Scientia Agricola
versão impressa ISSN 0103-9016

Sci. agric. v.57 n.1 Piracicaba jan./mar. 2000

doi: 10.1590/S0103-90162000000100006

Calibrated heat-pulse method for the assessment of maize water uptake

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ABSTRACT: Plant water requirements are important aspects of crop production to be determined in the field, in order to judiciously manage crop water usage. Water uptake by field grown maize (*Zea mays L.*), under well-watered conditions was verified with the heat-pulse system. The temperature difference between two radially inserted thermocouples, one 9 mm above and the other 4 mm below a heater piercing the maize stem, was measured every 0.3 seconds following emission of a heat-pulse. Comparisons of the heat-pulse system outputs, lysimetric measurement and transpiration model estimates were monitored on an hourly and daily basis. At normal and low atmospheric demand daily and hourly values of heat-pulse outputs and lysimetric measurement showed good agreement. Hourly agreement of a modified Penman-Monteith energy balance equation estimate and heat-pulse outputs showed accordance between measurement of sap flow and the plant water-loss theory. Study of the relationship between maize canopy water loss rate and heat velocity in the stem showed that these two parameters were proportional and a calibration factor of 1.51 for full soil foliage coverage was verified.
Key words: sap flow, transpiration, heat-pulse

Desenvolvimento do método do "pulso de calor" para determinação da absorção hídrica em milho

RESUMO: A determinação a campo das necessidades hídricas de plantas é um aspecto importante da produção agrícola, para o manejo correto do uso da água pelos cultivos. A absorção de água por uma cultura de milho (*Zea mays L.*), cultivado a campo, em condições de não limitação hídrica, foi verificada através da técnica do pulso de calor. Após a emissão de um pulso, procedeu-se a medições, a cada 0,3 segundos, do diferencial de temperatura entre dois termopares, inseridos radialmente no caule da planta. O primeiro foi colocado 9 mm acima e o segundo 4 mm abaixo de uma fonte de calor ("heater"). Foram feitas comparações entre as medições feitas pela técnica do pulso de calor, lisímetro e estimativas da transpiração computadas em modelo, numa base horária e diária. Comparações entre medições horárias feitas pelo pulso de calor e as estimativas da transpiração, feitas pelo modelo, mostraram concordância entre a determinação da transpiração através da medição do fluxo de seiva e, estimativa, baseada em desenvolvimento teórico. A taxa da perda d'água pelo dossel e a velocidade de propagação de energia térmica no caule do milho mostraram-se fenômenos proporcionais e um fator de calibração de 1,51 foi encontrado, para condição de cobertura total do solo pela folhagem do milho.

Palavras-chave: fluxo de seiva, transpiração, pulso de calor

INTRODUCTION

Plant water uptake is a critical aspect of crop growth and yield. A direct and reliable way to study plant water uptake of herbaceous plant under natural conditions is desirable for research purposes as well as for irrigation management. Available methods for direct assessment to the plant water requirements are costly, complex to operate and most of them can not be extrapolated from one field to another.

Huber & Schmidt (1937) first introduced the heat-pulse method. It was later used by Marshall (1958) and Decker & Skau (1964) to study its validity in trees. Closs (1958) also has attempted to apply the technique to cotton plants. These studies have shown that canopy water loss could be assessed by heat tracing the stem sap flow. Cohen et al. (1981) made progress towards calibration of the method. Recent studies have shown that reconsideration of theory and technical improvements allowed successful measurement of transpiration rate in trees (Cohen et al., 1985). Works carried out by Cohen et al. (1988) in herbaceous plant suggest that measuring the apparent velocity of the sap stream in a plant stem by the heat-pulse system offer much promise.

The aim of this study is to investigate the water uptake of field grown maize by applying the heat-pulse technique. An automated weighting lysimeter and a modified Penman-Monteith energy balance equation (Santos, 1998) were used in comparison with the heat-pulse method.

THEORY

Sap flow determinations using a heat-pulse as a tracer are based on the solution of the convective heat-diffusion equation. According to Carslaw & Jaeger (1947) and admitting uniformly moving sap in an isotropic medium, the two-dimensional heat transport equation from a line source perpendicular to the sap stream was solved by Marshall (1958) as follows:

$$T = (H/(4\pi\rho ckt))\ \mathrm{exp}[-(x - vt)^2 /(4kt)] \quad [1]$$

with T being the temperature elevation (^{o}C) produced by the heat pulse after time t at a distance x (mm) directly downstream of the linear heater; H is the heat output per unit length of the heater (J mm^{-1}); r(mg mm^{-3}), c (J mg^{-1} ^{o}C^{-1}), and k (mm^{2} s^{-1}) are, respectively, the density, specific heat and thermal diffusivity of wet wood; and v is the convective heat velocity (mm s^{-1}). Placing the line heater and the temperature probe in the same diametrical, longitudinal plane simplifies the solution to an apparent one-dimensional form as given by Equation [1].

The convective heat velocity, v, i.e., the contribution of sap flow, j_f (m s^{-1}) to the temperature change of wet wood is:

$$v = j_f \rho_s c_s / \rho c \quad [2]$$

with r_s being the density of sap, and c_s its specific heat.

The temperature wave reaches its maximum t_m seconds after emission of a heat pulse. If the derivative of T in respect to time in Equation [1] at $t = t_m$ is zero, then:

$$v = (x^2 - 4kt_m)^{0.5} / t_m \quad [3]$$

Herbaceous plants, such as maize are thermally coupled to environment. Therefore fluctuations in the ambient temperature disturb the temperature evolution described by Equation [1]. The thermal diffusivity of stems is also difficult to evaluate. To overcome these difficulties, Closs (1958) suggested to use a differential temperature measurement at two asymmetrically located points above and below the heat source. In this case the convective velocity, v, is:

$$v = x_1 - x_2 / 2t_0 \quad [4]$$

with x_1 and x_2 being the distances directly above and below the heat source line, respectively, and t_0 is the time required for the temperature difference between x_1 and x_2 return to its initial value.

The accuracy with which t_m in Equation [3], or t_0 in equation [4] can be detected depends on the absolute rate of temperature change as t_m or t_0 is approached.

Works by Coehen et al. (1988) in cotton have shown that tm and t0 detectibility is a function of the sap velocity and probe configuration. The temperature difference curves (Downstream minus upstream sensor) have an initial downward swing (Fig 1), which is more pronounced when the upstream thermometer is closer to the heater. The authors have pointed out an arrangement of x1 = 6 mm and x2 = 2 mm as the closest spacing achievable with heaters and thermometers built using the smallest standard hypodermic needle (0.55 mm, internal diameter). However, in practice, more reproducible results were possible with sensors placed 4 mm upstream and 9 mm downstream of the heater.

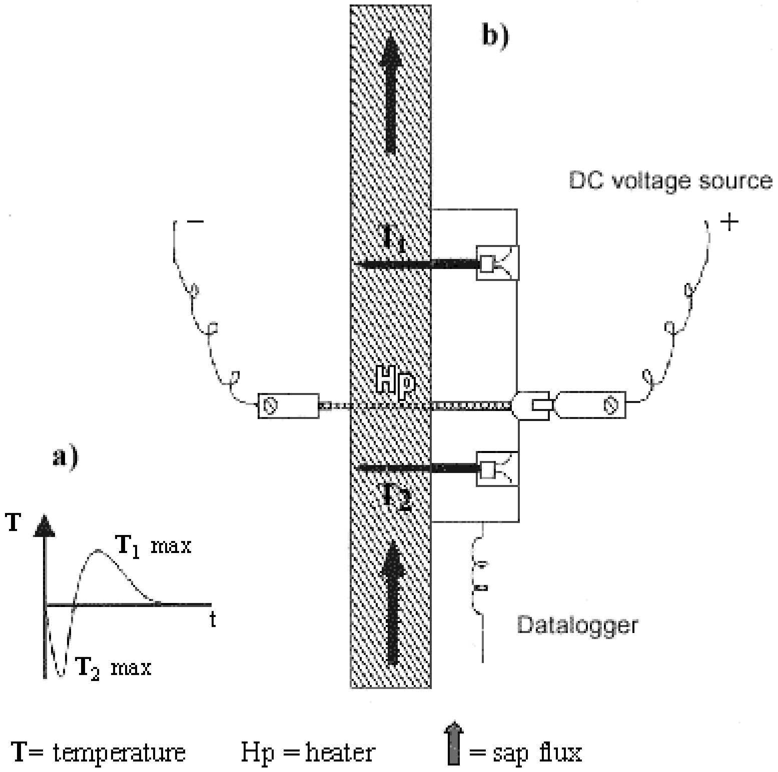

Figure 1 - Probe configuration for measurement of heat flux in the maize stem (b), by detecting differential temperature between T1 (downstream sensor) and T2 (upstream sensor) after a heat pulse emitted by the heater (Hp). Differential curve of temperature are shown (a).

Cohen et al. (1988) have shown in cotton, that in the range of sap velocity between 0.17 and 0.22 mm s^{-1} both t_0 and t_m can be measured with reasonable accuracy. Using t_0 we can determine v from Equation [4], and rebuild Equation [3] to determine k.

Transpiration rate (Tr) calculated with t_0 or t_m can finally be calculated as:

$$Tr = v(t_0, t_m).C_f \frac{d^2 \pi}{4} \quad [5]$$

where C_f is the calibration factor for the specific herbaceous specie and d is the averaged stem diameters in the local of probe installation.

MATERIAL AND METHODS

PLACE, TIME AND CROP

The study was conducted during the growing seasons of 1995/96 and 1996/97 in a 0.5 ha experimental area of maize (Zea mays L.), Hybrid Pioneer, in Eldorado do Sul, RS, South of Brazil (30^0 05'S 51^o 39'W, 46 m). The maize was planted in rows of 0.75 m spacing, during middle October in both years, in a typical plinthic soil (Melo et al., 1996). Fertilizer application was done according to soil analysis. Manual cultivation was done to control weed infestation. Plant population density was close to 67,000 plants ha^{-1}. In the center of the experimental area an automated weighting lysimeter with 5.1 m^{-2} was installed.

IRRIGATION

Watering was applied by an in-line sprinkler irrigation system installed in the center of the experimental area in the direction E-W, following the maize row. Water was delivered at decreasing rate to five experimental plots with five replications, according to procedure described and used by Cunha et al. (1994). Only the well-watered plots were used to study maize water uptake, at which soil water potential was maintained at field capacity level throughout the experiment.

ENVIRONMENTAL MEASUREMENTS

Global radiation (model LI200SZ, Licor Inc., USA), wind speed (model A100R, Vector Instruments, UK), air temperature and humidity (model HPMP35AC, Vaisala, FIN), and rainfall (model ARG100, Environmental Measurements Ltd., UK) were measured two meters above the soil at an automated meteorological station, (model W2000, Campbell Scientific, Logan, USA) located besides the experimental area.

INSTRUMENTATION FO HEAT PULSING

The probe block for sap monitoring that was installed in the maize stem consisted of a line heating element and two temperature sensors mounted on a fiber plate, 40 by 20 by 8 mm (Coehen et al., 1988). The heating element was a stainless steel of 0.55 mm (internal diameter) and 65 mm length. The temperature sensors comprised copper constantan thermocouples, inserted into a section of stainless steel hypodermic needles (0.55 mm ø, and 65 mm length). The needles (temperature sensors and heating element) were inserted in the stem diametrically. The heating element was connected to a 12-v car battery and the temperature sensors to a data logger (Figure 1).

EXPERIMENTAL PROCEDURE

Installation of heat pulse probes was done in the base of 8 maize stem, which were considered representative plants of the full range stem diameters. Prior to installation, the stem was "cleaned" of the first husks and measurement of the diameter was taken. A heat pulse of 0.3 s was applied to the stem and the temperature difference between the thermocouples above and below the heater was monitored at 0.3-s intervals by using a data logger (CR21X – Campbell Scientific, Logan, UT). After 7 to 10 days the block were removed and new plants were chosen in order to avoid stem damage due to over heating. Calibration of the heat-pulse technique was made by simultaneous measurements of the heat velocity in the stem and rate of water loss determined by the automated weight lysimeter, in the 1996/1997 growing season.

Simultaneous water loss estimates were done by using a modified Penman-Monteith energy balance equation (Santos, 1998) and the results were compared with the heat-pulse outputs.

RESULTS AND DISCUSSION

In this study, the range of sap velocity found in maize permitted the use of only t_0 values, for transpiration rate calculations. For days with high evaporative atmospheric demand, such as in the 1995/1996 growing season, values of t_0 around 25 seconds, for single maize plants was very common. For days with very low atmospheric demand such as occurred in the 1996/1997 growing season, values around 270 seconds was observed. Transpiration rates for single maize plants measured with heat-pulse ranged from 0 to around 300 cm^3 h^{-1} throughout the experiment.

Diurnal course of maize water uptake under normal atmospheric demand is shown in Figure 2. Heat-pulse and lysimetric values showed agreement for the daily total of water loss. Small disagreement between curves (Figure 2) was due to the wind that caused fluctuation on the automated lysimetric system (Bergamaschi et al., 1997).

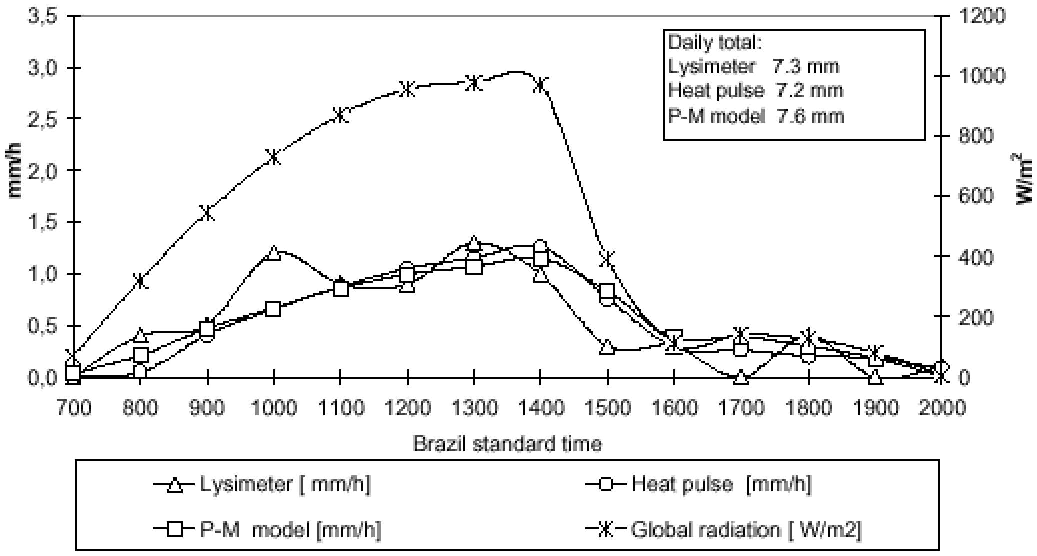

Figure 2 - Hourly course of measured and estimated maize water loss, under normal atmospheric demand condition, on 01-05-1997.

For the low atmospheric demand (Figure 3) closed agreement was observed between heat-pulse and lysimeter values with the daily total being very similar. Under this condition curves of water uptake also showed response for the change in the daily inputs of global radiation. These can demonstrate that heat-pulse system has good response to variables from the plant-atmosphere continuun, responsible for the plant water loss process.

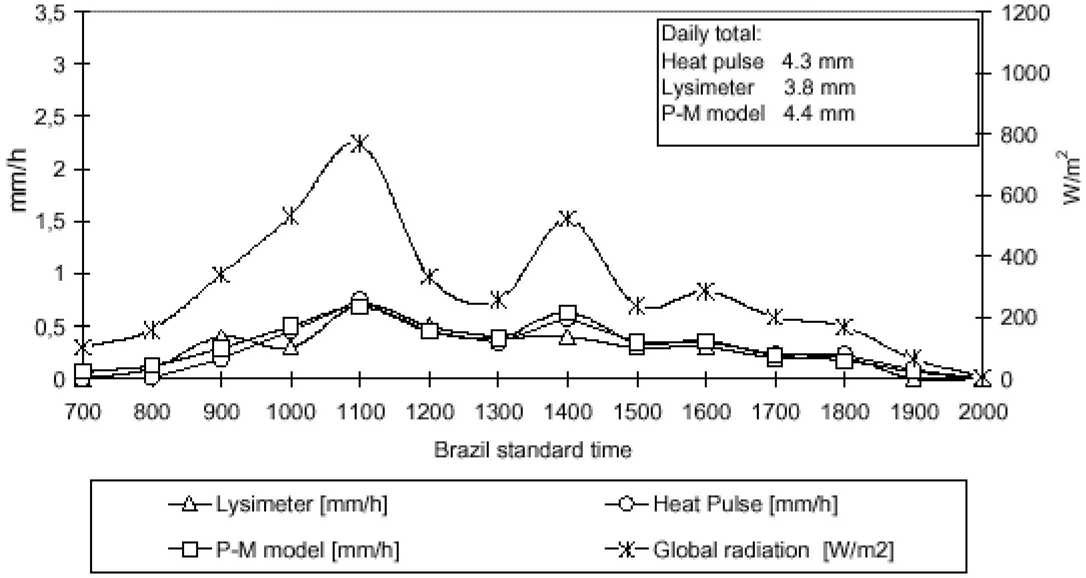

Figure 3 - Hourly course and daily total of measured and estimated maize water loss, under low atmospheric demand condition, on 01-09-1997.

Values from lysimeter (Figure 2 and 3) are higher in the early morning and lower in late afternoon when compared to the heat-pulse ones. This tendency is due to the differences in the phases of transpirational path assessed by each one. Lysimeter measure the water loss by the whole canopy which is due to the gas-liquid interfaces whereas sap movement in the stem is linked to those interfaces by a complex hydraulic system involving cell to cell diffusion as well as mass flow through an elastic network where the capacitance (Jones, 1994) is due to cause the heat-pulse values to have a lag phase in the morning. At the end of the afternoon, the water stored in the tissue below the probe installation still continue to flow while water loss from leaves has decreased. This causes the lysimeter to close first in comparison to heat-pulse system.

Estimates of water loss by Penman-Monteith energy balance equation showed agreement with the values from heat-pulse in normal and low atmospheric demand (Figure 2 and 3). These can demonstrate that measuring water uptake by using sap heat tracing is in accordance with the theory describing the processes involved in the transport of water from plant canopies to atmosphere.

Figure 4 shows the diagram of daily measurement taken throughout the growing season of 1996/1997. By forcing the linear regression through the origin produced a slope of 0.9 for heat-pulse and lysimeter comparisons with a R^2 of 0.89. This demonstrates that the heat-pulse values are in agreement with the values of lysimeter measurement in all condition of atmospheric demand during the experiment.

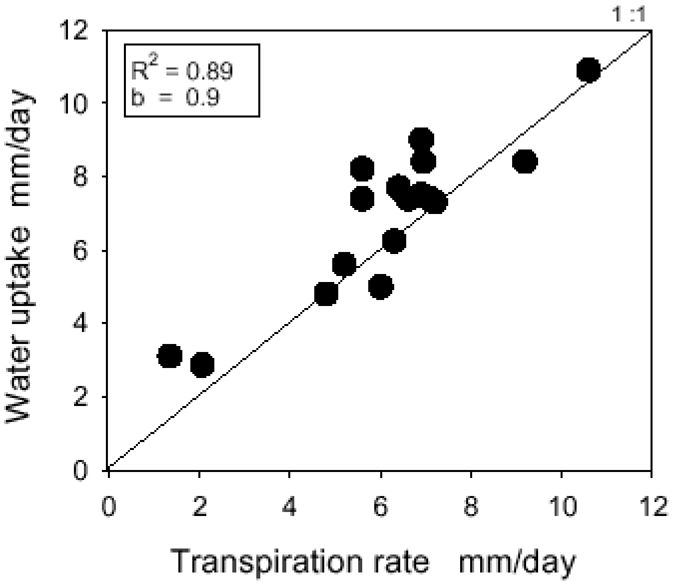

Figure 4 - Relationship between measured water uptake by heat pulse and transpiration rate by lysimeter, in maize, for the growing season of 1996/1997.

An example of the relationship between transpiration rate and convective velocity in the stem is shown in Figure 5. The data were collected every 15 minutes and averaged to an hour basis for several days. Line from Figure 5 crosses the axes at a point that is not significantly different from the axes origin. This demonstrates that maize water loss rate and heat velocity are proportional phenomena. This proportionality can change with the stem cross sectional area (Cohen et al., 1988). However, since the maize stem cross section has no significant changes in diameter, and for practical application, the verification of the slope of transpiration rate measured in the lysimeter in respect to simultaneous heat velocity observed with the heat-pulse can be considered as confident calibration factor. Analysis of this relationship produced a value of 1.51.

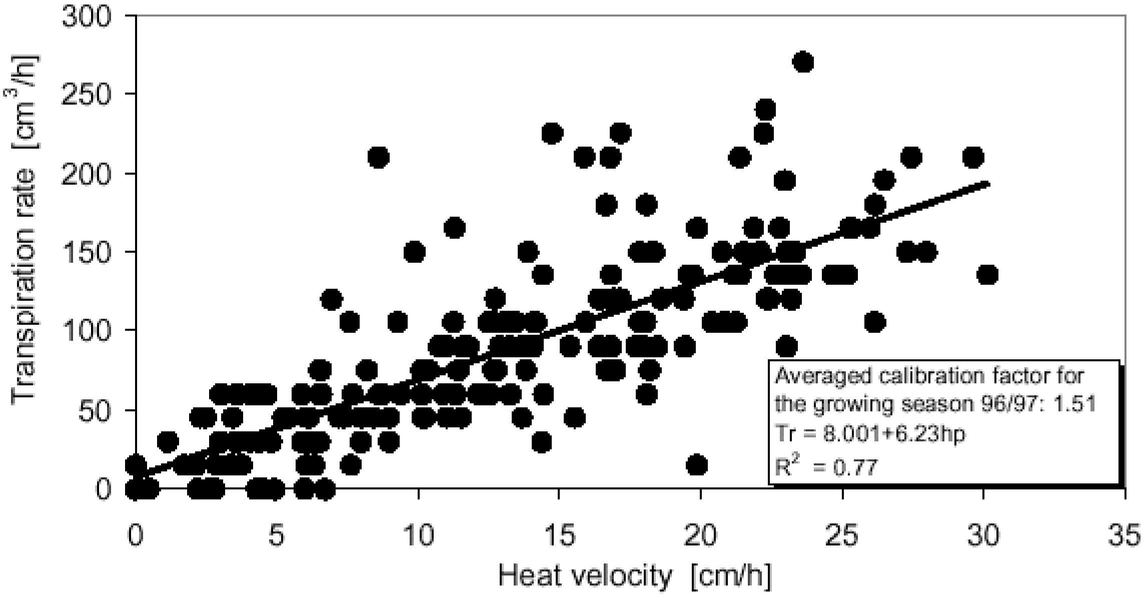

Figure 5 - Transpiration rate (lysimeter) in respect to steam heat velocity in maize crop, during the growing season of 1996/1997.

The position of the temperature sensors in relation to the effective sap conducting tissues is an important aspect of precise detection of sap movement and as a consequence the convective heat velocity. Therefore, further investigation is expected in respect to the depth of insertion of the temperature sensor into the plant stem, in the sense of the optimisation of the position of the sensor and the contact of it with the sap flow.

CONCLUSIONS

For the probe configuration used in this work, the heat-pulse technique could provide reliable measurements of water uptake by maize, based on the proportionality of water loss rate and stem heat velocity.

A value of 1.51 was found as a calibration factor for maize. This was obtained in a variety of atmospheric demand conditions.

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Received March 23, 1999