Diurnal variations of transpiration in a vineyard at different soil water availability

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Abstract: The water consumption of grapevines is one of the main factors influencing grape quality. Vineyards are discontinuous, heterogeneous canopies and they are often grown in stony soils, small fields and sloping grounds. Plant-based methods for measuring transpiration can therefore be suitable to the large range of vine-growing conditions. In this paper transpiration of vine-branches at decreasing soil moisture availability is analysed in relation to microclimate and plant vigour. A procedure is suggested to calculate transpiration of the whole plot by scaling up from sap flow measurements in a sample of vine-branches by using plant leaf area. Transpiration was monitored through sap flow measurements in an irrigated table grape vineyard, trained by the overhead system ("Tendone"), in Southern Italy, in July 1998 for six days in the interval between two irrigations. Stem heat balance gauges were installed on vine-branches of seven plants, and sap flow of one shoot per plant was measured. Leaf area supported by the shoot above the gauge was measured and plant vigour was estimated through the length and number of branches; leaf area of a sample of four vines was estimated. At decreasing soil water availability sap flow rate decreased and modified its daily pattern, anticipating the peak of maximum rate. Both the reduction of sap flow rate and the shift of the peak were related to plant vigour. The scaling up procedure, based on plant leaf area and flow rates per unit leaf area, gave reasonable estimates of plant transpiration.

INTRODUCTION

The precise determination of plant water use is an important requirement for achieving high water-use efficiency in crops. Vineyards are discontinuous, heterogeneous canopies, in which the contribution to hydric consumption of water evaporated through the plant canopy (transpiration) and through soil largely varies, due to variations in plant form, size and spacing, and growing techniques. Moreover, vines are often grown in stony soils, small fields and sloping grounds, and measuring crop evapotranspiration by means of its components - plant transpiration and soil evaporation - may often be the only viable method to determine water consumption in vineyards.

The present research, in which transpiration is deduced from measurements of sap flux, was made as a part of the short-term experiment "FLUEN", designed to characterise the surface energy balance of a typical Mediterranean table grape vineyard, trained with the overhead system ("Tendone"). In table grape producing countries, overhead vineyards represent a considerable fraction of irrigated vineyards (Rants, 1994); moreover the training system is developing in countries with a young, intensive agriculture (e.g. 10.000 ha in the last 10 years in Northern Africa).

One of the aims of the FLUEN experiment was to compare vineyard evapotranspiration estimated by separate measurements of the soil evaporation and transpiration fluxes with the estimates obtained using micrometeorological methods. Sap flow was measured with a commercial heat tracing system, the stem heat balance technique (SHB, Dynamax Inc); since the measurements were performed at shoot level, a procedure for scaling up from sap flows in individual shoots to the area-average transpiration had to be developed.

This paper analyses the variation of sap flow rates in individual shoots at decreasing soil water availability. Moreover, a procedure is proposed to calculate transpiration by scaling up from sap flow measurements in a sample of shoots to the whole plot.

MEASUREMENTS

THE SITE AND THE CROP

The experiment was conducted in a vineyard whose characteristics meet the conditions for an unbiased application of the micrometeorological methods. The study was carried out in a 20 hectares vineyard in Southern Italy (Adelfia-Bari, 41° N, 17° 54' E), in a site with a semi-arid climate. The experiment took place between 21 and 26 July 1998, when the vines were at the veraison phenological phase.

The cultivar grown in the vineyard is "Italia", the most common and appreciated table grape in Europe. Vines were planted in 1992 in a square pattern (2.3 by 2.3 m). They are trained with the overhead system: the branches are maintained by wires in a horizontal plane at 2 m over the soil surface; shoots and leaves create a horizontal layer of vegetation, approximately 0.4 m thick, with about 80% of green leaves contained in a central layer 0.2

m thick; grape clusters grow in a layer 0.3 to 0.5 m thick, below the leaves. Vegetation extended over the soil surface completely shading the ground, except for some sunflecks due to penetration of solar radiation through the canopy.

The soil is stony, with a thick calcareous hard pan at 0.6 - 0.7 m depth; drainage occurs through cracks in the rocky subsoil.

The vineyard is drip-irrigated every 10 days. Measurements were taken during six days in the interval between two irrigations, starting three days after an irrigation and ending the day before the following one. The experimental field is located in a region where table grape vines extend over an area of approximately 150 km^2, so the field is surrounded mainly by irrigated vineyards.

Standard weather variables were measured, and canopy net radiation was gauged by a radiometer (CNR1, Kipp & Zonen) mounted 3.5 meters above the ground. Measurements from all weather sensors were recorded as 5 minute averages using automatic dataloggers.

In two days, actual evapotranspiration (ET_{act}) was measured by the Bowen Ratio/Energy Balance method. Temperature and humidity gradients were measured at 2.8 and 3.8 m above the ground; heat flux into the soil was estimated by four heat flux plates (FP-1, Campbell Sci.) at 0.05 m depth. All the measurements were recorded every 10 s and their 12-minute averages were stored in a data logger (CR10, Campbell Sci.). The fetch was over 300 m in all directions.

SAP FLOW MEASUREMENTS

Sap flow was estimated with the “stem heat balance” method (Sakuratani, 1981; Baker et al., 1987; Steinberg et al., 1990). Sap flow rate (F, g s^{-1}) is calculated from:

$$F = \frac{Q_i - Q_v - Q_r}{c_w \cdot \Delta T} \qquad (1)$$

where Q_i (W) is a steady, known amount of heat applied to a segment of the stem. The heat input is balanced by heat fluxes out of the segment: conduction along the stem (Q_v, W) and outward through the gauge (Q_r, W). Conductive fluxes are estimated from thermal conductivities - known or measured - and temperature gradients measured by thermocouples placed against the stem. Subtraction of the conductive fluxes from the known heat input yields the heat transported by convection in the transpiration stream. The residual heat is divided by the heat capacity of sap (c_w, J g^{-1} K^{-1}) and by the temperature gradient across the heater (ΔT, K) to calculate the mass flow rate of the sap. The sap flow rate measured at the base of a shoot is equal to the sum of the transpiration from all leaves attached to that shoot, if changes in shoot water content are neglected. Five minute averages of flow rate were calculated from measurements recorded every 30 s using a data logger (CR10X, Campbell Sci.).

Continuous sap flow measurements were made through the six days. At the start of the measurement period seven vines were selected and one shoot per vine was fitted with sap flow gauges (models SGB10 and SGB13, Dynamax Inc.), placed at the base of the shoot. The selected shoots ranged in basal diameter, d, from 9 to 14 mm. One of the seven gauges did not work and data had to be rejected.

PLANT MEASUREMENTS

At the end of the measurement period, the gauged shoots were harvested. All leaves were stripped and their area was measured with a leaf area meter (LI 3100, LI-COR), allowing the calculation of total leaf area for each shoot (A_{shoot}, m^{-2}). The mean area per leaf (A_{leaf}, m^2) was determined by dividing the total leaf area in the sample of shoots by the number of leaves. The basal diameter d (mm) of each sampled shoot was also recorded. The length l (m) of all shoots of each cane, which supported a gauged shoot, was also measured. An index to indicate vegetative plant vigour (I_v) was calculated as the total length of the shoots in the cane:

$$I_v = \sum_{i=1}^{n} l_i \qquad (2)$$

where n is the number of shoots of the cane.

A further sample of four vines was randomly selected, and the basal diameter d of all shoots was recorded, to determine the frequency distribution of d. Moreover, the number of leaves of each vine was counted, and the leaf area of the plant (A_{plant}, m^2) was estimated by multiplying the mean area per leaf - measured in the gauged shoots (A_{leaf}) - by plant leaf number.

Calculation of area-average transpiration

Cumulated daily sap flow was calculated for each gauged shoot and, within each day, the average flow of the six shoots was computed (T_{shoot}, kg day^{-1}). We assumed that sap flow is proportional to leaf area, and we estimated daily transpiration at plant level (T_{plant}, kg day^{-1}) by means of the average sap flow in shoots (T_{shoot}), the average leaf area of the gauged shoots (A_{shoot}), and the plant leaf area (A_{plant}, m^2):

$$T_{plant} = T_{shoot} \frac{A_{plant}}{A_{shoot}} \qquad (3)$$

Through Eq.(3) the daily plant transpiration of each sampled vine has been calculated. The average T_{plant} of the four vines was then used to determine daily transpiration at field scale (T_{field}, mm day^{-1}), taking into account plant spacing:

$$T_{field} = T_{plant} \frac{1}{S_{plant}} \qquad (4)$$

where S_{plant} (m^2) is the land surface area theoretically set to a plant.

RESULTS AND DISCUSSION

WEATHER VARIABLES

In Fig.1 net radiation (Rn, Fig.1a), air vapour pressure deficit (VPD, Fig.1b) and wind speed (Fig.1c) curves are drawn; their points have been determined by averaging concurrent hourly data from 21 to 26 July, and standard deviation bars are shown. Diurnal courses of net radiation are very similar during the whole experimental period, following symmetrical bell-shaped curves with the maximum value at local noon, typical of clear days. In the six days of the experiment, daily courses of *VPD* follow similar patterns, with values increasing in the morning until early afternoon, and quickly decreasing later on. Wind speed curves have also a similar pattern, with higher values during the central hours of the day. *VPD* and wind speed data have a slightly higher variability compared to the net radiation ones. As a consequence of these uniform weather conditions, reference evapotranspiration values (ET_0), estimated on a daily basis (Allen et al., 1998), are fairly constant from 21 to 26 July, and average 6.4 (sd = ±0.1) mm per day. Fig.1d shows the ratio between actual evapotranspiration (ET_{act}) and net radiation (Rn), in two days, on 22 July and at the end of the experiment. The ratio is used as an indicator of soil water availability. On 22 July, the second day of the experiment, ET_{act}/Rn is higher than 0.8. Riou et al. (1994) showed that this value is associated with non-restrictive water conditions in vines.

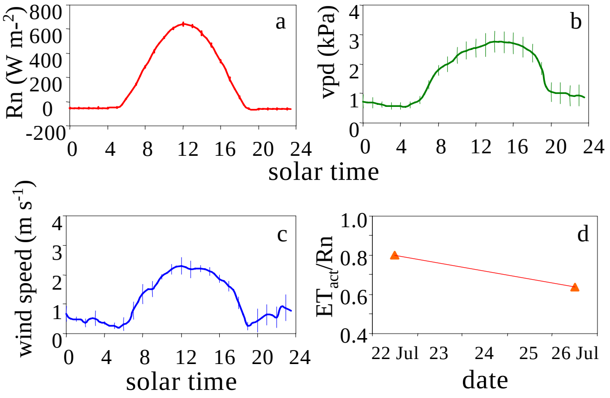

Figure 1. Net radiation (a), vapour pressure deficit (b) and wind speed curves (c) determined by averaging concurrent hourly data from 21 to 26 July; bars indicate standard deviation. Ratio between actual evapotranspiration and net radiation (d) on 22 and 26 July.

SAP FLOW MEASUREMENTS

Figure 2 shows an example of the sap flow rate of two shoots on three days, 22, 24 and 26 July, i.e. from 4 to 8 days after irrigation. On 22 July, the pattern of diurnal variation in sap flow is an almost symmetrical curve about midday, with a rapid increase after sunrise and a rapid decrease in the afternoon, reflecting the dependence of transpiration on net radiation and vapour pressure deficit. At decreasing soil water availability, sap flow rate curves become less symmetrical, reduce their maximum values and shift their peak from around noon (22 July) to mid-morning hours (26 July). The difference in flow rate between the two shoots corresponds to the ranking of their measured leaf areas (1.5 and 0.7 m^2 in Fig.2a and 2b, respectively). Strong positive correlations have been observed between the diurnal trends of sap flow rates measured in all shoots (data not shown). The change of pattern of diurnal courses of gas exchanges at decreasing soil moisture is a common response in plants (e.g. Körner, 1994); and similar patterns in sap flow rates of savannah shrubs have been found by Allen and Grime (1995).

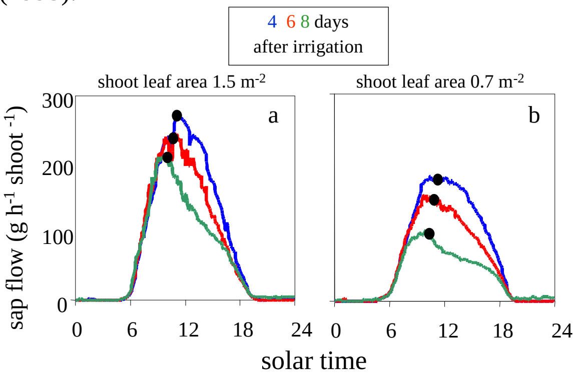

Figure 2. Sap flow rates of two shoots (a and b) on 22, 24 and 26 July, i.e. 4, 6 and 8 days after irrigation (blue, red and green lines, respectively). Dots indicate the peaks of maximum flow rate.

At increasing water shortage, cumulated daily sap flow decreases and it has been analysed with respect to plant vigour. In the six shoots, the reduction of sap flow from the beginning to the end of the experiment has been expressed in relative terms. Cumulated daily sap flow ($\int F$) has been calculated for each shoot, and the difference between the flow on 21 July (day 1) and on 26 July (day 6) has been divided by the flow on 21 July:

$$sap\ flow\ relative\ reduction = \frac{\int F_{day1} - \int F_{day6}}{\int F_{day1}}$$

Fig.3a shows the relative reduction in sap flow related to the index of vegetative plant vigour (*Iv*) for the six shoots. In most cases, the reduction of cumulated flow is inversely proportional to *Iv*, and the shoots belonging to the more vigorous plants have, on the average, a smaller reduction in their cumulated flow.

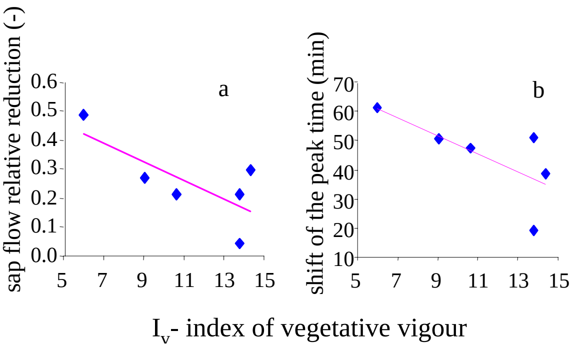

Figure 3. (a) Sap flow relative reduction - as defined in the text - and (b) shift of the peak in flow rate for six shoots, as related to plant vigour.

The different occurrence in time of the peak of maximum flow, at different soil water availability, has also been analysed with respect to *Iv*. Fig.3b shows the difference between the time of the peak on 26 July and the time on 21 July, related to *Iv*, for the six shoots. When analysing the earlier occurrence of the peak of maximum flow rate on 26 July, compared to the time of the peak on 21 July, the behaviour of the shoots is different. The shift of the peak in flow rate to mid-morning hours of the shoots in more vigorous plants is, in two cases over three, smaller than in less vigorous ones.

In plants with different *Iv*, sap flow rate - at shoot level - changes differently at decreasing soil moisture availability. Daily cumulated flow reduces differently as a consequence of plant vigour, and this may have an implication when scaling up sap flow data from shoot to stand level.

PLANT MEASUREMENTS

Fig.4a shows, for the sample of four vines, the frequency distribution of basal diameter of the shoots (*d*), in 2 mm classes. The shoot diameter classes with higher frequencies are those centered at 9 and 11 mm. The total basal cross-sectional area of shoots in each diameter class has been calculated, and the total area per class is shown in Fig.4b. Available sap flow measurements have been taken in the 11 and 13 mm classes; four shoots of the 11 mm class were gauged, and two of the 13 mm. Unfortunately, the gauge that did not work was placed on a shoot of about 9 mm basal diameter, and our sampling missed this class of population. Assuming that a strong linear relationships exists between basal shoot cross-sectional area and sapwood area (e.g. Grime, 1992), Fig.4b represents how the conductive area of the shoots in the sample is distributed in the diameter classes. The shoots in the 11 and 13 mm classes represent 58% of the total sapwood area, so, despite the failure of one gauge, sap flow measurements sampled quite an important section of the shoot population.

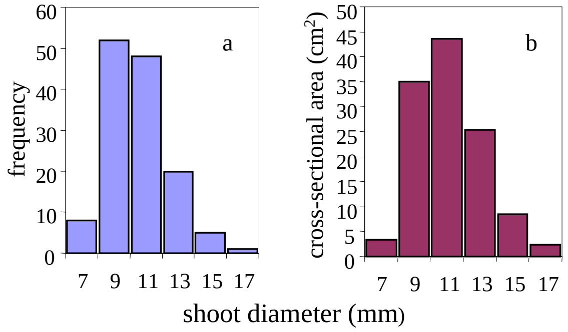

Figure 4. Frequency distribution of basal diameters of shoots (a) and total basal cross-sectional area of shoots in the same diameter classes (b), in the sample of four vines.

CALCULATION OF AREA-AVERAGE TRANSPIRATION

The six gauged shoots have been grouped according to their basal diameter (two shoots in the 13 mm diameter class, and four in the 11 mm); and the diurnal trends of sap flow rates have been averaged within groups. Fig.5a and 5b show averaged flow rates, for the two groups, on 21 and 24 July. Similarly to Fig.2, the consistent differences in sap flow rates between the two groups correspond to the ranking of their measured leaf areas; 1.37 and 0.77 m^2 are the leaf area averages of the gauged shoots in the 13 and 11 mm class, respectively. The standard error bars show that the flux variability is much higher in the shoots belonging to the 13 mm diameter class. Fig.5c and 5d show, on the same two days, the sap flow rates per unit leaf area: flow rate of each shoot has been normalised by its leaf area (A_{shoot}), and the averages within groups have been calculated as described above. The time series overlie one another almost exactly, showing that the difference in sap flow between the two groups are much smaller when flow rate is calculated per unit leaf area.

Similarly, Lascano et al. (1992) showed that the variability of transpiration among plants was reduced by expressing the sap flow measurements per unit leaf area.

These results suggest that Eq.3 and 4 can provide reliable estimates of area-average transpiration. In fact, transpiration rate calculated per unit leaf area has been used in scaling up sap flow data from plant to stand level by means of leaf area estimates (e.g. Zhang et al., 1997).

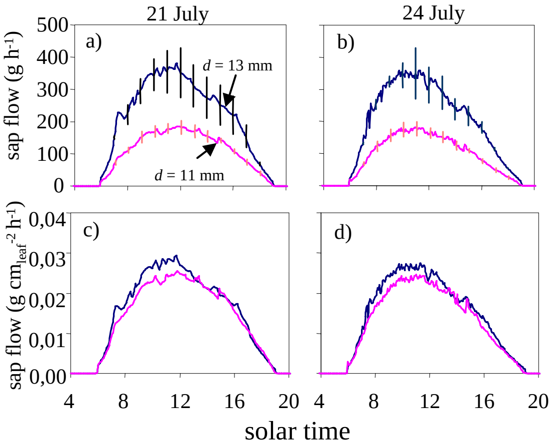

Figure 5. a) and b) show averaged sap flow rates, on 21 and 24 July, of shoots grouped in two classes according to their basal diameter; bars indicate standard error. c) and d) show the corresponding flows calculated per unit leaf area.

Eq.3 and 4 have been used to estimate transpiration at field level. Average leaf area of the four sample vines is 11.2 m^2, and corresponding leaf area index is 2.1. The trend in daily area-average transpiration is shown in Fig.6, together with the reference evapotranspiration (ET_0) for the 6-days period. Actual evapotranspiration (ET_{act}), measured by the Bowen Ratio, is also shown on 22 and 26 July, the two days when these measurements were available. Values of daily ET_0 are quite stable in the period and area-average transpiration has a decreasing trend, in agreement with decreasing soil water availability. Area-average transpiration values (T_{field}) vary from 4.7 mm day^{-1} at the beginning of the period (21 July) to 3.5 mm day^{-1} on 26 July. Soil evaporation, calculated as the difference between ET_{act} and T_{field}, is around 1 mm day^{-1}, i.e. approximately 18% of actual evapotranspiration.

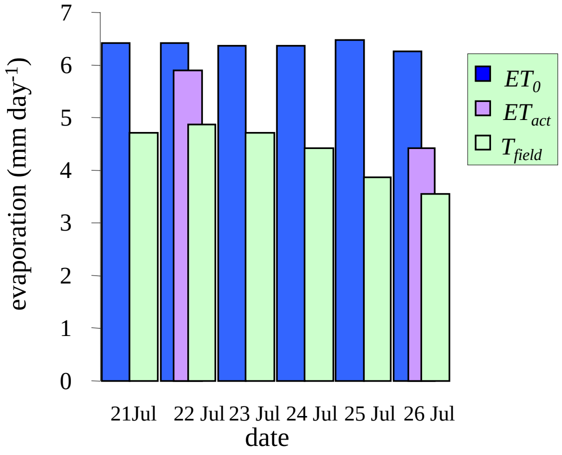

Figure 6. Daily reference evapotranspiration (ET_0) and area-average transpiration (T_{field}) in the 6-days period; actual evapotranspiration (ET_{act}) is shown on 22 and 26 July.

There are few similar studies with which these results can be compared; moreover, due to the heterogeneity of plant development and vine growing conditions, water consumption values are difficult to compare. However, the observed values of daily transpiration agree with values measured by other authors. In a Texas vineyard, Heilman et al. (1996) measured a crop transpiration up to 4.2 mm day^{-1} with a leaf area index of 1.4. For Southern France, Trambouze et al. (1998, 2001) report a vine transpiration of approximately 2.5 mm day^{-1}, at full vegetative growth (maximum leaf area index: 1.8).

With respect to soil evaporation, the observed values are well within the range of values measured by other authors. In fact, as it has been already stated, in sparse crops like vines the soil contribution to evaporation varies a lot. For instance, Heilman et al. (1996) showed that soil evaporation can account for 16-68% of evapotranspiration in a vineyard, when hedgerows density changes. Sene (1994) estimated, in a sparse vine crop under semi-arid conditions, soil evaporation values which accounted for 35% of total water consumption.

CONCLUSIONS

At full water availability, sap flow rates in individual shoots were strongly related to net radiation and vapour pressure deficit. Over the measurements period, the sap flows observed in shoots belonging to different plants were correlated with one another, supporting the feasibility of estimating area-average transpiration, with reasonable accuracy, from a small number of shoots.

The proposed procedure to calculate transpiration by scaling up from sap flow measurements in a sample of shoots to the whole plot, by means of leaf area estimates, gave reasonable values of plant transpiration.

At decreasing soil water availability shoot transpiration may reduce differently due to different plant vigour. Therefore, for up scaling of measurements from plant to canopy, some effort has to be spent in planning adequately the sampling strategy.

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