty circles, respectively).

the bottom one. Such phenomena, increased flux densities at the upper part of the tree, could be explained by the water capacitance of the stem. As water is removed from the parenchymatous tissue into the xylem vessels, it could compensate for root failure following the high water demand at the time of peak transpiration. Such a hypothesis was raised by Sellami and Sifaoui (2003), following their research on date palm trees, where they detected increased sap flows at the upper part of the stem as well as differences in the daily curves for 1.5 and 6 m measurement heights. Variation between inflow (extraction of water from soil) and sap flow was also discussed by Granier (1987), suggesting that they are caused by changes in stem water content, and are dependent on soil water status, stem density and stem age. The preferred value for transpiration assessment through sap flow would be that of the upper measurement (Swanson 1994, Grime et al. 1995). Naturally, the amount of daily water supplied by the stem's reservoir is highly dependent on the soil and climatic conditions, where drier circumstances will lead to more water use from the storage (Cabibel and Do 1991). These results agree with the findings of Holbrook and Sinclair (1992) concerning the palm stem's functionality as a water reservoir due to the high modulus of elasticity of its parenchyma tissue as an additional mechanism for avoiding hydraulic damage.

In this research case, the estimated amount of water passing through the top part of the tree would be 123 l a day (according to the sensors installed at the top of the tree), which is in agreement with the lysimeter measurements. Nevertheless, the lower sensor sensed only 87 l per day, which is 29% less than the prediction. Based on all that was discussed above, one could assume that water was supplied by the stem's reservoir, and would be compensated for during night time by root water uptake. Nevertheless, at the current stage neither our sensors nor our calculations could detect those lower fluxes and support this hypothesis. Therefore, such a hypothesis should clearly be further investigated. Assuming unlimited soil water supply and sufficient root hc, we should also consider decreased hc in the older parts of the stem. As a monocot, the palm stem is of primary origin and no secondary growth is involved (Tomlinson 1990). Therefore, the initial hc may undergo changes related to aging. Thus, in a 10-year-old palm tree, where the upper parts of the stem are many years younger than its lower parts, hydraulic properties could be somewhat different.

Field experiment

Figure 10 shows the effect of irrigation deprivation in a cultivated tree. This experiment was performed as further evaluation for the modified sensor's ability to detect changes in sap flow under field conditions. The average daily output from three sensors installed at the center of a single tree is presented. During the first week sap flow variations (full circles) over a well-irrigated period were evident; there is a very clear correspondence between the daily sap flow and the climatic conditions (line). On day 220 of the year irrigation was discontinued in the tree's vicinity. Figure 10 clearly exhibits the reduction of daily sap flow due to the deprivation of water from a tree at a most crucial time of the year, when the evaporative demand is very high (>7 mm a day) and fruit growth is at its peak. Sap flow continues to decrease for the duration of the experiment, as soil water content is also reduced due to the tree's exploitation of the available water storage. The potential evapotranspiration is also presented in this figure, exhibiting no dramatic changes throughout the experiment.

Conclusions

Despite several obvious obstacles that have limited previous research, sap flow measurements using the heat dissipation method are feasible in the deep sap wood of date palm trees. Yet, an increase of flow towards the inner part of the stem, as observed by the modified sensors and by mechanistic measurements of the specific hydraulic conductivity, stress the importance of conducting measurements even at the most inner parts of the stem. Such deep measurements could only

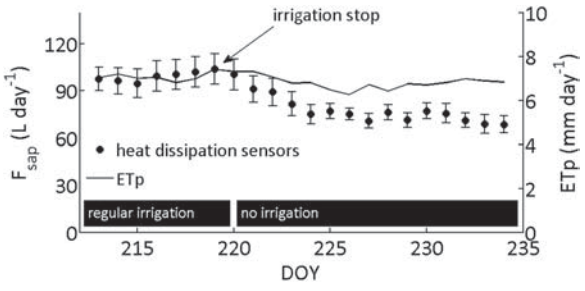

Figure 10. Response of sap flow to irrigation deprivation. A set of three sensors were placed at the stem's center of a fully grown date palm in a commercial plantation in order to monitor sap flow (full circles). After a week of base measurements, irrigation was stopped. The sensor's measurements are followed by the potential evapotranspiration (line).

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be achieved by an extremely long and tough sensor, such as the one presented for the first time in this research. Sap flow, calculated according to Granier's original equation and the stem's inner fluxes, proved to be highly correlated with transpiration measured by lysimeters yet required an excessive correction factor (40%) due to underestimation of flow. Nevertheless, when inducing radial changes in sap flux densities, and using Renninger et al.'s (2010) modified sap flow calibration for palms, the error was drastically reduced to 9%. The sap flow, as measured by the heat dissipation sensor, follows the daily transpiration with a time delay of ~1 h. This time interference could easily be corrected at the calculations stage, yet from a practical point of view it seems that such high resolution is not needed for the field of irrigation science. The daily resolution on the other hand is both highly relevant for the improvement of irrigation applications, and exhibits no time offsets. On the vertical axis there was an acceleration of flow towards the upper parts of the tree, raising several hypotheses that should be further looked at. Finally, the modified sensor successfully provided indications of water stress under field conditions, and therefore should be considered for use as an irrigation controller.

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Conflict of interest

None declared.

References

Ben-Gal A, Shani U (2002) A highly conductive drainage extension to control the lower boundary condition of lysimeters. Plant Soil 239:9–17.

Cabibel B, Do F (1991) Thermal measurements of sap flow and hydric behavior of trees. 1. Theoretical-analysis of the errors in sap-flux estimations and measurement validation in the presence of external thermal-gradients. Agronomie 11:669–678.

Clearwater MJ, Meinzer FC, Andrade JL, Goldstein G, Holbrook NM (1999) Potential errors in measurement of nonuniform sap flow using heat dissipation probes. Tree Physiol 19:681–687.

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

Ford CR, McGuire MA, Mitchell RJ, Teskey RO (2004) Assessing variation in the radial profile of sap flux density in *Pinus* species and its effect on daily water use. Tree Physiol 24:241–249.

Granier A (1985) A new method of sap flow measurement in tree stems. Ann Sci For 42:193–200.

Granier A (1987) Evaluation of transpiration in a Douglas-fir stand by means of sap flow measurements. Tree Physiol 3:309–319.

Grime VL, Morison JIL, Simmonds LP (1995) Including the heat-storage term in sap flow measurements with the stem heat-balance method. Agric For Meteorol 74:1–25.

Holbrook NM, Sinclair TR (1992) Water-balance in the arborescent palm, Sabal-Palmetto. 1. Stem structure, tissue water release properties and leaf epidermal conductance. Plant Cell Environ 15:393–399.

Liu HJ, Cohen S, Tanny J, Lemcoff JH, Huang GH (2008) Transpiration estimation of banana (*Musa* sp.) plants with the thermal dissipation method. Plant Soil 308:227–238.

Lu P, Muller WJ, Chacko EK (2000) Spatial variations in xylem sap flux density in the trunk of orchard-grown, mature mango trees under changing soil water conditions. Tree Physiol 20:683–692.

Lu P, Woo KC, Liu ZT (2002) Estimation of whole-plant transpiration of bananas using sap flow measurements. J Exp Bot 53:1771–1779.

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

Parthasarathy MV, Klotz LH (1976) Palm wood. 1. Anatomical aspects. Wood Sci Technol 10:215–229.

Renninger HHJ, Phillips N, Salvucci GD (2010) Wet- vs. dry-season transpiration in an Amazonian rain forest palm *Iriartea deltoidea*. Biotropica 42:470–478.

Roupsard O, Bonnefond JM, Irvine M, *et al.* (2006) Partitioning energy and evapo-transpiration above and below a tropical palm canopy. Agric For Meteorol 139:252–268.

Sellami MH, Sifaoui MS (2003) Estimating transpiration in an intercropping system: measuring sap flow inside the oasis. Agric Water Manag 59:191–204.

Smith DM, Allen SJ (1996) Measurement of sap flow in plant stems. J Exp Bot 47:1833–1844.

Swanson RH (1994) Significant historical developments in thermal methods for measuring sap flow in trees. Agric For Meteorol 72:113–132.

Tomlinson PB (1990) The structural biology of palms. Oxford Science Publications, Oxford.

Tripler E, Ben-Gal A, Shani U (2007) Consequence of salinity and excess boron on growth, evapotranspiration and ion uptake in date palm (*Phoenix dactylifera* L., cv. Medjool). Plant Soil 297:147–155.

Tripler E, Shani U, Mualem Y, Ben-Gal A (2011) Long-term growth, water consumption and yield of date palm as a function of salinity. Agric Water Manag 99:128–134.

Zimmermann MH, Sperry JS (1983) Anatomy of the palm *Raphis excelsa*. IX. Xylem structure of the leaf insertion. J Arnold Arboretum 64:599–609.

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