Revista Brasileira de Agrometeorologia, Santa Maria, v. 8, n. 2, p. 175-183, 2000
Recebido para publicação em 16/08/2000. Aprovado em 11/11/2000.

ISSN 0104-1347

Measurements of water requirements of table grapes in Arizona (USA)

Determinação dos requerimentos hídricos da videira no Arizona (EUA)

Bernardo Barbosa da Silva[1], Donald Carl Slack[2], Michael W. Kilby[2] and Aung Kyaw Hla[2]

Abstract - *New varieties of seedless table grapes have been introduced in Arizona and their water requirements need to be obtained in order to optimize water use. A field experiment was carried out in Tucson, AZ (USA), on two varieties: Glenora and Reliance, six years old and irrigated with a drip system. The objectives of the study were the determination of the transpiration rate (Tr) and the crop coefficient (Kc) of these varieties. Sap flow gauges were used for measuring the Tr and the crop evapotranspiration (ETa) was obtained from concurrent measurement of a water balance by using a neutron probe and TDR. In the period of 6 (Days After Budbreak, DAB = 80) to 10 (DAB = 84) of June 1997, the mean ETa of the Reliance reached 7.6mm/d, while that of the Glenora was 7.5mm/d. The mean Tr in that period were equal to 4.83mm/day and 4.16mm/day for Reliance and Glenora, respectively. During June the mean Tr of the Glenora was approximately equal to 55% of its ETa, and 60% in the Reliance. The crop coefficient of the two varieties on DAB=85 reached the unit value, and from that time were, in general, greater than one. The total water use on Glenora and Reliance were equal to 621.9mm and 668.1mm, respectively, during the entire crop season. One important result is that while the soil remains exposured to the sun the soil evaporation is high, despite the irrigation system used. The feasibility of using sap flow gauges for measuring transpiration in table grapes plants was confirmed.*

Key words*: Stem heat balance, sap flow, transpiration rate, actual evapotranspiration.*

Resumo - *Novas cultivares de videiras sem sementes estão sendo introduzidas no Estado do Arizona e há necessidade de que os seus requerimentos hídricos sejam determinados de forma a otimizar o uso da água no processo de irrigação. Conduziu-se um experimento de campo em Tucson, AZ, com duas cultivares: Glenora e Reliance, com seis anos de idade e irrigadas por gotejamento, com o objetivo de determinar suas taxas de transpiração (Tr) e coeficientes de cultura (Kc). Foram usadas sondas para quantificar a Tr e uma sonda de nêutrons e TDR (Time domain reflectometry) para determinação da evapotranspiração real da cultura (ETa), baseado no balanço hídrico do solo. No período de 6 (Days After Budbreak, DAB = 80) a 10 de junho (DAB = 84) de 1997 a ETa da cultivar Reliance foi de 7,6mm/dia, enquanto que na Glenora foi 7,5mm/dia. A Tr média diária naquele mesmo período foi de 4,83mm/dia e 4,16mm/dia, nas cultivares Reliance e Glenora, respectivamente. Durante os meses de maio e junho a Tr da Glenora e Reliance foi da ordem de 55% e 60% da ETa, respectivamente. O coeficiente de cultura (Kc) das duas variedades alcançou a unidade no DAB = 85, e à partir dessa data foi, geralmente, superior a um. As lâminas de água aplicadas na Glenora e Reliance durante toda a estação de cultivo, foram respectivamente iguais a 621,9mm e 668,1mm. Observou-se que a evaporação do solo foi elevada, não obstante o sistema de irrigação utilizado, em virtude, principalmente, do solo ter sido mantido exposto à ação direta dos raios solares. Ficou confirmada a possibilidade de se medir o fluxo de seiva da videira.*

Palavras-chave*: Balanço de calor caulinar, fluxo de seiva, taxa de transpiração, evapotranspiração.*

[1]Doutor em Agrometeorologia, Pesquisador CNPq e Professor do Departamento de Ciências Atmosféricas, Universidade Federal da Paraíba. Av. Aprígio Veloso, 882. CEP 58.108-090 Campina Grande, PB, e-mail: bernardo@dca.ufpb.br.

[2] Professor of the Department of Agricultural and Biosystems Engineering, College of Agriculture, University of Arizona. Tucson, AZ.

Introduction

Estimation of evapotranspiration from vegetated surfaces is a basic tool to compute water balances and to estimate water availability and requirements. Research in this area is very abundant and provides sound theoretical knowledge and applications, mainly validated through adequate field measurements. In particular, the theoretical developments fully recognize interrelationship between the three compartments of the soil-plant-atmosphere system.

One of the most widely used combination methods of irrigation scheduling is the so-called water-balance-method. In this approach, the soil is viewed as a water storage reservoir from which the plant extracts water. Water is replaced by irrigation or precipitation. In order to utilize this approach, reliable soil characteristics are required as well as accurate and reliable methods of measuring crop water use.

Crop water use can be estimated by measuring changes in soil moisture in the field with instruments such as neutron probe, time domain reflectometry probes (TDR) and others, or by gravimetric soil sampling. Since these methods become tedious on a large scale, water use is often estimated by utilizing *reference crop evapotranspiration* (Eto) which defines the evaporative demand of the atmosphere and a crop coefficient (Kc) that modifies the Eto to reflect the effects of the particular crop physiology on evapotranspiration.

Measurement of sap flow in the stems of herbaceous plants and trees is of great interest to those working in plant-water relations, micrometeorology, and plant physiology. Two basic methods have been developed to measure flow based on the movement of heat within the stem. The first method to evolve was the heat pulse method, which involves the application of a heat pulse to a segment of the plant stem or trunk. The time required for the heat pulse to travel from the input location to a point downstream of the source is correlated with the velocity of the sap stream. This technique may damage the plant since thermocouples and heating elements are inserted into the stem tissue and requires calibration (HAM & HEILMAN, 1990).

An alternative method of estimating sap flow is the heat balance method (HBM) which measures the thermal energy balance of a stem or trunk. Direct measurement of the water use from single plants without altering the environmental or physiological factors that affect transpiration has been possible since the work of SAKURATANI (1981) and BAKER & VAN BAVEL (1987). The HBM has been widely used with herbaceous plants such as cotton (BAKER & VAN BAVEL, 1987; DUGAS, 1990; HAM et al., 1990), sunflower (SAKURATANI, 1981; BAKER & VAN BAVEL, 1987), soybean (SAKURATANI, 1981; 1987), rice (SAKURATANI, 1990) and others, as well as with trees (DAUM, 1967; SCHULZE et al., 1985; FICHTNER & SCHULZE, 1990; DEVITT et al., 1993; CHANDRA et al., 1994; TRAMBOUZE et al., 1998).

The accuracy of the method has been reported to be within 10%, although this accuracy can be reduced at high flow rates (HAM & HEILMAN, 1990; BAKER & NIEBER, 1989). LASCANO et al. (1992) reported accuracy within 5% to 10% for daily values of transpiration of grapes as compared with gravimetric measurements. STEINBERG et al. (1989) applied the Sakuratani design to small trees at low to moderate flow, and were able to measure daily water losses to within 4%.

The objectives of this research are (a) determination of the water use for individual plants by using the stem heat balance method; and (b) the crop coefficient of two table grape varieties under Arizona climatic conditions.

Theoretical considerations

The theory of the energy balance approach to sap flow measurement in herbaceous plants has been described in detail by SAKURATANI (1981) and BAKER & VAN BAVEL (1987) and others. A flexible heater encircles the stem and provides a known amount of heat Q_i (W) (Figure 1). An insulation encloses the stem heated segment and extends for some centimeters both above and below

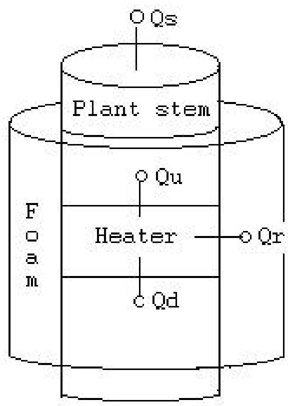

Figure 1. Illustration of the gauge used in the study.

it. The energy balance in the heated segment can be expressed as follows:

$$C_{st}\frac{dT_{st}}{dt} = Qi - Qu - Qd - Qr - Qs \quad (1)$$

where the left-hand term in the equation represents the change in heat storage within the segment, C_{st} is the heat capacity of the stem ($J.K^{-1}$) and T_{st} the average temperature of the stem segment (K), Q_u (W) and Q_d (W) are the heat loss from the segment by conduction in upstream and downstream direction, respectively, Q_r (W) is the radial heat loss, and Q_s (W) is the heat loss by convection in the sap stream.

If we consider a steady-state condition, the equation (1) becomes equal to zero. Then, it follows that:

$$Qs = Qi - (Qd + Qu + Qr) \quad (2)$$

Q_i can be calculated from the input voltage, V, in volts and the resistance, R, in ohms, of the heater, according with:

$$Qi = \frac{V^2}{R} \quad (3)$$

and the conductive fluxes above and below the heater are calculated by applying Fourier's law:

$$Q_{u,d} = Kst.A.\frac{dT_{u,d}}{dX} \quad (4)$$

where K_{st} is the thermal conductivity of the stem ($W.m^{-1}.K^{-1}$), A is the cross sectional area of the stem (m^2), and dT/dX are the temperature gradient ($K.m^{-1}$) above and below the heater. In the gauges used there are two differentially wired thermocouples both measuring the rise in sap temperature. The distances separating the upper thermocouple pair and lower thermocouple pair, dX, are fixed for each gauge. The vertical components (Qu and Qd) can be combined with a common denominator, what results in:

$$Q_v = \frac{K_{st}.A.(BA - AH)}{dX * 0.040} \quad (5)$$

where the factor 0.040 converts the thermocouple differential signals to temperature in Celcius degrees.

In Equation 2 Qs corresponds to the heat carried by the sap flow, and is equal to F.Cp.dT, where F is the sap flow rate ($Kg.seg^{-1}$), Cp is the heat capacity of water ($J.kg^{-1}.K^{-1}$), and dT is the temperature (K) increase of the sap flowing through of the heated stem segment. Then, the sap flow rate can be calculated with the equation:

$$F = \frac{(Qi - Qv - Qr)}{Cp.dT} \quad (6)$$

After measuring the signals AH and BH in mV, the temperature incrase of the sap (dT) can be obtained from the equation:

$$dT = \frac{(AH + BH)/2}{0.040} \quad (7)$$

The radial heat loss is computed by Qr = Ksh.CH, where the Ksh is the thermal conductance constant for a particular gauge, and must be determined experimentally. In this study we calculate the Ksh values for each gauge by averaging the values recorded between 4h and 6h a.m. In this sense we considered F = 0, and solving the equation (6) in terms of Ksh, as follows:

$$Ksh = \frac{(Qi - Qv)}{CH} \quad (8)$$

As we can see above, the sap flow determination requires measurements of the signals AH, BH, CH, all of them in mV, and the voltage supplied to the heater. As these signals are small, a sensitive and accurate system must be used in order to produce good results.

Material and methods

This research was carried out in a vineyard located at the University of Arizona's Campus Agricultural Center, Tucson, Arizona (32°16'49"N; 111°58'16"W; 713m), during the growing season (February to July) of 1997. The soil was classified as Coarse loamy, Mixed, Calcareous, Thermic, Torrifluent, Gila (GELDERMAN, 1972). Particle size analysis done by KHAN (1994) for the first 0.30m layer yielded average values of 51% sand, 38% silt, and 11% clay. During the experiment period six precipitation events occurred, and the air temperature varied from -0.3°C to 40.3°C. Two varieties of six-year-old table grapes (*Vitis labrusca* Hybrids) were considered: Reliance and Glenora. The vines were planted at a spacing of 2.2m within rows and 3.5m between rows. A drip irrigation system of one emitter per plant with a capacity of 4 l/h was used. These varieties have been introduced in Arizona by researchers at the University of Arizona.

Direct measurements of transpiration were made in four plants of each variety with commercially available stem-flow gauges (Dynamax, Houston, Texas, USA) and with gauges manufactured at the University of Arizona. The heat balance method (HBM) previously described was used. A datalogger CR10, a multiplexer AM416 and a storage module SM192 (all of them from Campbell Scientific) were used to record the sap flow readings. The heater gauges were supplied with a voltage regulator. The system was set to read the signals (Ah, Bh, and Ch) generated by the gauges at 1 min intervals and average them at 30 min interval. Measurements started in April and continued up to the end of June, 1997. The data were downloaded to a laptop computer every week and the stems and gauges checked according with directions proposed by manufacturer. The value used for K_{st} in Equation 4 was 0.422w.$m^{1}.K^{-1}$ as suggested by STEINBERG et al. (1989).

The measurement of actual crop evapotranspiration (ETa) was determined by measuring the change in soil water content over a period of time in general coinciding with an irrigation interval. A neutron probe (Model CPM) was used to measure the soil water content (SWC) from 0.20m to 1.60m, using four tubes per variety. The SWC in the layer from the soil surface to 0.20m was obtained with a TDR (Traser Moisture, Corp, 1995). The access tubes and the TDR probes were installed at 0.30m from the trunk of the vines, and kept at the same distance from each emitter of an automatic drip irrigation system.

The average rate of ETa between neutron probe readings was calculated using the equation below, where n is the number of layers considered, θ_1 and θ_2 is the difference in water content at the first and second samplings ($m^3.m^{-3}$), ΔZ_i is the thickness of each layer (m), R is the rainfall (mm) between samplings, I_a is the irrigation applied between readings:

$$ETa = \frac{[\sum_{i=1}^{i=n}(q_1 - q_2).\Delta Z_i + R_e + I_a]}{\Delta t} \quad (9)$$

The θ_i values, which occurred in the first layer (soil surface to 0.20m) were determined with a TDR, and the result added to that obtained with the equation above. Readings were made before each irrigation event. It was assumed zero drainage at 1.6m depth and no runoff.

The reference evapotranspiration (ETo) was obtained directly from the weather station AZMET located at approximately 500m from the experimental site. The AZMET weather station uses the methodology proposed by FAO-Penman, and presented hourly and daily values of ETo. The AZMET weather station collects solar radiation, wind speed, relative humidity, and air temperature.

Results and discussion

The ETo values derived directly from the AZMET weather station located near the experimental area are plotted in Figure 2. The values presented a clear tendency to raise with time, reflecting the atmosphere behavior. The minimum value of ETo in the period was 2.8mm, registered on day after bud break (DAB = 18). The maximum value occurred on DAB = 118, and it was equal to 11.3 mm. The total irrigation water applied in both varieties was equal to 623.2mm, while the accumulated precipitation was equal to 37.8mm. During the study period six rainy days occurred.

The crop evapotranspiration (ETa) for both varieties is also shown in Figure 2. No significant differences were found between the polygonal trace. The oscillations of the ETa values follow the variation of the ETo values, which are very dependent of daily solar radiation values. After DAB = 80 ETa is greater than ETo values, for both species studied. The accumulated ETa on Glenora was equal to 621.9mm, while on Reliance it reached 668.1mm. In the same period the ETo was equal to 867.2mm. The mean ETa obtained by LASCANO et al. (1992) with another grape variety over the measurement period was equal to 528.1mm. EVANS et al.(1990) measured, for a three years period and with lysimeters, the ETa of mature vines in south central Washington State as 360mm/year on average. This result is considerably lower than other published USA data are similar to published South African and South Australian values.

The crop coefficient (Kc) was plotted in Figure 3. The values present an accentuated variation, but with a clear increasing tendency. Around DAB = 40 a decline in Kc values occurred for both varieties, probably associated to limitation of the accuracy of the measurements and variation in interval of reading. The minimum and maximum values were equal to 0.18 and 1.17, respectively. The crop coefficient of the two varieties on DAB = 85, reached the unit value,

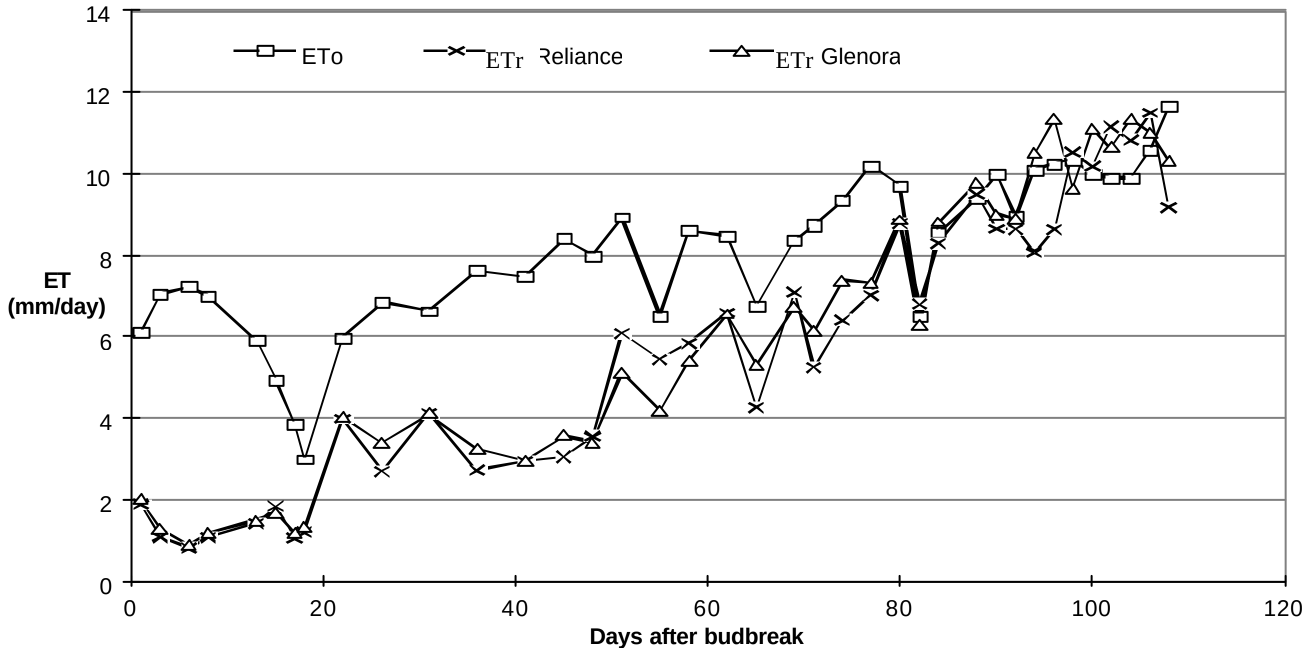

Figure 2. Reference evapotranspiration and crop evapotranspiration of Reliance and Glenora in 1997.

and from this time were in general greater than one. After the final harvest, that occurred on the second week of July, the vineyard continued to be irrigated, but those values are not included in this research.

The transpiration rate (Tr) of the two plants for each variety is shown in Figures 4 to 7. In each figure six days, May 02 (DAB = 45) through May 07 (DAB = 50) were considered. The daily values of Tr (kg) were included under the correspondent curve. It can be noted that the Reliance variety presented, in general, values greater than those of the Glenora variety. On that period, the maximum Tr value was equal to 4.8kg.day^{-1}, registered on May 06 for Reliance vine. The maximum Tr value of Glenora was registered on plant 3 on May 07. The results obtained by LASCANO et al. (1992) with five three-year-old Chardonnay plants, indicated that the mean rate of mass flow increased from 2.4 to 6.7kg.day^{-1}, thereafter remained relatively constant for 20 days declining to 3.2kg.day^{-1}. It is not surprising that the maximum daily rates of water use occurred early in the growing season (mid-May to mid-June), due to the unseasonably warm, clear, and dry weather over the period of observation. In the period from June 30 to

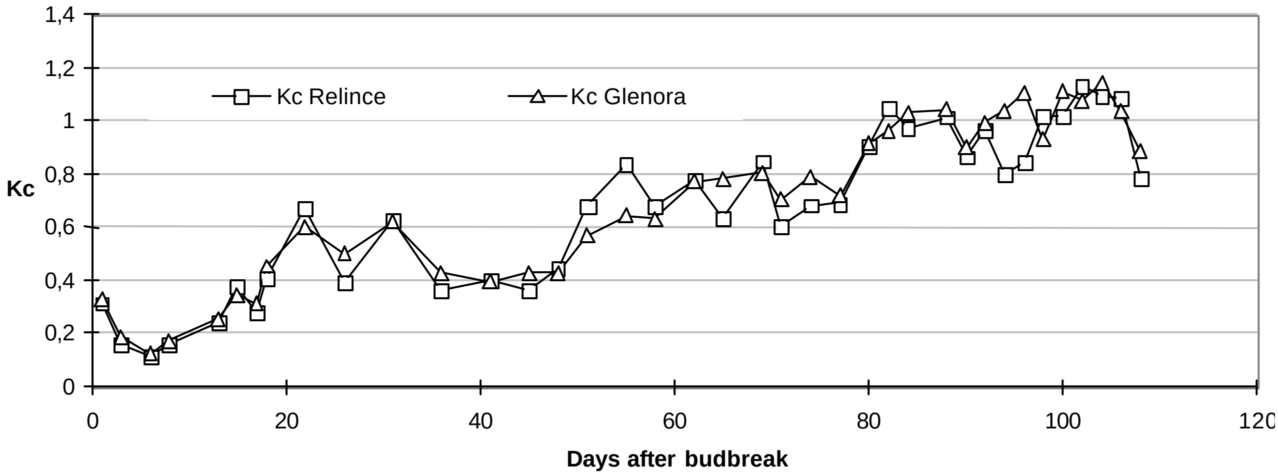

Figure 3. Crop coefficient (Kc) of Glenora and Reliance in Tucson, AZ.

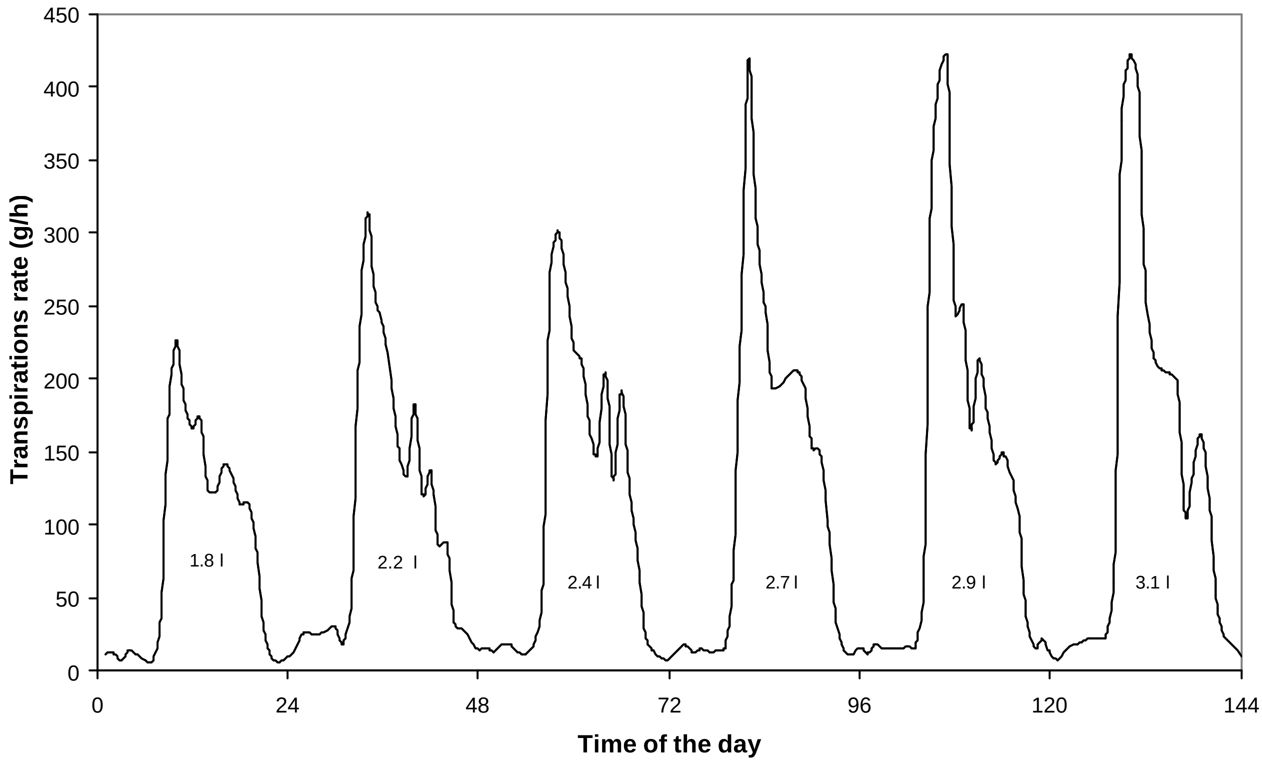

Figure 4. Transpiration rate of Glenora 1 on May 02-07, 1997, in Tucson, Arizona.

July 03, the mean Tr were 5.68kg.day^{-1} and 5.27kg.day^{1-}, for Reliance and Glenora, respectively.

It is important to notice that there is no large difference among vines of the same variety and that the differences observed can be related to differences in leaf area and vigor of the plants. LASCANO et al. (1992) reported that differences among Tr of young vines were reduced by dividing the Tr to the

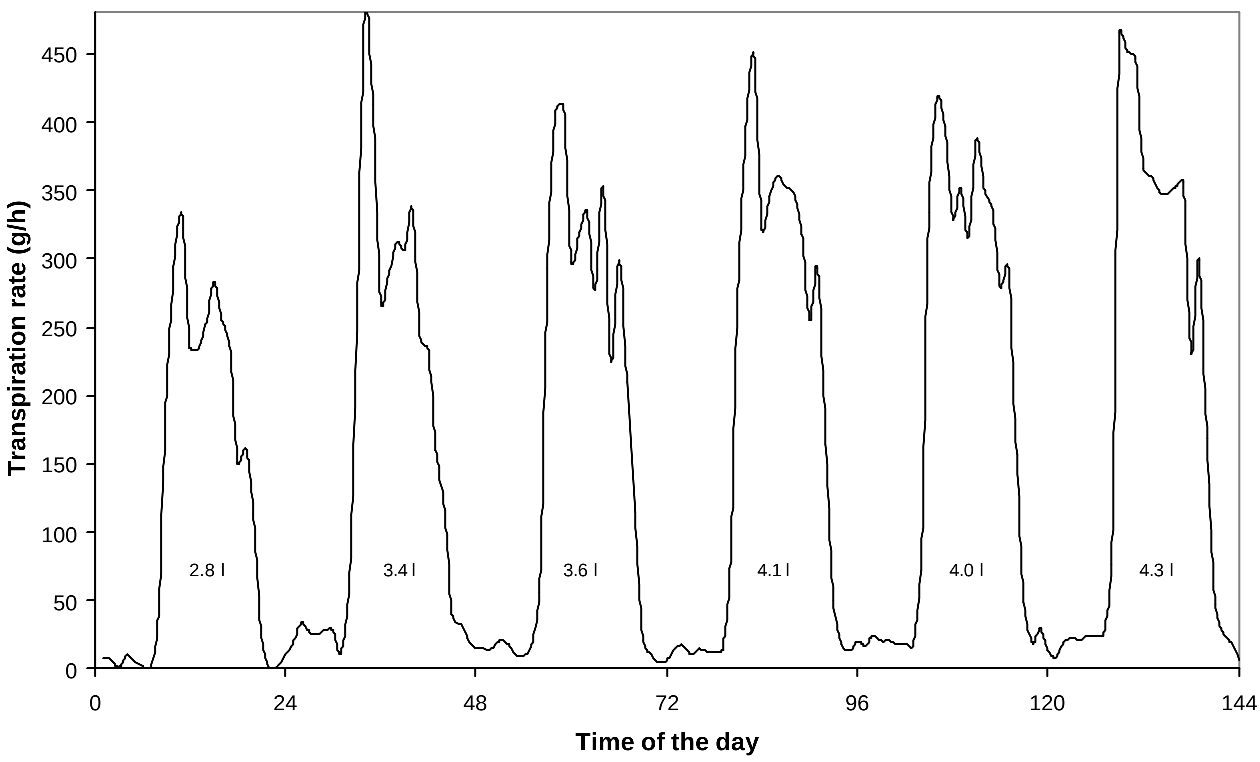

Figure 5. Transpiration rate of Glenora 3 on May 02-07, 1997, in Tuscon, Arizona.

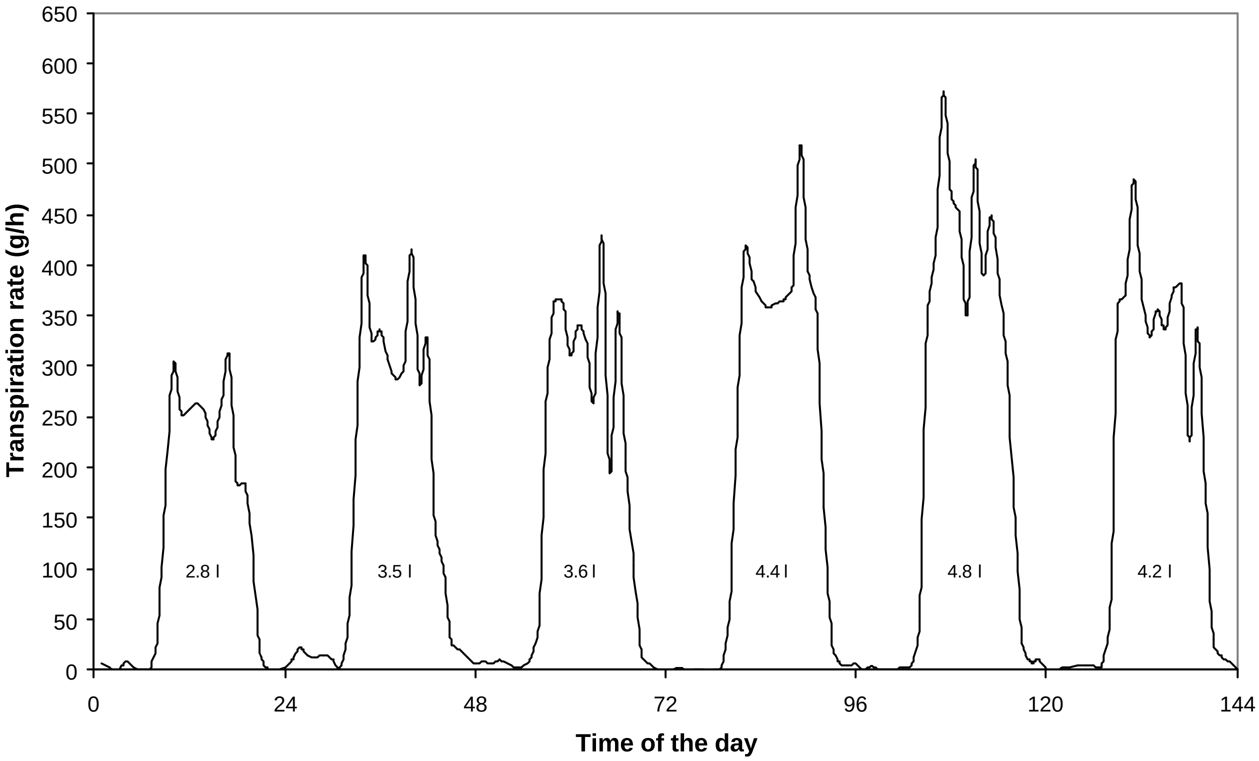

Figure 6. Transpiration rate of Reliance 3 on May 02-07, 1997, in Tucson, Arizona.

correspondent plant leaf area. Even though we did not measure leaf area in this research, we could note visual differences in this variable among plants, either in the vine trunk diameter.

In this research we did not use a procedure, which consist of reducing the voltage supplied for each gauge during the night periods. This fact produced heating in the stem of the vines during those

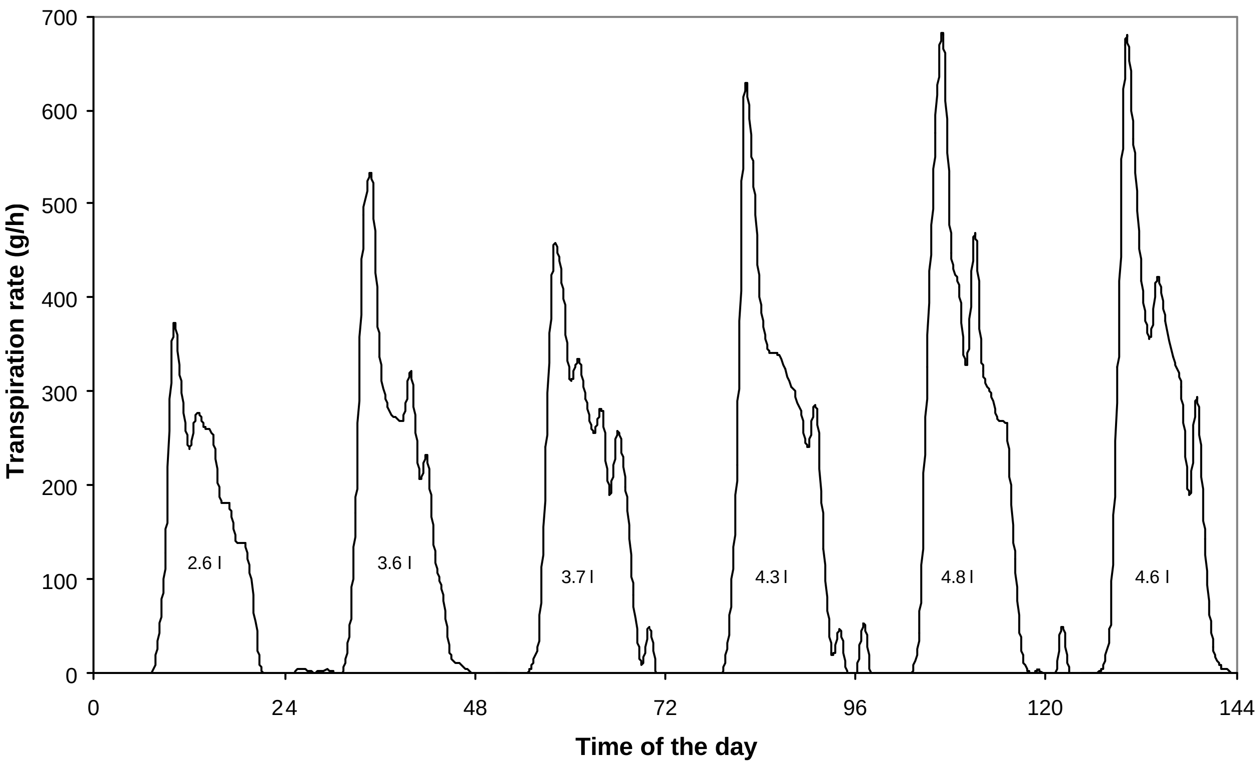

Figure 7. Transpiration rate of Reliance 1 on May 02-07, 1997, in Tucson, Arizona.

periods. The hourly variations of the sap temperature Ts (°C) of three plants per variety were analyzed. It could be seen that the Ts increased to 4.5°C, and produced visual injuries in the trunk of some vines. For avoiding this problem the voltage of each gauge should be diminished during night periods by using a controller-timer. The voltage applied for each gauge was equal to 4 volts. ZHANG & KIRKHAM (1995) also analyzed Ts values of sorghum and sunflower. They concluded that the form of the Ts curve can be used to assess gauge accuracy. SENOCK & HAM (1993) give a mathematical analysis to show that changes in sap flow rate are inversely proportional to Ts. The sap flow rate is specially susceptible to errors when Ts is less than 1.0 °C (ZHANG & KIRKHAM, 1995). The manual supplied by the manufacturer of commercially available gauges (DYNAMAX, 1994) recommends that the constant power input to the heater should be adjusted to maintain Ts within a certain range: Ts > 0.3K under high flow rates, and less than 8-10K at night. Furthermore, to eliminate spurious estimates of sap flow when Ts becomes small at very high and very low rates, DYNAMAX (1994) recommends the use of certain filters.

The mean transpiration rates measured in four plants per variety ($kg.day^{-1}$) are presented in Figure 8. As can be seen the Reliance variety in general transpires more than the Glenora variety, but the difference between them are small. The reading reached the maximum values in the second half of June (around DAB=100). At that time the daily solar radiation was approximately equal to 32 $MJ.m^{-2}$. There was a great difference among Tr of a same variety (not represented in Figure 8), that can be associated with differences in their total leaf area. This kind of problem was resolved in LASCANO et al.(1992), by dividing the transpiration rate for the total leaf area of each plant.

The relationship between the mean transpiration rate (Tr) and the actual evapotranspiration (ETa) at the end of the experimental period was approximately equal to 60%. It means that the evaporation rate is around 40%, and it is associated with the irrigation system used in this research. LASCANO et al. (1992) working with Chardonnay vine plants flooding irrigated concluded that the soil evaporation at the end of the experimental period was equal to 77% of the ETa. This great difference can be explained as a consequence of the irrigation systems used in that mentioned research.

Conclusions

According with the results obtained we conclude that there was not a great ETa difference between the two varieties. During June month the Tr of the Glenora was approximately equal to 55% of its ETa, and 60% in the Reliance. One important result is that while the soil remains exposured to the sun the soil evaporation is high, despite the irrigation system used. The feasibility of using sap flow gauges for measuring transpiration in table grapes plants was confirmed.

Acknowledgements

This research was supported by the Department of Agricultural and Biosystems Engineering of The University of Arizona. The first author was also granted by CAPES, Brazil.

Bibliographic references

BAKER, J.M., VAN BAVEL, C.H.M. Measurement of mass flow of water in the stem of herbaceous plants. **Plant, Cell and Environment,** Oxford, v. 10, p. 777-782, 1987.

BAKER, J.M., NIEBER, J.L. An analysis of the steady-state heat balance method for measuring sap flow in plants. **Agricultural and Forest Meteorology**, Amsterdam, v. 48, p. 93-109, 1989.

CHANDRA, S., LINDSEY, P.A., BASSUK, N.L. A gauge to measure the mass flow rate of water in trees. **Plant, Cell and Environment**, Oxford, v. 17, p. 867-874, 1994.

DAUM, C.R. A method for determining water transport in trees. **Ecology**, Durham, v. 48, n. 3, p. 425-431, 1967.

DEVITT, D.A., BERKOWITZ, M., SHULTE, P.J. et al. Estimating transpiration for three woody ornamental tree species using stem-flow gauges and lysimetry. **HortScience**, Alexandria, v. 28, p. 320-322, 1993.

DUGAS, W.A. Comparative measurement of stem flow and transpiration in cotton. **Theoretical Applied Climatology**, Heidelberg, v. 42, p. 215-221, 1990.

DYNAMAX. **Flow 32 installation and operation manual.** Houston, TX : Dynamax, 1994.182 p.

EVANS, R.G, SPAYD, S.E., WAMPLE, R.L. et al. Water requirements of Vitis vinifera grapes. In: NATIONAL IRRIGATION SYMPOSIUM, 3, Oct 28-Nov 1, 1990, Phoenix, AZ, **Proceedings...** Phoenix : ASAE, 1990, p. 154-161.

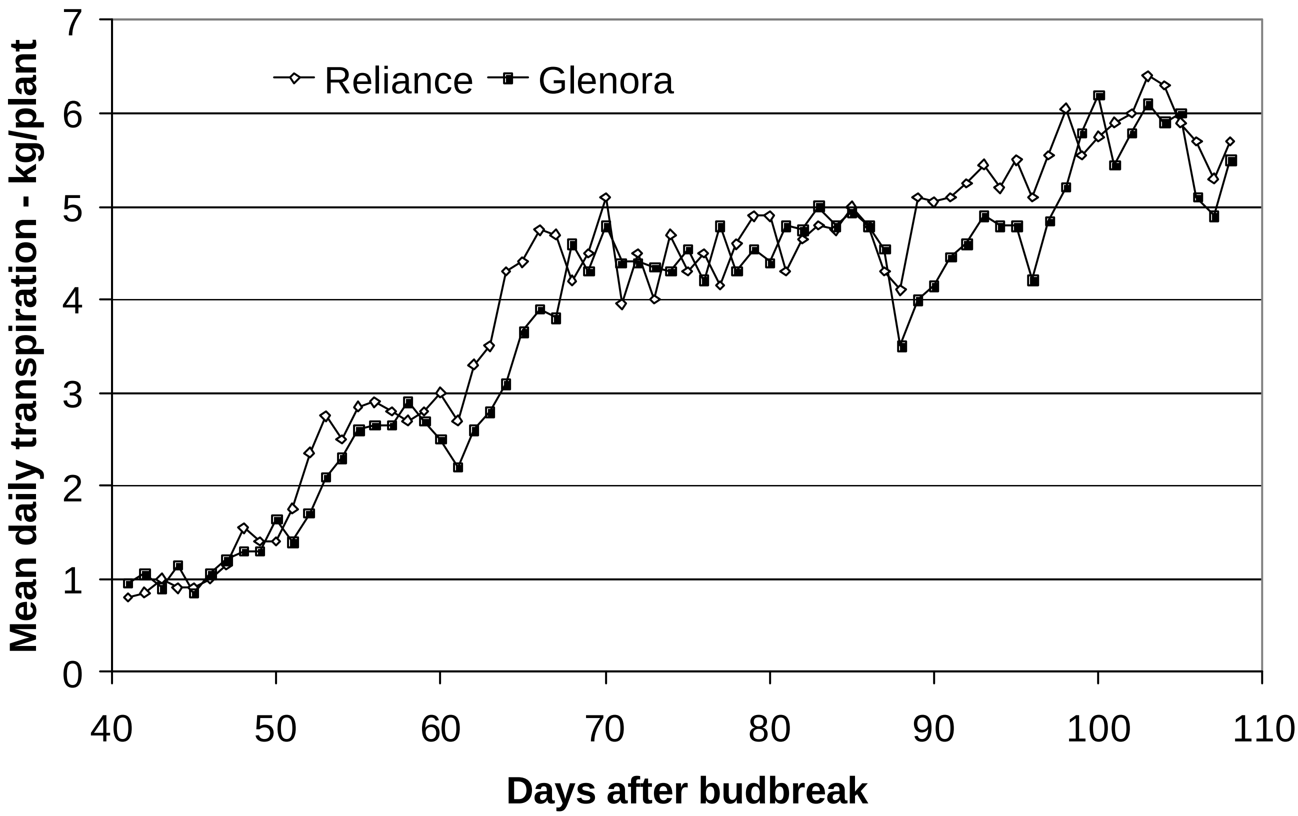

Figure 8. Seasonal variation of the mean daily transpiration of Reliance and Reliance table grapes in Tucson, Arizona, 1997.

FICHTNER, K., SCHULZE, E.D. Xylem water flow in tropical vines as measured by steady state heating method. **Oecologia**, Berlin, v. 82, p. 355-361, 1990.

GELDERMAN, F.W. **Soil survey of the Tucson-Avra Valley Area, Arizona**. Soil Conservation Service. USDA, U.S. Government Printing Office : Washington D.C. 1972. 65 p.

HAM, J.M., HEILMAN, J.L. Dynamics of a heat balance stem flow gauge during high flow. **Agronomy Journal**, Madison, v. 82, p. 147-152, 1990.

HAM, J.M., HEILMAN,J.L., LASCANO, R.J. Determination of soil water evaporation and transpiration from energy balance and stem flow measurements. **Agricultural and Forest Meteorology**, Amsterdam, v. 52, p. 287-301, 1990.

KHAN, A.A. **Field evaluation of water and solute movement from a point source**. Arizona : University of Arizona, 1994, 224 p. PhD dissertation - Department of Agricultural and Biosystems Engineering, The University of Arizona, 1994.

LASCANO, R.J., BAUMHARDT, R.L., LIPE, W.N. Measurement of water flow in young grapevines using the stem heat balance method. **American Journal of Enology and Viticulture**, Lockeford, v. 43, n. 2, p. 159-165, 1992.

SAKURATANI, T. A heat balance method for measuring water flux in the stem of intact plants. **Journal of Agricultural Meteorology,** Tokyo, v. 37, p. 9-17, 1981.

SAKUTARANI, T.A. Studies on evapotranspiration from crops (2) Separate estimation of transpiration and evaporation from a soybean field without water shortage. **Journal of Agricultural Meteorology,** Tokyo, v. 42, n. 4, p. 309-317, 1987.

SAKUTARANI, T. A. Measurement of the sap flow rate in stem of rice plant. **Journal of Agricultural Meteorology**, Tokyo, v. 40, p. 277-280, 1990.

SENOCK, R.S., HAM, J.M. Heat balance sap flow gauge for small diameter stems. **Plant, Cell and Environment**, Oxford, v. 16, p. 593-601, 1993.

STEINBERG, S., VAN BAVEL, C.H.M., MCFARLAND, M.J. A gauge to measure mass flux rate of sap in stems and trunks of woody plants. **Journal of American Society of Horticultural Science**, Virginia, v. 114, n. 3, p. 466-472, 1989.

SCHULZE, E.D., CERMAK, J., MATYSSEK, R. et al. Canopy transpiration and water fluxes in the xylem of the trunk of Larix and cuvette measurements. **Oecologia**, Berlin, v. 66, p. 475-483, 1985.

TRAMBOUZE, W., BERTUZZI, P., VOLTZ, M. Comparison of methods for estimating actual evapotranspiration in a row-cropped vineyard. **Agricultural and Forest Meteorology,** Amsterdam, v. 91, p. 193-208, 1998.

ZHANG, J., KIRKHAM, M.B. Sap flow in a dicotyledon (Sunflower) and a monocotyledon (Sorghum) by the heat-balance method. **Agronomy Journal**, Madison, v. 87, p. 1106-1114, 1995.