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Full Length Research Paper

Sap flow estimates of *Quercus suber* according to climatic conditions in north Tunisia

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The determination of oak tree transpiration could be a key factor in understanding the species response to climate change and especially to drought events. This experiment was carried out on four cork oak trees using a thermal dissipation probe (TDP) for measuring the sap flow density (SFD) during the 2008 vegetative season in Aïn Snoussi forest (North Tunisia). The natural thermal gradient (NTG) seemed to exert a minor effect on computing the sap flow. The maximum SFD varied from 0.7 to 3.1 L dm^{-2} h^{-1}. The average SFD was positively related with climatic factors, such as air temperature (Ta), vapor pressure deficit (VPD) and photosynthetic active radiation (PAR). The general behavior indicated that SFD increased proportionally with increasing temperature, VPD or PAR for values of those parameters. However, SFD tended to a threshold value when temperature, VPD and PAR demand continued to increase. Finally, sap flow followed the pattern of the reference evapotranspiration estimated by the Penman-Monteith formula on a diurnal basis.

Key words: Africa, cork oak, Mediterranean climate, radiation, temperature, transpiration.

INTRODUCTION

The intensity and frequency of droughts are the most feared phenomena involving degradation of oak stands around the Mediterranean basin. In Tunisia, the cork oak area shows several indices of degradation and non-natural regeneration. The counting of the woody rings showed a strong decrease in the regeneration of cork oak during last decades: 47.46% of the trees were aged between 100 and 180 years, compared to only 6.78% between 0 and 60 years (Stiti et al., 2005). For this purpose, the study of oak water use and its relations with climate could be a key factor to understand the effect of drought on degradation and constitute basic data for the forestation and management of cork oak areas in the future.

In order to quantify tree transpiration, a thermal dissipation probe (TDP) developed by Granier (1987) is largely used in the forest field. Numerous investigations since the 1990s have evaluated the sap flow of oaks and their relation to climate in the northern Mediterranean basin, but not in African countries.

In the case of an oak stand (*Quercus robur* L), Vincké et al. (2005) freported a range of sap flow density (SFD) from about 0.5 to 2 L dm^{-2} h^{-1} and described its diurnal variation according to the reference evapotranspiration. Cermak et al. (1980) obtained a maximum sap velocity of up to 250 cm^3 h^{-1} per cm of the trunk circumference for *Quercus roseta*. *Q. robur* L. can consume 400 kg J^{-1} water, according to Cermak et al. (1982). In the case of a 90-year-old *Quercus rubra* stand, Bovard et al. (2005) found that SFD varied from 3.5 to 7.5 g.cm^{-2} h^{-1} according to the season. Their study showed that the photosynthetic active radiation (PAR) and vapor pressure deficit (VPD) can explain 82% of the diurnal variation of this transpiration. In North Spain, the sap flow of *Quercus pubscens* was estimated to be 2.5 L dm^{-2} h^{-1}. By comparing two types of oak, *Quercus petra* and *Quercus cerris*, Tognetti et al. (1996) estimated a sap speed ranging from 5 to 10 cmh^{-1} when using the heat pulse technique. In south Portugal, David et al. (2004), while testing on a 90-year-old *Quercus rotundifolia*, found maximum SFD of about 3.2 L m^{-2} h^{-1}. In the same way, in the semi-arid climate of Spain, Moreno and Cubera (2008) obtained an SFD range of 0.5 to 1.5 L.dm^{-2} h^{-1} for *Quercus ilex*.

This study used the TDP technique to evaluate the

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diurnal variation of individual sap flow on cork oak trees in a Northern Tunisian forest. The main objectives were to evaluate the diurnal transpiration and understand the interaction between transpiration and climate variability.

MATERIALS AND METHODS

The experiment was carried out during the 2008 vegetative season in a cork oak forest located in Aïn Snoussi (N = 36°47'50''~ 36°52'40''; E= 8°52'07''~ 8°57'01'', altitude = 640 m a.s.l.) with a slightly sloped topography, oriented North. The climate is humid and temperate with a mean annual precipitation of 1,550 mm and a mean annual temperature of 15.2°C.

The tree ages were estimated between 71 to 131 years old, with a high density of about 300 to 500 trees/ha. The diameter at breach height of varied from 70 to 132 cm. Four trees were chosen and equipped with a TDP sensor of Granier (1987). The sensors were continuously heated and inserted to a depth of 2 cm inside the woody core after striping the cork.

Measurement of climatic data

Common climatic factors were measured in a nearby HOBO station, where precision weather sensors were placed at 1.5 m above the ground for continuous monitoring. The climatic factors were measured with a smart, RGA-MOXX rainfall sensor with a resolution of 0.1 inch was used (mm), a S-WCA-M003 wind sensor for measuring wind direction and velocity (degrees and ms^{-1}), a S-TMB-MOXX sensor for measuring soil temperature (°C), a S-SMA-M005 smart sensor with a high resolution of 0.0004 m^3/m^3 for monitoring soil humidity (m^3m^{-3}), a Li-COR sensor for measuring photosynthetic quantum flux, PAR ($\mu molm^{-2}s^{-1}$), and a temperature/humidity sensor installed inside an appropriate shelter for continuously measuring temperature (°C) and relative humidity (%). A HOBO data logger was used for recording all data at 30-s intervals and stored every 30 min. Appropriate HOBO software was used for lodging the program and down lodging data once a month.

Measurements and calculations of sap flow densities (SFD)

The TDP method, largely developed by Granier (1987), was used. The SFD J (10^{-6} ms^{-1}) was calculated using the calibration equation:

$$J = 136.828 * (K)^{1.2997}$$

Where the flow index K was obtained by

$$K = (dTmax – dT) / dT$$

Where, dTmax = the temperature difference at zero flow (J=0); dT = the measured temperature difference at a given flow density J.

Data were recorded in a (DL-2e *Ejelkamp*) data logger. Sensors were installed in each tree in the southeast direction.

RESULTS

Natural thermal gradient (NTG)

The natural thermal gradient (NTG) in the trunk is a major source of error in computing SFD, especially when reaching high values. Do and Rocheteau (2002) indicated the importance of NTG in *Acacia tortolis*. These discrepancies can be attributed to thermal isolation from sunlight and/or the thermal gradient between soil and trunk, especially in cases of short trunks as observed in an apple orchard (Nasr and Ben-Mechlia, 2007). In order to illustrate and test the magnitude of NTG in our case, the heated (in tree 1) and non-heated (in tree 2) sensors were monitored over several sunny days. Figure 1 shows the dT variations for the two TDP sensors.

The thermal heated gradient in tree 1 showed a maximum value of 16.3°C at 04:00 AM and remaining more or less constant until 07:00 AM, then decreased quickly in parallel to the sap velocity. It reached a minimum value of 12.5°C at 12:00 and varied slowly around this minimum values. It increased at 3:00 PM when the sap flow velocity began to decrease. NTG showed a very weak diurnal variation from +0.3°C at 06:00 AM to -0.0075°C at 12:00. In this case, the observed NTG was very weak and did not involve any correction on sap flow computing.

Diurnal courses of sap flow

The variations of hourly SFD over two days are shown in Figure 2. SFD was characterized by a fast increase in the morning and reached a maximum value at around 12:00, with the maximum values varying between 1.2 and 3.1 L dm^{-2} h^{-1} during the first day. This pattern was followed by a slight stabilization for two hours, after which the SFD decreased in the afternoon to approximately zero during the night. Tree 4, having the highest SFD, showed a slight decrease for the maxima at noon. The SFD during day 2 followed the same pattern but maximum value did not exceeding 1 to 2.4 L dm^{-2} h^{-1}.

Relations between hourly sap flow and climatic parameters

Correlation of the average SFD calculated from individual values (trees 1 to 4) with main climatic data of radiation (PAR), VPD (Ed- this abbreviation has already been defined earlier) and air temperature (Ta) are given in Figure 3 (a, b and c). The best relationship was obtained with Ta, and the highest SFD was obtained with a temperature ranging around 25°C. The relashionship between VPD and SFD showed a better correlation for High values of VPD greater than 1 kPa. When PAR increased above 800 to 1000 µmol $m^{-2}s^{-1}$, average SFD reaches a threshold value of 2 L dm^{-2} h^{-1} in this case and tended to be stabilized.

Relationship between sap flow and Penman reference evaportranspiration

During four sunny days, the reference evapotranspiration was computed using the Penman formulation (PET). The

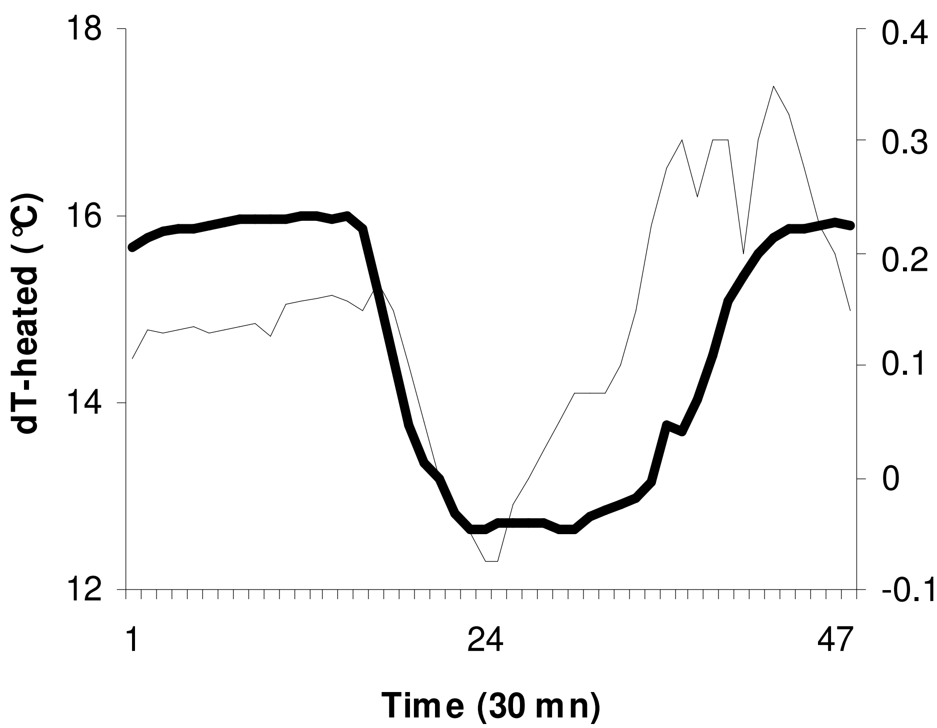

Figure 1. Hourly variations of dT observed in the oak trunk: heated (bold) and non heated (thin) trees.

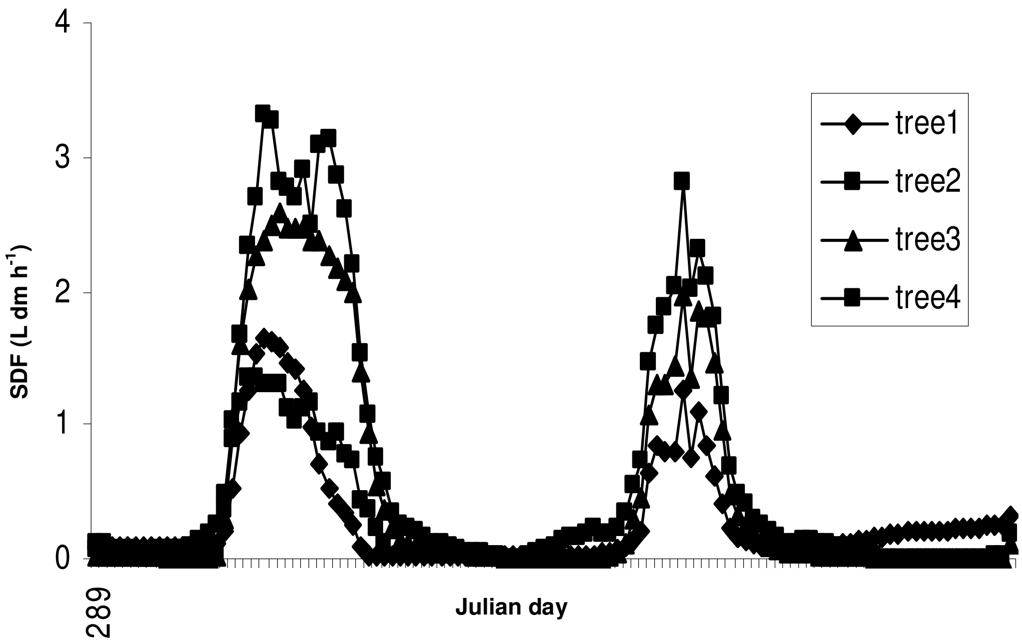

Figure 2. Diurnal course of SFD during two days in four oak trees monitored inside a forest in north Tunisia, between Julian days 289 and 290.

PET varied from 4.3 mmd^{-1} (day 245) to 6.8 mmd^{-1} (day 244) and the maximum SFD varied from 0.6 to 1.2 $L.dm^{-2}$ h^{-1}. SFD and PET exhibited similar patterns during the four days, as shown in Figure 4.

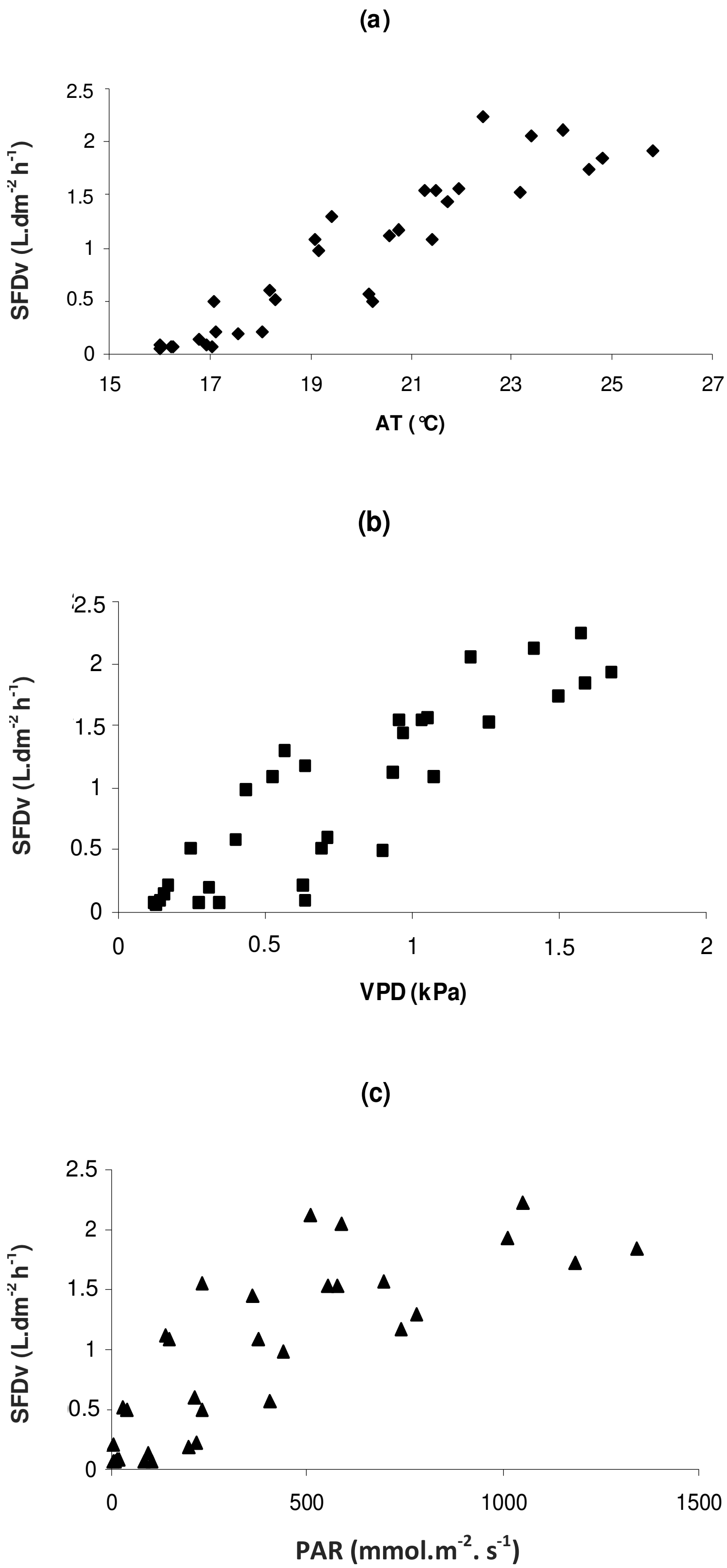

Figure 3. Correlations between (a) sap flow density (SFD) and AT, (b) SFD and VPD, and (c) SFD and PAR measured inside the oak stand in north Tunisia.

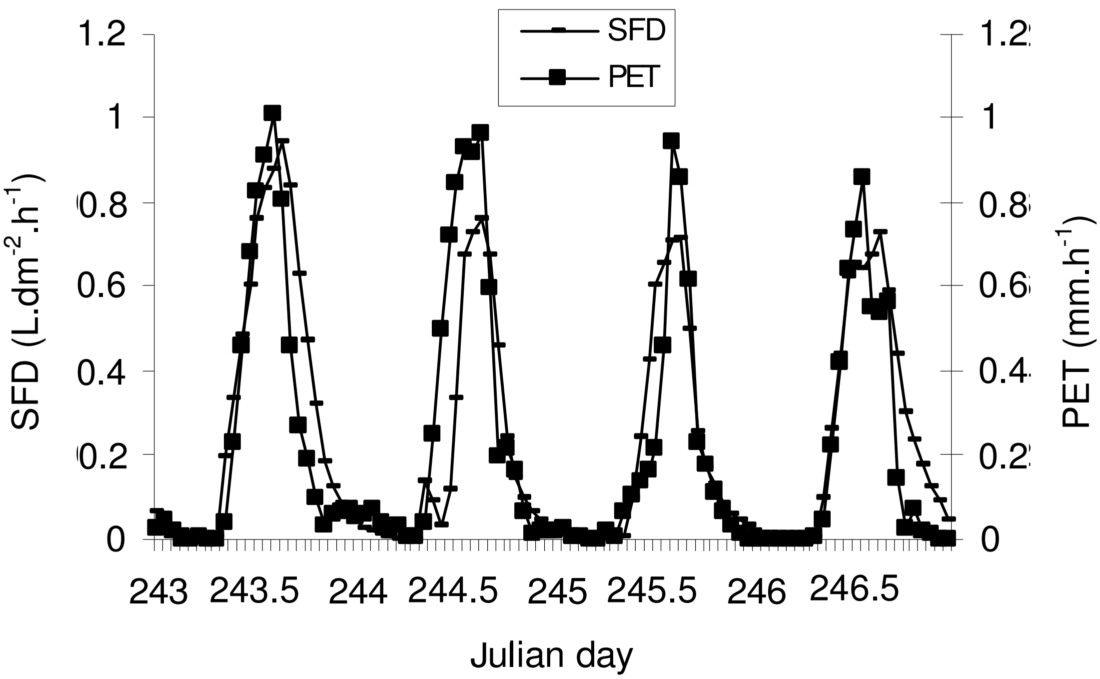

Figure 4. Hourly variations of SFD and PET during the summer season in an oak forest in north Tunisia.

DISCUSSION

Disparity of sap flow between trees and modeling approach

The maximum SFD varied from 1.2 to 3.1 L dm^{-2} h^{-1}. This range was attributed to differences in tree ages: trees having the highest SFD were the youngest with the lowest diameter at breast height (the youngest; DBH_2 = 72 and the oldest; DBH_4 = 105 cm). Vincké et al. (2005) reported that the oldest trees could show shorter SFD values.

The relations between sap flow and the climatic data showed that in trees exposed to high climatic conditions of PAR, VPD or Ta, the sap flow tended to be stabilized around a threshold value and did not increase with increasing PAR, VPD or AT. This behavior was attributed to the role of stomata closure which played an important role in controlling transpiration. A linear relation was established between leaf transpiration and stomata conductance in the same oak stands. This behavior also indicated the strategy of the cork oak trees in avoiding water stress in times of increasing drought by reducing stomata conductance.

The SFD values in good agreement with the Penman-Monteith formula demonstrated the possibilities of modeling oak stands evapotranspiration using the Penman approach. Leaf conductance, leaf area index and soil water content are the most important parameters needed for this modeling approach. The aerodynamic conductance was evaluated by Rana et al. (2005) who proposed a simplified method using only climatic data. Sap flow measurements could be used to validate the proposed model. This approach promises to give an effective simulation of oak stands' transpiration using historical or predicted climate data.

Effect of sensor depth and orientation

In the present investigation, SFD values obtained using the TDP technique were discussed in terms of the two error sources that have been proposed by Granier et al. (1994). Granier et al. (1994) measured SFD at different depths in a 13.7 cm diameter trunk of Sessile Oak and concluded that most of the flow occurred in the current-year ring. Nevertheless, there was a significant flow in the older rings of the xylem. Those results showed that more than 85% of the total sap occurred in the outer ring of the trunk to a depth of 0 to 11 cm. In the same way, Poyatos et al. (2007) concluded that the rates of sap flow were higher close to the cambium, although they also found a small contribution of the inner sapwood during the morning and late in the day.

When Infante et al. (2007) monitored sap flow using TDP at three orientations (NE, NW and S) from May to September on *Quercus ilex* in south Spain, they found that SFD varied according to orientation from 2 to 3.5 $L.dm^{-2}$ h^{-1}. The highest SFD was obtained in the NE and NW in both diurnal and seasonal time scales. Those differences were less pronounced during cloudy days than sunny days.

Conclusions

According results of study, NTG in Oak trees seems to play a minor role with no significant errors in the computation of sap flow. Nevertheless, sensor orientation was an important source of variability and the calculation of sap flow from only one side should be avoided in future study or corrected for.

In spite of these errors, the SFD values estimated in the present experiment were comparable to those obtained by different authors around the Mediterranean region for oaks. Measuring the water use of oak trees by TDP was found to be an appropriate method. Many future applications of this method can be considered, including modeling oak transpiration stands, evaluation of water use efficiency, and evaluating the effects of cork stripping on tree transpiration.

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