FIELD DETERMINATION OF YOUNG ACID LIME PLANTS TRANSPIRATION BY THE STEM HEAT BALANCE METHOD

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ABSTRACT: The stem heat balance method (HBM) measures sap flow (SF) in plants, and can be used to estimate daily transpiration flow. It is a powerful technique for water relations and irrigation field studies, but it has to be tested in species of particular interest. This paper discusses effectiveness of the HBM to estimate transpiration of young acid lime plants (*Citrus latifolia* Tan. cv. Tahiti), grafted on citrumelo cv. Swingle (*Poncirus trifoliata* Raf. x *C. paradisi* Macf.), in the field using commercial gauges (model SAG10-ws, Dynamax Inc., Huston), in Piracicaba, State of Sao Paulo, Brazil. SF was correlated to transpiration determined by weighing lysimeters and by a steady-state null-balance porometer. The mean ratio between daily values of SF and lysimetric measurements was practically unitary, showing a mean difference of only 0.05%, being the comparisons of values in periods shorter than 24 hours impaired by effect of wind turbulence on lysimeters. The same occurred (mean difference of 0.38%) when SF and canopy transpiration estimated from porometer measurements were compared in 20-min periods, but transpiration tended to exceed SF in periods of higher transpiration and data dispersion was high ($r^2 = 0.48$). An analysis of the sources errors of the techniques was done, including the comparison of the daily course of SF and net radiation. Despite of the dispersion of the comparative data between the HBM and the other two techniques, HBM had a good performance, permitting to recommend its use in studies of water relations in young citrus plants under field conditions.

Key words: SF, maximum transpiration, lysimeter, porometer, citrus

DETERMINAÇÃO DA TRANSPIRAÇÃO DE PLANTAS JOVENS DE LIMA ÁCIDA A CAMPO PELO MÉTODO DE BALANÇO DE CALOR CAULINAR

RESUMO: O método de balanço de calor caulinar (MBC) é usado na estimativa de fluxo de seiva (SF) de plantas herbáceas e lenhosas, sendo uma ferramenta útil na determinação de transpiração em estudos de relações hídricas e no manejo da irrigação. É recomendável testar o seu desempenho em espécies de interesse. Neste estudo ele foi testado em plantas jovens de lima ácida (*Citrus latifolia* Tan. cv. Tahiti) enxertadas em citrumelo cv.'Swingle' (*Poncirus trifoliata* Raf. x *C. paradisi* Macf.), em um pomar localizado em Piracicaba (latitude de 22°42'30"S, longitude 47°38'00" W e altitude de 580 m), SP, no período de outubro de 2001 a fevereiro de 2002, tendo ocorrido o início das medidas quatro meses após o plantio das mudas no campo. As estimativas de FS foram relacionadas com a transpiração determinada com lisímetros de pesagem e com porômetro de balanço de nulo em equilíbrio dinâmico (Tp). Os valores diários de FS apresentaram uma boa concordância com os dados lisimétricos, com diferença média de 0,05% e r^2 de 0,72, não tendo sido possível a comparação em escala de tempo inferior a 24 horas devido à ação do vento sobre os lisímetros. Ao comparar FS com Tp, foi verificado um padrão relativamente próximo de variação das curvas de cada tipo de medida ao longo do dia, mas com tendência dos valores mais elevados para Tp em horários de maior transpiração. A correlação entre ambas as variáveis revelou uma pequena diferença média, mas com dispersão alta dos pontos. Foi feita uma análise sobre as fontes de erro das técnicas usadas, ao lado de uma comparação do curso diário do fluxo de seiva e do saldo de radiação. Conclui-se que o MBC apresentou bom desempenho e pode ser aplicado em estudos de relações hídricas em plantas jovens de lima ácida 'Tahiti' crescendo em condições de campo.

Palavras-chave: fluxo de seiva, transpiração máxima, lisímetro, porômetro, citros

INTRODUCTION

Quantifying transpiration is of great interest in studies of water relations applied to fruit trees and irrigation management. Lysimetry, for instance, used in field experiments, can be used to determine transpiration, provided that soil evaporation is avoided. However, not only its application is usually restricted to agricultural practices, but also this technique can present problems affecting the representation and quality of the obtained data (Jensen et al., 1990; Wright, 1991; Grebet & Cuenca, 1991; Howell et al., 1995).

Transpiration of leaves and entire plants can be determined by the use of gasometric chambers, which measure the increase in air vapor concentration originated from leaf transpiration. Principles involved in the measurement of transpiration in the chambers are also present, for instance, in the steady state null-balance porometer. However, using the chamber may eventually cause disturbances around the leaf, leading to errors. An additional set of difficulties restricts its use in research.

The evolution of the thermal methods based on heat supply to the stem to determine sap flow (SF) represents an advance in the measurements of water consumption by woody plants. Under conditions of good soil water availability, SF represents well the daily transpiration (Valancogne & Nasr, 1993), the same occurring over shorter time periods, depending on the stem diameter. Heat, when properly applied either in pulses or continuously, in principle does not cause disturbances to plants. The thermal method of stem heat balance (HBM), employed in its most usual form (Sakuratani, 1981), presents the advantage of allowing accurate determination of SF values without calibration. One of its best features is the possibility of checking raw data in order to verify the reliability of the results (Weibel & Boersma, 1995).

The HBM has been largely studied under the most varied conditions of species, age, stem diameter, with special attention to the installation of the gauges. Results of HBM were usually compared to simultaneous measurements by weighing lysimeters or scales (Devitt et al., 1993; Valancogne & Nasr, 1993; Gutiérrez et al., 1994; Weibel & de Vos, 1994; Rose & Rose, 1998; Braun & Schmid, 1999). Measurements made by the two methods in periods from 30 minutes up to 24 hours have presented differences below 10%. However, literature mentions the possibility of occurrence of significant errors in HBM results if measurements are not taken carefully to minimize sensitivity to sources of errors.

In a study with acid lime seedlings cv. Tahiti under greenhouse conditions, Trejo-Chandia et al. (1997) observed that HBM tended to yield SF values about 11% and 13% greater than the transpiration measured by weighing, respectively for hourly and the 24-hour periods. Marin et al. (2003) observed an uneven response between HBM measurements in comparison to transpiration measured by weighing in orange seedlings. These authors observed similar results for daily periods for plants with larger stem girth (25 mm), while for those with thinner stems, five and 19 mm, SF exceeded transpiration in 13% and 30%, respectively.

In this paper, the results obtained with the HBM in the SF measurement in young lime acid plants are compared with transpiration measured by lysimetry and porometry, in order to test its performance under the specified conditions.

MATERIAL AND METHODS

Crop material and cultivation conditions

The work was carried out from October 2001 to February 2002 in a 'Tahiti' acid lime orchard, with crowns of the IAC 5 clone grafted on citrumelo cv. Swingle, planted in June 2001, spaced 7.0 m × 4.0 m, in Piracicaba, State of Sao Paulo, Brazil (22º42'30'' S; 47º30'00'' W; altitude 546 m). Orchard's soil is a Rhodic Kandiudalf, clay texture, 5% average slope. Local climate is humid subtropical, average total annual rainfall 1,278 mm (Sentelhas et al., 1998), with rainy summers and dry winters. The orchard was drip irrigated with four emitters per plant, 4 L h^{-1} flow, keeping soil matrix water potential above -20 kPa (average daily readings from four tensiometers per plant, ten different plants) at 0.5 m depth.

Lysimetric measurements

SF was monitored in five plants, two of which were growing in two weighing lysimeters (one plant per lysimeter), allowing simultaneous measurement of transpiration. The tanks of the lysimeters were made of carbon steel with 0.80 m diameter and 0.6 m depth. Lysimeters were placed in the center of the orchard and calibrated just before seedlings were planted, showing minimum hysteresis and detecting 0.0075 kg mass variation with 0.019 kg accuracy (Campeche, 2002) The weight variation of each lysimeter was monitored by three electronic load cells (Omega Engineering, Inc.) and plants growth inside them did not differ from those of the orchard. The soil water potential in the lysimeters was kept about –10 kPa at 0.15 m depth, always close to field capacity.

To measure just the variation of the soil water storage caused by transpiration and compare the SF with measurements of the lysimeters, the soil was covered with plastic canvas during a period of 21 days with diverse atmospheric water demand. A datalogger CR23X (Campbell Sci., Inc.) linked to a multiplexer (AM 416 Relay Multiplexer, Campbell Sci.) was used to collect data from lysimeters every 3 seconds, recording averages every 20 minutes, following methodology recommended by Campeche (2002).

Despite of the observed high precision, accuracy and sensitivity of lysimeters to field-detected mass variations before planting, pronounced fluctuations of lysimetric measurements were observed in periods of measurements between 20 min and 12 hours, showing inconsistent weight gain or excessive transpiration, not justified even by accentuated variation of environmental conditions. These fluctuations probably result from the wind effects and small size of the lysimeters (Campeche 2002). Therefore, comparisons in periods of up to 12 hours were disregarded, and only the 24-hour range readings (difference between readings at 0:00 h of each day) were considered.

SF measurements

SF was determined by gauges operating in the stem heat balance principle (Sakuratani, 1981; Baker & Van Bavel, 1987), model SAG10-ws (Dynamax, Inc.), with data stored in a CR10 datalogger linked to one AM 416 (Campbell Sci., Inc.) multiplexer. Readings were made every second, and averages were recorded every 20 minutes (Trejo-Chandia et al., 1997).

The gauges were installed along almost the entire branchless portion of stem, composing an insulated section of stem in which the heat balance was calculated. A gauge (see Steinberg et al., 1989) is composed of a heater extended around the stem, surrounded by a thermopile composed of thermojunctions on each side of a cork sheath. Thermo junction pairs, installed on two strips, one just above and another just below the heater, allow the measurement of the temperature differences in the limits of the sampled section of stem. To minimize effects of the environment variation on the gauge response, an insulation material covers the other parts of the gauge and an aluminum foil is wrapped around each gauge.

The procedures to calculate SF were the same proposed in the manufacturer's operating Manual, with minor modifications. The theory of the HBM and the used procedures are below discussed in summary. According to Sakuratani (1981), a constant power P_{in} (in watts) applied to the insulated section of the stem is divided in the following heat flows:

$$P_{in} = Q_r + Q_v + Q_s + Q_f \qquad (1)$$

where Q_r is the radial heat flow by conduction in the stem; Qv the heat transported by conduction along the axis of the stem, corresponding to the sum of the heat flows by conduction above (Q_c) and below (Q_b) the heating element; Q_s is the energy stored per time unit in the heated section; Q_f is the heat transported by convection through the moving sap.

The radial heat flow was estimated according to the expression:

$$Q_r = K_{sh}\Delta T_r \qquad (2)$$

where K_{sh} (W K^{-1}) is the thermal conductivity of the cork sheath of the radial thermopile and ΔT_r is the difference of temperature between the inner and the outer surface of the sheath, which can be determined from the electromotive force generated in the thermopile.

In this work K_{sh} values were estimated considering that sap flow (and the corresponding Q_f) is null or near zero, normally occurring in the pre-dawn under good soil water conditions, and solving equations (1) and (2) for K_{sh}, using the lowest value estimated in the pre-dawn. The K_{sh} values estimated for each day presented minute variation during the measuring period.

The heat flow transported along the axis (Q_v) was calculated as:

$$Q_v = AK_{st}\frac{(\Delta T_c + \Delta T_b)}{\Delta z} \qquad (3)$$

where *A* is the cross section area of the heated stem; K_{st} is the thermal conductivity of the stem, assumed as 0.42 W m^{-1} K^{-1} for woody species (Steinberg et al., 1989); $\frac{(\Delta T_c + \Delta T_b)}{\Delta z}$ is the sum of the upper (ΔT_c) and lower (ΔT_b) temperature differences of the heated stem segment, divided by Δz, which is the distance between the pairs of junctions fixed just above and below the heating jacket.

The heat flow carried in the plant sap (Q_f) is calculated as the residual term in equation (1) and related to the SF by the equation:

$$Q_f = FC_p\Delta T_{sap} \qquad (4)$$

where F is the mass of sap, C_p is the heat capacity of sap, taken as the same as of pure water (4.186 kJ kg^{-1} K^{-1}); T_{sap} is the difference of the sap temperature between the upper and lower limits of the heated segment, calculated by the equation:

$$\Delta T_{sap} = \frac{\Delta T_c - \Delta T_b}{2} \qquad (5)$$

Therefore, SF is:

$$SF = \frac{Q_f}{C_p\Delta T_{sap}} \qquad (6)$$

The heat storage (Qs) was neglected because the stem diameter was lower than 3 cm (Weibel & Vos, 1994; Grime et al., 1995; Weibel & Boersma, 1995) and because Trejo-Chandia et al. (1997) found a minute contribution of Q_s in the SF estimate of acid lime seedlings.

Porometry

SF was compared to the transpiration measures using a steady-state null-balance porometer (model LI

1600, Li-Cor, Inc.). Readings extended from 8h10 to 19h00, with sequential measurements in three plants in which SF gauges were installed. Each series of measurements took an average of 18 minutes, close to the 20 minutes period taken for each series of sap flow measures. The average value of sampled leaf in each series ($\mu g\ cm^{-2}\ s^{-1}$) was multiplied by the plant leaf area (PLA) to estimate the whole plant transpiration. PLA was determined by measurements of the length (L) and width (W) of all leaves. These measures were used in the calculations of area of each leaf (LA) according to the expression LA=K L W, with K value equal to 0.72 (Coelho Filho et al., 2003).

Analysis of Results

Data were submitted to regression analysis. Differences between transpiration measurements in the lysimeter and SF in 24 hours period, and differences between SF and Tp over the 20-minute period were quantified by estimating the mean of the absolute relative differences (MARD):

$$MARD = \frac{\sum_{i=1}^{n} \left| \frac{(Ti - Pi)}{Pi} \right|}{n} 100 \qquad (7)$$

where T_i is the SF estimated by the HBM or the transpiration determined with the porometer; *Pi* is the measure by the reference method i.e. the weighing lysimeter, being HBM chosen as the reference when the relation between the transpiration measured by the porometer and SF was studied.

RESULTS & DISCUSSION

Even though the dispersion was relatively high ($r^2 = 0.72$), SF correlated well with lysimetric measurements, as can be seen by the slope of 1.0 of the straight line of Figure 1. The standard deviation (SD) of the regression was 0.16 L day^{-1}, or 14.5% of the daily SF average, and MARD was 9.5%, taken the lysimeter measurements as reference.

The comparison between SF and Tp in the 20-min period measurements is shown in Figure 2, each point corresponding to the average of 28 porometric readings (measured leaves surface corresponded to approximately 0.3% and 0.5% of the total LA). The average adjustment between both measurements showed, approximately, a 1:1 ratio, but the dispersion of the points was even greater than to that registered for the comparison with lysimetric measurements, with SD = 0.014 L 20 min^{-1}, and MARD = 45%.

The SF estimates correlated well with transpiration determined by lysimetric and porometric methods, for both 20 minutes and daily periods, but the high dispersion of data reflects the sum of errors of the two methods compared in each figure, and deserves further discussion.

Dispersion was larger when the HBM was compared to the porometer. Porometric measurements present two problems (Angelocci, 2001). The first one refers to the environmental condition, because during the measurement part of the sampled leaf remains inside the porometer cuvette and is exposed to conditions differing from the natural environment, especially concerning to wind velocity. Second, as a result the heterogeneity of the stomatal conductance in certain regions of a single leaf,

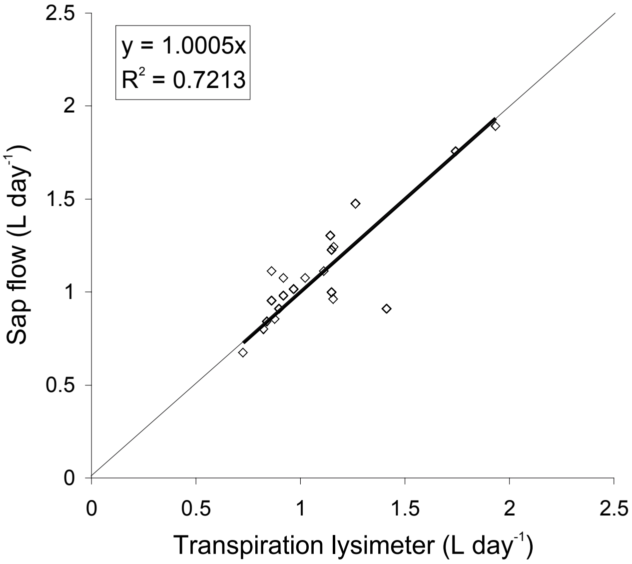

Figure 1 - Relationship between sap flow (SF) determined by the heat balance method in 'Tahiti' acid lime plants and the transpiration measured by weighing lysimeters T_L.

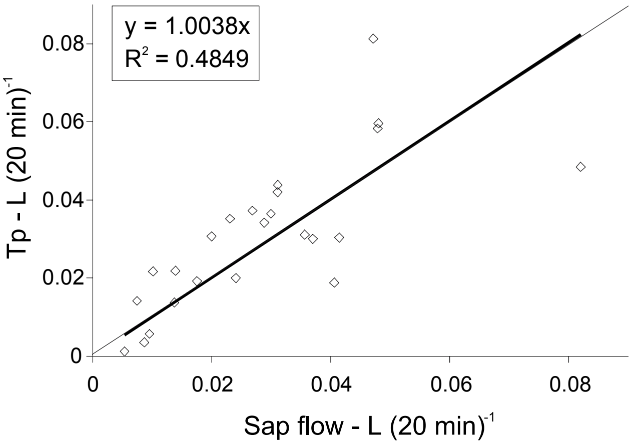

Figure 2 - Relationship between transpiration estimated by mean of 28 porometric readings (Tp) and the sap flow determined by the heat balance method in three 'Tahiti' acid lime plants.

the spatial variability of measurements is very large (Weyers & Lawson, 1997). The same is true among leaves of a single plant, as a function of the variation in exposition to sunlight. These variations can increase dispersion and errors of measurements.

The 1:1 value for the ratio between the values of the two techniques was not observed in acid limes of similar size by Trejo-Chandia et al. (1997), who recorded SF in average 11% and 13% higher relative to the transpiration measured by weighing, respectively for the hourly and for the 24-hour periods. Marin et al. (2003), working with young orange plants with stem diameter between 5 mm and 19 mm, observed overestimation, respectively of 13% and 30%, of daily values of SF given by HBM, in relation to the transpiration measured by weighing; in only one, 25-mm stem plant, a relationship very close to 1:1 was recorded. However, the dispersion between the two measurements, and therefore, the mean difference were smaller than in the present study, probably in consequence of the fact that those authors worked in more controlled conditions than that observed in the present field study.

Comparison between SF measured by HBM and transpiration estimated from porometry are scarce in the literature. Ansley et al. (1994), in a field work with *Prosopis glandulosa* trees in semi-arid conditions of the State of Texas, USA, compared hourly values of stem SF measured by the HBM with porometric transpiration values scaled to the leaf area of plant, using stem leaf area. In the month of June, excepting in two days, they found similar diurnal patterns of variation of values obtained by the two techniques, with an average relation of 0.99 between both and a relatively great dispersion (r^2=0.79). But, during October the estimates from the porometric measurement were greater (averaging more than 30%) than the SF, which they attributed to errors in consequence of the leaves sampling in the porometer technique, because in this month many leaves in the field were damaged and probably had lower transpiration rates.

Values of SF determined by the HBM and of transpiration estimated from the porometer measurements (Tp) were compared, for the three studied plants, throughout the day (Figure 3). The diurnal course of both was typical for the weather conditions in the season. There was a reasonable concurrence between the two techniques, but large deviation is observed in some measurements, as example at about 10h00 and 12h00 for plant 2 and 14h00 and 16h00 for plant 3. For three of these points, higher values of Tp were observed. Steinberg et al. (1990) obtained similar results comparing SF determined in pecan trees with 43 m^2 leaf area and average Tp, but with small deviations between the values of both techniques. Ansley et al. (1994) also noted that during the afternoon, Tp values tended to overcome SF, and suggested that results could be linked to the susceptibility of the porometer's cuvette to environmental variations, because readings were performed with the equipment continually exposed to fluctuating environmental conditions. Steinberg et al. (1990) and Ansley et al. (1994) also found the greatest differences between the two measuring techniques in periods of high transpiration.

For transpiration estimated from the porometric measurements, there was a trend to have an asymmetric distribution, extended amplitude of values and tendency for increasing the coefficient of variation, with a peak between 13h00 and 14h00, in periods of high values of transpiration (Table 1; Figure 4). Besides the fact that the observed mean values are less representative, this indicates a more extended sampling should be recommended. Because of the asymmetric distributions of data in critical periods, analyses were performed over medians (Figure 4).

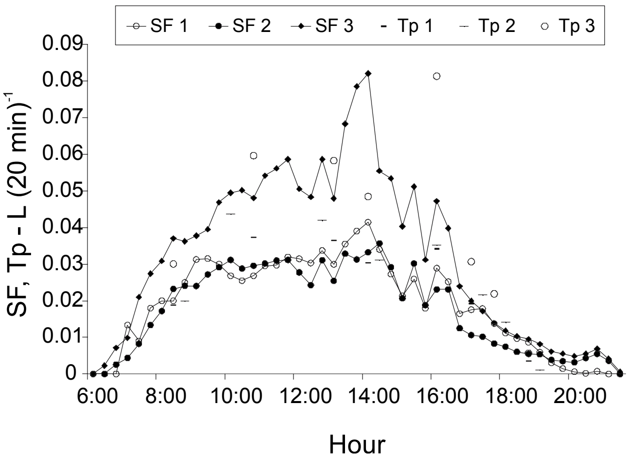

Figure 3 - Course of sap flow (SF) measured by heat balance method and transpiration estimated from porometric measures (Tp) for three plants of 'Tahiti' acid lime with different leaf areas.

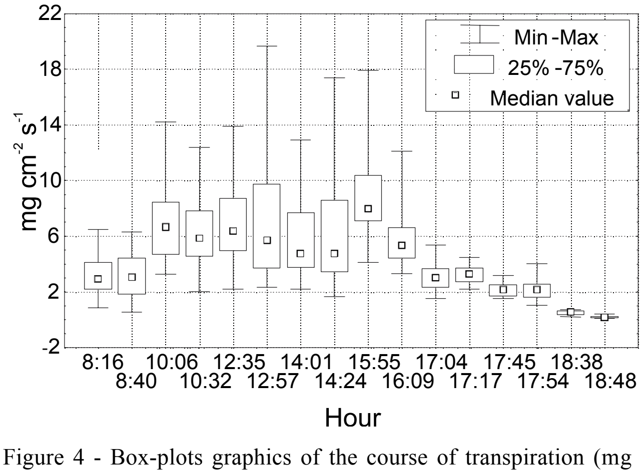

Figure 4 - Box-plots graphics of the course of transpiration (mg cm^{-2} s^{-1}) of two 'Tahiti' acid lime plants estimated from measures by porometry.

Table 1 - Statistical summary of transpirations measurements ($\mu g\ cm^{-2}\ s^{-1}$) in a day, in two plants of 'Tahiti' acid lime (SF 2 and SF 3), using steady-state null-balance porometer, being SD the standard deviation and CV the variation coefficient.

H	Number of samples	Mean	Median	Minimum	Maximum	Amplitude	SD	CV	Skewness	Kurtosis
08:16	35	3.16	2.95	0.85	6.50	5.66	1.34	45.33	0.73	0.40
08:40	42	3.14	3.04	0.53	6.30	5.77	1.51	49.78	0.26	-0.71
10:06	41	7.05	6.67	3.26	14.20	10.94	3.07	46.09	0.74	-0.54
10:32	44	6.28	5.87	2.02	12.39	10.37	2.43	41.33	0.42	-0.25
12:35	36	7.12	6.39	2.21	13.90	11.70	2.86	44.69	0.77	0.12
12:57	34	6.95	5.71	2.32	19.68	17.36	3.91	68.49	1.15	1.74
14:01	35	5.77	4.75	2.21	12.93	10.72	2.68	56.50	0.97	0.22
14:24	33	6.14	4.74	1.67	17.40	15.73	3.93	83.03	1.16	0.65
15:55	23	8.79	7.97	4.12	17.91	13.79	3.02	37.94	1.20	2.56
16:09	26	6.07	5.35	3.29	12.12	8.83	2.37	44.25	1.27	1.02
17:04	26	3.11	3.01	1.51	5.39	3.88	0.97	32.42	0.64	0.23
17:17	17	3.30	3.29	2.18	4.49	2.31	0.73	22.06	0.32	-0.87
17:45	19	2.18	2.14	1.52	3.19	1.67	0.51	23.97	0.60	-0.59
17:54	14	2.30	2.15	1.04	4.05	3.01	0.91	42.14	0.76	-0.26
18:38	14	0.51	0.55	0.20	0.74	0.53	0.17	30.82	-0.41	-1.08
18:48	10	0.21	0.18	0.10	0.39	0.29	0.10	56.04	0.83	-0.18

At the beginning and at the end of the day, when distributions of both methods values converge, averages and medians got closer, but they became different when transpiration increased. The increase in variability and asymmetry at 18h48 could be a consequence of the little sampling (n = 10 leaves) and the lack of equilibrium in the porometer cuvette, as a result of the low transpiration values. However, examining the small values of transpiration in this period of the day, the contribution to the error for the daily or the diurnal values of transpiration is negligible.

The average Tp measured along the day with the porometer presented differences of -6, 13 and 4% in relation to the average of SF, respectively for plants numbered one, two and three. Given the limitations of the use of porometers in determining the transpiration of entire plants, these can be considered small differences.

The way by which Figure 3 was composed renders impossible to conclude on the existence of a time lag between sap flow and transpiration, as referred in the literature. This lag is a consequence of the imbalance between transpiration and sap flow, because in the morning transpiration follows R_n and tends to occur partially at the expense of the water stored in tissues, while by the end of the daytime and in the night, when transpiration decreases sharply or evens stops, SF continues to occur at a rate that tends to replace the tissues water loss during the day. So, SF and transpiration do not show the same course during the day (Heilman & Ham, 1990; Shackel et al., 1992; Valancogne & Nasr, 1993; Weibel & Vos, 1994). Working with acid lime seedlings, Trejo-Chandia et al. (1997) observed a lag time pattern contrary to the expected, once transpiration tended to be smaller than SF in the morning. These authors attributed overestimation of SF measures to intrinsic HBM errors. In stems of very small diameter, with low hydraulic capacitance, time lag between sap flow and transpiration is not necessarily pronounced.

SF values were relative to the energy available (net radiation) throughout the day, showing good dynamic response of the HBM to environmental variations (Figure 5). Dynamic response of the HBM in herbaceous and woody plants ranges from five to 20 min (Baker & van Bavel, 1987; Steinberg et al., 1989). For 'Tahiti' acid lime seedlings with 0.3 m^2 leaf area, Trejo-Chandia et al. (1997) observed a dynamic response between 8 min and 20 min. At any rate, the dynamic response of the sensors is not a critical point for the use of HBM to estimate transpiration (Steinberg et al., 1989).

Comparing the SF variation curves and net radiation R_n (Figure 5), a time lag between both is observed. Perhaps, this is explained just by the time lag between SF and transpiration (which was not possible to be detected in Figure 3), because transpiration follows more the energy availability (net radiation), while the sap flow normally is delayed in relation to transpiration.

Sources of error, and therefore of variability, are associated to determination of the component flows of the heat balance. In spite of the lesser importance of axial flow values (Q_v), mainly when transpiration is high, they

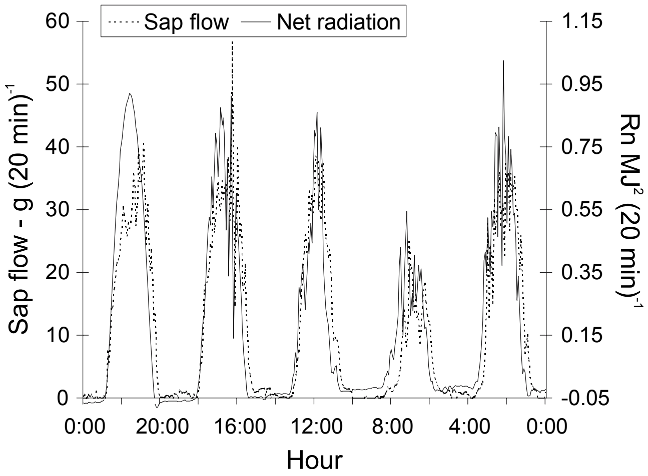

Figure 5 - Variation of sap flow of a 'Tahiti' acid lime plant and of net radiation measured above the orchard from 337th to the 341th day of the year.

are important for estimating K_{sh} and, therefore, Q_r, which influences markedly the heat balance. Steinberg et al. (1989) reported that when the axial flow was eliminated from the analysis, overestimation of SF of potted *Ficus benjamina* (LA = 6.2 m^2; stem diameter = 0.045 m) reached 17% in relation to the transpiration measured by using a scale; but, when Q_v was included, overestimation reached only 4%.

In addition to the effects of Q_v on K_{sh} values, they can vary as function of temperature differences registered by the thermopile, due to a fault thermopile, gauge deformations, or miss contact with the stem. Gerds et al. (1994), studying the sensitivity of the method to K_{sh} variations, reported errors between -8.2 and +37.5% in SF estimates.

When Q_v is measured, errors can also occur because of bad contact of thermocouples with the stem, and also because of to the heat input by the environment as a consequence of inadequate gauge isolation, resulting in non representative upper and lower temperature gradients in the heated stem section. Weibel & Vos (1994) reported errors of 25% resulting from bad contact between the commercial gauge (SGB35-ws) and the irregular stalk of apple trees. Attempts to reduce miss contact by filling gaps between the gauge and the stalk with silicone were not successful.

Inadequate measurements of temperature gradients also affect ΔT_{sap}, introducing another source of error. When SF is high and ΔT_{sap} tend to decrease, measurements are subject to larger errors, given that ΔT_{sap} is the denominator of the mass flow estimation equation (6). When ΔT_{sap} is too low, minor variations can result in large errors in the estimation of flow mass. Senock & Ham (1993), working with small gauges for determining SF in soybean plants, detected for SF conditions above 50 g h^{-1}, that an error of 0.1°C in ΔT_{sap} led to an error of approximately 15% in SF estimation.

The use of very low values of power supplied to the stem (P_{in}) can increase the susceptibility of the measurements to the low ΔT_{sap} values (<0.5°C) in periods of high atmospheric demand, which could have contributed to increase the differences between SF and Tp A recommendation for minimizing problems at peak SF hours is monitoring ΔT_{sap} in order to have values not too close to zero, but using power levels not harmful to the plants stems. Van Bavel (1994) suggested that ΔT_{sap} values should not exceed 8°C in the morning and should remain above 0.3°C at peak SF periods. Special care was taken in this work to maintain ΔT_{sap} at recommended limit; minimum values observed during peak SF periods (< 0.5°C) and in the morning (2.5°C), were below critical values that could have been harmful to the plants stems.

Evidently, the dispersion observed when comparing SF with transpiration measured by the lysimeters or estimated from the porometer is also caused by the errors of these two techniques. It is difficult to have a conclusion about what of the methods contributed more to the dispersion, but it is possible to suppose that the determination of transpiration, specially the estimation from the porometer measurements, contributed in large part to spread comparative data. Considering all sources of errors discussed about the HBM, the procedures to minimize them and the results obtained in this work, we conclude that the performance of the method in determining transpiration in the field of young acid lime plants in the 24-hour period was good, and allowed reliable measurements. For 20-min values, the dispersion observed makes difficult to draw any similar conclusion. At any rate, it shall be considered that errors arising from the porometric measures may have played important role in this dispersion.

So, the HBM seemed to be a reliable methodological alternative in field studies on transpiration of young 'Tahiti' acid lime plants, specially in computed 24-hr periods. It is necessary to emphasize that good results can only be obtained when special care is taken with sources of errors, especially regarding the thermal and radiant insulation of the gauge. Care should also be taken to have a good contact between the gauge and the stem, it is important to avoid water infiltration in the system and to provide adequate heat dissipation rate (power) by the heater, therefore avoiding large errors in the results.

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