CALIBRATED HEAT PULSE METHOD FOR DETERMINING WATER UPTAKE IN MAIZE[1]

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ABSTRACT

Plant water needs is an important aspect 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.*), in 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 heat pulse system outputs, lysimetric measurement and transpiration model estimates were done in an hourly and daily basis. At normal and low atmospheric demand daily and hourly values of heat pulse outputs and lysimetric one showed good agreement. Hourly agreement of modified Penman-Monteith energy balance equation estimates and heat pulse outputs showed accordance between measurement of sap flow and plant water loss theory. Study of the relationship between maize canopy water loss rate and heat velocity in the stem showed they were proportional and a calibration factor of 1.51 was found.

Keywords: sap flow, transpiration, irrigation

INTRODUCTION

Plant water uptake is a critical aspect of crop growth and yield. A direct and reliable way to study water uptake of herbaceous plant under natural conditions is desirable for many research purposes. The most obvious range from the study of plant water relationship to irrigation management.

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Present available methods of direct evaluation of plant water requirements are costly, complex to operate, and most of them can not be transported field to field.

The heat pulse method was first introduced by Huber & Schmidt (1937) and was 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 fllow. Progress towards calibration of the method was made by Cohen et al. (1981). 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 apparent velocity of the sap stream in a plant stem by using the heat pulse system offers much promise.

The aim of this work is to investigate the water uptake of field grown maize by applying the heat pulse technique. An automated weight lysimeter and a modified Penman-Monteith energy balance equation (Santos et al., 1998) were used to make comparison with heat pulse data output.

THEORY

Sap flow determinations using a heat pulse as a tracer are based on heat conduction and convection in a homogeneous and isotropic medium (Swanson & Whitfield, 1981). For conduction:

$$\frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \qquad [1]$$

where T is the temperature departure from ambient (^oC), **t** is the time and **k** is the thermal diffusivity ($m^2\ s^{-1}$).

For convection:

$$-au\rho_s C_s \frac{\partial T}{\partial x}\Delta x \qquad [2]$$

where ***a*** is the sap conducting fractional cross sectional area of stem (m^2), ***u*** is the velocity ($m\ s^{-1}$), ρ_s and C_s are respectively the density ($g\ m^{-3}$) and specific heat ($J\ g^{-1}\ {}^oC^{-1}$) of plant sap, $\partial T/\partial x$ is the temperature gradient across the stem ($^oC\ m^{-1}$) and Δx is the distance between cross sectional area and any plane area perpendicular to the x axis (m).

For a two-dimensional simplification of a three-dimensional heat flow condition and assuming the linear heater and point temperature sensors are installed radially into the xylem and so, heat conduction and convection in the two direction perpendicular to the heater must be accounted for and also if sap flows along x direction, we may combine conduction and convection and write for the time variation of temperature (Marshall, 1958; Carslaw & Jaeger, 1947):

$$\frac{\partial T}{\partial t} = k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2} - au \frac{\rho_s C_s \Delta T}{\rho C \Delta x} + \frac{Q}{\rho C} \qquad [3]$$

where k_x and k_y are the axial and tangential thermal diffusivities (m^2 s^{-1}) of the wood-sap mixture, ρ and C respectively the density (g m^{-3}) and specific heat (J g^{-1} $^oC^{-1}$) of wet wood and Q is the temperature rise due to internally generated heat.

Marshall (1958) defined heat pulse velocity as:

$$v = au \frac{\rho_s C_s}{\rho C} \qquad [4]$$

and showed that if Q represents an instantaneous heat pulse at x = y = t = 0, the heater and sensors are infinitely small, the xylem is infinitely large, thermally homogenous and isotropic ($k_x = k_y$) and also the sap stream is uniformly distributed, equation [3] may be solved for T as:

$$T = (Q/(4\pi\rho Ckt)) \exp[-(x - vt)^2 + y^2 /(4kt)] \qquad [5]$$

with T being the temperature elevation (^{o}C) produced by the heat pulse after time t and at a distance x (mm) directly downstream of the linear heater; Q is the heat output per unit length of the heater (J mm^{-1}; and v is the convective heat velocity (mm s^{-1}).

Equation [5] may be manipulated in several ways to extract ***v*** from the temperature variation with time at one or more points (x, y) in the xylem.

Placing the line heater and the temperature probe in the same diametrical, longitudinal plane simplifies the solution of equation [5] to an apparent one-dimensional form (Santos et al., 1998). The temperature wave reaches its maximum t_m seconds after emission of a heat pulse. If the derivative of T with respect to time in Equation [5] at $t = t_m$ is zero, then:

$$v = \left(x^2 - 4kt_m\right)^{0.5} / t_m \qquad [6]$$

Herbaceous plants, such as maize are thermally coupled to environment. Therefore fluctuations in the ambient temperature disturb the temperature evolution described in Equation [5]. The thermal diffusivity of stems is also difficult to evaluate. To overcome these difficulties, Closs (1958) suggested the use of a differential temperature measurement at two asymmetrically located points above and below the heat source. In this case, if the two sensors indicate the same temperature ($T_1 = T_2$), the convective velocity, v, is given as:

$$v = (x_1 - x_2)/2t_0 \qquad [7]$$

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

The accuracy with which t_m in Equation [6] or t_0 in Equation [7] can be detected depends on the absolute rate of temperature change as t_m or t_0 is approached.

For cotton, Cohen et al. (1988) have shown that t_m and t_0 detectibility is a function of the sap velocity and probe configuration. The temperature difference curves (downstream minus upstream sensor) have an initial downward swing, 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). However, in practice, more reproducible results were possible with sensors placed 4 mm upstream and 9 mm downstream of the heater.

Cohen et al. (1988) have shown for 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 [7], and rebuild Equation [6] to determine k.

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

$$Tr = v(t_0, t_m).C_f \frac{d^2 p}{4} \qquad [8]$$

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

MATERIAL AND METHODS

Local, Time, Crop and irrigation

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). Plant population density was close to 67,000 plants. ha^{-1}. 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. Well-watered plots were used to study maize water uptake, which was maintained at field capacity all throughout the experiment.

Environmental Measurement

Global radiation, wind speed, air temperature and humidity and rainfall were measured two meters above the soil at an automated meteorological station located besides the experimental area.

Instrumentation for 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 (Cohen 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 and 65 mm length). The needles (temperature sensors and heating element) were inserted in the stem diametrically. The heating element was wired in both ends to conduct the heating current from a 12-v car battery. The temperature sensors were wired to conduct data from stem heat tracing to a data logger.

Experimental Procedure

Installation of heat pulse probes was done in the base of 8 maize stem considering representative plants of the full range stem diameters. Prior to installation the stem was “cleaned” of the first husks and measurement of 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. After 7 to 10 days the blocks were removed in 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 pulse in the stem and rate of water loss determined by 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 et al., 1998) and computations were compared with heat pulse outputs.

RESULTS AND DISCUSSION

During the experiment, 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 were very common. For days with very low atmospheric demand such as occurred in the 1996/1997 growing season, values around 270 seconds were observed. Transpiration rates for single maize plants measured with heat pulse ranged from 0 to around 300 $cm^3\ h^{-1}$ during the experiment.

Under normal and low atmospheric demand, heat pulse and lysimeter values showed agreement for the hourly and daily totals being very similar.

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

When transpiration was high the precision of t_0 determination depended on the shortest scanning interval of the data logger (Cohen & Fuchs, 1989). In this study, a 0.3 seconds scanning interval was used. This was considered enough for a correct detection. However, for low sap velocities detection the most crucial point was the influence of ambient heat properties over the sap stem, which can cause mixing with the heat coming from the pulsing. This can produce wrong values of t_0. Prior to a heat pulse, the temperature difference between the two thermocouples is often zero, or at least constant (T1 = T2). However when the ambient air around the stem is changing rapidly, which is very common in the early morning and late afternoon, temperature gradients develop along the stem. For low sap velocities the gradient magnitude (drift) may be of the same proportion as the rate at which the temperature difference approaches its initial value. To minimize errors, the rate of temperature change was measured 60 seconds prior to each emission of a heat pulse and extrapolate linearly with time, in order to adjust temperature differences. This procedure was a shortcut used to eliminate the influence of the ambient temperature on the heat carried in the stem.

Therefore, the used probe configuration allowed the correct detection of sap movement. Despite the measurement water uptake using the sap heat tracing being based on idealized heat transport theory (for example, Swanson & Whitfield, 1981), which is quite complex, the use of probe configuration and a calibration factor (Cohen et al., 1981; Santos et al., 1998) is a practical alternative to the solution of those formal heat transport equations.

The relationship between transpiration rate and convective velocity in the stem, observed throughout the experiment, demonstrated that maize water loss rate and heat velocity were 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, for practical reasons, 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 throughout this work produced a value of 1.51.

The position of the sensors of temperature in relation to the effective sap conducting tissues is an important aspect of precise detection of sap movement and in 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 order to optimize the position of the sensor and the contact of it with the sap flow.

CONCUSIONS

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

Analysis of the relationship between maize transpiration rate and stem heat velocity produced a calibration factor of 1.51.

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