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RELAÇÕES ÁGUA-SOLO-PLANTA-ATMOSFERA

SUNLIT AND SHADED MAIZE CANOPY WATER LOSS UNDER VARIED WATER STRESS[1]

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ABSTRACT

The precise estimation of transpiration from plant canopies is important for the monitoring of crop water use and management of many agricultural operations related to water use planning. The aim of this study was to estimate transpiration from sunlit and shaded fractions of a maize (*Zea mays L.*) canopy, using the Penman-Monteith energy balance equation with modifications introduced by Fuchs et al. (1987) and Fuchs & Cohen (1989). Estimated values were validated by a heat pulse system, which was used to measure stem sap flow and by a weighing lysimeter. A relationship between incident radiation and leaf stomatal conductance for critical levels of leaf water potential was used to estimate transpiration. Results showed that computed transpiration of the shaded canopy ranged from 27 to 45% of the total transpiration when fluctuations in atmospheric demand and the level of water stress were taken in account. Hourly and daily estimates of transpiration showed agreement with lysimeter and heat pulse measurements on the well-watered plots. For the water-limited plots the precision of the estimate decreased due to difficulties in simulating the canopy stomatal conductance.

Key words*:* transpiration, Penman-Monteith, heat pulse**,** *Zea mays* L.

PERDA D'ÁGUA DOS EXTRATOS ENSOLARADO E SOMBREADO DE UM DOSSEL DE MILHO SOB DIFERENTES CONDIÇÕES DE ESTRESSE HÍDRICO

RESUMO

A precisão na estimativa da transpiração de dosséis de plantas é importante para o monitoramento das necessidades hídricas dos cultivos e gerenciamento das operações agrícolas relacionadas com planejamento e uso da água. O objetivo deste estudo foi estimar a transpiração dos extratos ensolarado e sombreado de um dossel de milho (*Zea mays L.)*, usando a equação de Penman-Monteith, com modificações introduzidas por Fuchs et al. (1987) e Fuchs & Cohen (1989). Os valores de estimativas foram validados pelo sistema pulso de calor, que foi utilizado para medir o fluxo de seiva no caule do milho, e por um lisímetro de balança. A relação entre radiação solar incidente e potencial da água na folha foi utilizada, na estimativa da transpiração. Os resultados mostraram que a estimativa da transpiração da parte sombreada variou de 27 a 45% da transpiração total do dossel, considerando-se condições variáveis de demanda atmosférica e nível de estresse

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hídrico da planta. Estimativas horária e diária mostraram concordância com valores simultâneos medidos pelo pulso de calor e lisímetro, nas parcelas sem restrição hídrica. Para parcelas com restrição hídrica houve perda de precisão na estimativa, devido a dificuldades em corretamente simular a condutância estomática do dossel.

Palavras-chave: transpiração, Penman-Monteith, pulso de calor, *Zea mays* L.

INTRODUCTION

Progress in the automation of meteorological network data has provided an opportunity for improved management of agricultural systems. Dissemination of information can be used to assist in the water use monitoring of several key operational areas. Moreover, the introduction of automated irrigation systems contributed to an accurate control of the timing and amount of water provided. However, these new technologies require real time determination of crop water use at field level. Timely application of water is an important aspect of an efficient crop production. The efficiency of water use can be maximized and losses from deep percolation can be avoided if precise application of water is implemented.

Measurement of evapotranspiration with micrometeorological devices, lysimeters or heat tracer methods for detecting sap flow, while precise are generally restricted in their usefulness to research, due to the high costs involved and difficulties in field level routine application. It is easier to estimate evapotranspiration of crops through indicators of atmospheric evaporative demand and plant parameters.

Formulae to estimate the actual evapotranspiration of crops from meteorological data have been presented and reviewed by several researchers (Doorenbos & Pruitt, 1977; Smith, 1992). They depend, however, on the crop coefficients to calculate actual evapotranspiration with changing location, season and crop management, and this could increase inaccuracy of detecting water loss by crops. Fuchs et al. (1987) and Fuchs & Cohen (1989) suggested models aimed at providing a real time estimate of cotton transpiration from routine meteorological data. Petersen et al. (1992) later on expanded the same models to include the shaded fraction of cotton canopy transpiration.

Because shaded leaves comprise a large fraction of the leaf area in the later stages of the growing season, their overall water loss may be significant, since even in low irradiance the stomata still have some degree of aperture, mainly driven by the blue light (Zeiger & Field, 1982).

Results from Petersen et al. (1991) showed that the fraction of shaded canopy of cotton may contribute to a significant portion of total transpiration. Fuchs & Cohen (1989), in turn, suggested that their model's systematic underestimation of cotton transpiration may be due to neglecting the water loss from the shaded foliage.

In maize, the most critical stage in relation to water stress is from the beginning of flowering to the end of grain filling (Matzenauer et al., 1995), when the crop foliage has covered the soil and therefore the shaded fraction is significant. It is necessary to investigate the aspects of transpiration in this portion of canopy in order to achieve precise monitoring of water use.

The objective of this study was to provide a simple computation of transpiration from the sunlit and shaded fractions of a maize canopy using the Penman-Monteith energy balance equation. A relationship between absorbed photosynthetically active radiation (PAR) and leaf conductance for varied water stress was adjusted. A heat pulse system was used to measure the maize stem sap flow and provide independent field validations. A weighing lysimeter was also used when non-water stress condition was considered.

MATERIAL AND METHODS

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; elevation 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}. Leaf area index (LAI) and plant height were monitored weekly (França, 1997).

Irrigation

Water was applied by an in-line sprinkle irrigation system installed at the center of the experimental area in the E-W direction, following the maize row. Water was delivered at decreasing rate to 5 experimental plots with 5 replications, according to the procedure described by Cunha et al. (1994). Three experimental plots were used to study maize transpiration: a well-watered plot which was maintained at field capacity throughout the experiment and two water-limited plots. At 1 of these 2 water-limited plots irrigation was not applied and severe moisture stress was allowed to develop.

Water stress levels based on midday sunlit leaf water potential, soil water potential and soil moisture (dry mass fraction of water) typical of the growing season are presented in Table 1.

Table 1. Typical values of leaf and soil water potential and soil moisture for the well-watered and water-limited plots of maize in the experimental area

Water Availability	Noon Sunlit Leaf Water Potential (MPa)	Soil Water Potential at 45 cm Depth (MPa)	Soil Moisture (Dry Mass Fraction of Water) at Depth 45 cm
Severe stress	< - 1.8	< - 0.06	8.35%
Moderate stress	- 1.8 to - 1.0	- 0.06 to - 0.02	
Non-stress	> - 1.0	> - 0.02	

Environmental measurements

A steady state porometer, Model LI 1600 was used to measure stomatal conductance. Porometric data were obtained on two separate cloudless days. Measurements were taken every half hour throughout the day, beginning no earlier than 09:00 AM, to ensure the complete dryness of the shaded leaves.

Leaf water potential was measured with a pressure chamber (Model 3000, Soil Moisture Co. USA). Measurements were taken at approximately 12:00 noon on sunlit leaves. To avoid sources of error in leaf water potential measurement, leaves were placed in a plastic bag at the time of excision.

Soil water potential was monitored with mercury manometer tensiometers installed in each plot at several depths. Photosynthetically active radiation (PAR) was measured by a quantum sensor (LI-190S, LI-COR) mounted on the porometer's sensor head. Porometry and PAR measurements were taken simultaneous. Wind speed profile was measured above and inside the maize plots along the growing season by changing anemometer's (Model A100R, Vector Instruments, UK) height as the crop developed, keeping geometrical distance between them and having always one of them on the top of sunlit and shaded canopy.

Global radiation (Model LI200SZ, Licor Inc., USA), air temperature and humidity (Model HPMP35AC, Vaisala, FIN), and rainfall (Model ARG100, Environmental Measurements Ltd., UK) were measured 2 m above the ground by an automated meteorological station, (Model W2000, Campbell Scientific, USA) located beside the experimental area. Data were averaged for each 10-min interval and recorded with a battery-powered data logger (CR10, Campbell Scientific).

Model

Transpiration (W m^{-2}) was calculated separately for sunlit and shaded leaves in accordance with the Penman-Monteith energy balance equation (Monteith, 1965) as:

$$Tr = \frac{[\ s/(s+\gamma)Rn] + [\rho C_p \ \ e(T_a) - e_a \ \ /(s+\gamma)(1/g_v)]}{\{1 + [\ \gamma/(\gamma+s)(g_v/g_s)]\}} \quad (1)$$

With s being the slope of the saturation vapor pressure curve (kPa/°K), γ the psychometric constant (kPa/°K), Rn the net radiation flux density at the surface of the sunlit or shaded leaves (W m^{-2}), ρ the density of air (kg m^{-3}), C_p the specific heat of air (J/kg.°K), $e(T_a)$ the saturation water vapor pressure at air temperature (kPa) and $\mathbf{e_a}$ the actual water vapor pressure of the air (kPa). Since the Eq. (1) concerns leaves, the flux density into the soil can be neglected (Berlato & Molion, 1981).

The aerodynamic conductance (g_v) for the transport of vapor of the sunlit and shaded canopy is a function of the leaf boundary layer conductance (g_b) and the turbulent transfer coefficient (g_a).

The leaf boundary layer conductance of a leaf is (e.g. Gates 1980):

$$g_b = 300\left(\frac{U}{d}\right)^{0.5} \quad (2)$$

with d (m) being the average width of maize leaf and U (m s^{-1}) the wind speed as computed at the top of sunlit or shaded canopy.

The turbulent transfer coefficient (g_a) for the crop is computed after Fuchs et al. (1987):

$$g_a = k^2 U / \{[\ln(z-d)/z_0][\ln(z-d)/z_E]\} \quad (3)$$

with k = 0.41 as the von Karman constant for turbulent diffusion, U is the wind speed (m s^{-1}) measured at height z(m), $\mathbf{d}$ is the displacement height (m), z_0 is the roughness length, z_E the roughness length for sensible heat transfer (m). The d and z_0 were calculated from the wind profile and z_E was taken as 20% of z_0 (Garratt & Hicks, 1973).

The g_b conductance was connected in parallel through the entire sunlit or shaded leaf area and in series with g_a (Thom, 1975) to express g_v:

$$g_v = g_a + (g_b LAI_\Delta) \quad (4)$$

with LAI_Δ being either the sunlit or shaded leaf area index.

Integrated stomatal conductance of the foliage, g_s (m s^{-1}) was determined as:

$$g_s = g_f LAI_\Delta \quad (5)$$

where g_f is the stomatal conductance of either a sunlit or shaded leaf and LAI_Δ is either sunlit or shaded leaf area index.

Leaf conductance for varied water stress conditions was determined in the field and adjusted to PAR (μmol m^{-2} s^{-1}) according to the model (Gates, 1980):

$$g_f\ (non-stress) = \frac{1.39PAR}{\left\{1+\left[\frac{(1.39)\ (PAR)}{(568.73)}\right]\right\}} \quad (6)$$

$$g_f\ (\text{moderate stress}) = \frac{0.56PAR}{\left\{1+\left[\frac{(0.56)\ (PAR)}{(414.52)}\right]\right\}} \quad (7)$$

and

$$g_f\ (severe\ stress) = \frac{0.32PAR}{\left\{1+\left[\frac{(0.32)\ (PAR)}{(149.85)}\right]\right\}} \quad (8)$$

Sunlit leaf area (LAI*) was estimated from the total leaf area index (LAI), assuming a spherical leaf angle distribution (Lemeur, 1973):

$$LAI^* = [1 - EXP(-fLAI)]/f \quad (9)$$

with f being the mean horizontal area of shadow cast by a unit leaf area and according to Monteith (1975):

$$f = 0.5/\cos\theta \quad (10)$$

with θ being the sun zenith angle.

Total leaf area index (LAI), for the plots under all water stress conditions was estimated from the height of crop. This was based on previous determination in the experimental area, using the same crop, density and growing conditions (França, 1997).

The direct components of the global radiation (R_d) at the top of canopy were computed using methodology adapted by Fuchs et al. (1984) and Santos (1998):

$$R_d = \left(\frac{R_{de}}{R_{ge}}\right)(R_g) \quad (11)$$

with R_{de} being the estimated direct radiation , R_{ge} the estimated global radiation (Campbell, 1977) and R_g the measured global radiation. The diffuse component of global radiation (R_{di}) was considered as the difference between measured global radiation and the direct component calculated by Eq. (11).

Net radiation was calculated as detailed in Fuchs et al. (1987):

$$Rn = LAI_{\Delta}[\alpha(R_{de} + \chi R_{di}) + \chi R_l \quad (12)$$

where α is the leaf absorption coefficient for short wave irradiance, taken as 0.5 (Jones, 1992), R_l is the exchange of long wave radiation between exposed leaves and sky. χ is the view factor for isotropic radiant transfer between leaves and sky (Fuchs et al., 1987), and was defined as:

$$\chi = \left(\frac{1}{\pi}\right)\int_0^{2\pi}\int_0^{\pi/2} \exp(-fLAI)\, sin\theta \cos\theta \; d\theta \; d\phi \quad (13)$$

where ϕ is the sun azimuth angle.

Net radiation for the sunlit canopy fraction considered both the direct and diffuse components of global radiation while for the shaded fraction only the diffuse component was used.

Computation of PAR intercepted by the sunlit foliage followed the procedure described by Santos (1998).

Model validation

Stem sap flow was measured simultaneously on 8 maize plants using the heat pulse technique (Cohen et al., 1988). This was done over the well-watered and water-limiting plots, during both the growing seasons. For the well-watered condition the heat pulse system was installed over a weighing lysimeter.

The plants selected for the sap flow measurement were representative of the full range of stem diameters in the experimental area. For each plant two needles with a thermocouple were inserted in the base of the stem in a asymmetric distance from the heating element which comprised of 9 mm and 4 mm, for the downstream and upstream sensors, respectively (Santos et al., 1988). During the field measurement the probes were typically left in the same plant for 7 to 10 days. After this period they were replaced by new ones in order to avoid damage by tissue overheating. A battery-operated datalogger (CR21X, Campbell Scientific) was used to monitor the probes, control the pulse donator and store the data in the field.

A weighing lysimeter with 5.1 m^2 area, installed in the center of the experimental area was used to monitor the maize water loss in the well-watered plots. It was operated manually in the 1995/96 season. In the 1996/97 growing season the lysimeter was monitored by a datalogger (CR10, Cambpell Scientific) and data were recorded minute-by-minute throughout the day (Bergamaschi et al., 1997).

RESULTS

The maize leaf conductance as a function of photosynthetically active radiation (PAR), including non-stress, moderate stress and severe stress, as identified by midday sunlit leaf water potential, are shown in Figure 1. The derivative of stomatal conductance with respect to PAR decreased as PAR increased, with most of change occurring in the PAR range typically obtained in the shaded fraction of the canopy, for all conditions of stress. The magnitude of stomatal conductance with respect to PAR, in non-stress condition is similar to that reported by Machado & Lagoa (1994), for the same crop. As the water stress increased (Table 1) the response of leaf conductance to PAR decreased.

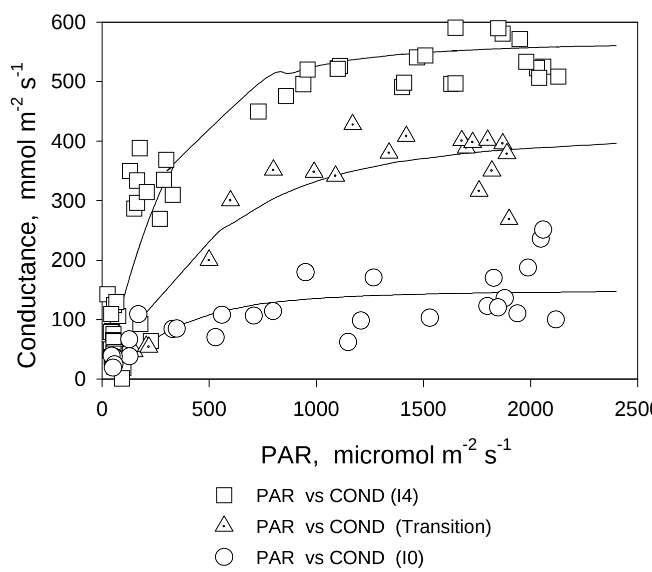

Figure 1. Maize stomatal conductance with respect to photosynthetically active radiation (PAR) for non-stress (I4), moderate stress (transition) and severe stress conditions (I0), for the 1995/1996 and 1996/97 growing seasons

Diurnal course of estimated transpiration and measured water uptake by heat pulse, in the well-watered and water-limited plots (severe stress) for two different days are shown in Figures 2 and 3 respectively. These days represent typical high and low evaporative atmospheric demand. By comparing the hourly values in Figure 2, we can conclude that the estimated curves and measured ones are very close all over the day, when the non-stress condition is considered. Daily totals of estimated and measured values also show agreement. Meteorological conditions for those particular days were characterized by very low humidity and high temperatures, together with moderate wind speed. This increased advection of sensible heat into the canopy, which resulted in transpiration rates higher than 1 mm h^{-1}.

On 01/09/1997 and under low evaporative atmospheric demand (Figure 3), the computation of transpiration and heat pulse measurement had similar curves all over the day. The change in inputs of global radiation show response in the model's curve of estimation, which can demonstrate the model responds correctly to the alteration in the radiation regime.

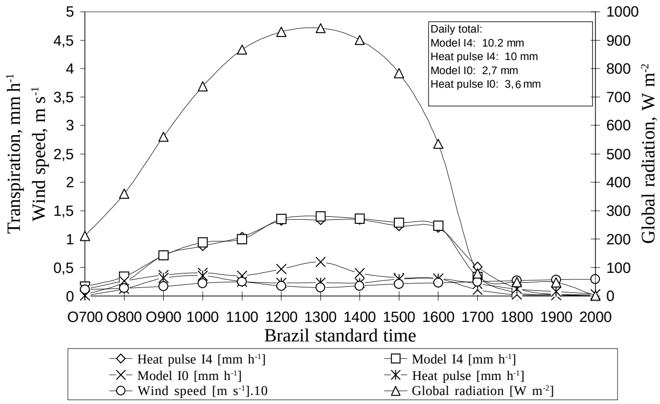

Figure 2. Hourly and daily estimated transpiration and measured water uptake by heat pulse technique, in maize, during non-stress (I4) and severe stress conditions (I0), with high evaporative atmospheric demand, on 12/16/1995

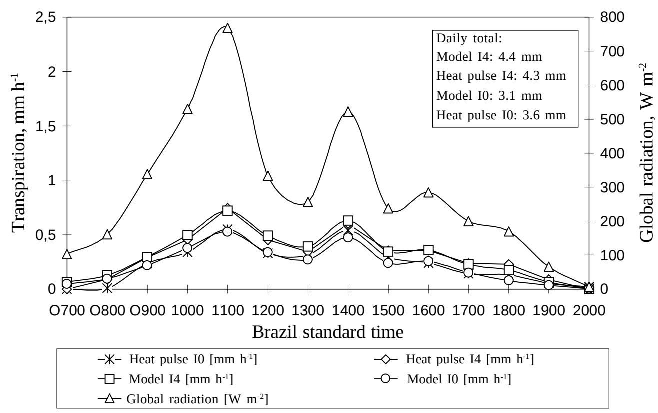

Figure 3. Hourly and daily estimated transpiration and measured water uptake by heat pulse technique, in maize, during non-stress (I4) and severe stress conditions (I0), with low evaporative atmospheric demand, on 01/09/1997

Under these conditions of high and low atmospheric evaporative demand (Figures 2 and 3) and for well-watered plots, the daily estimated transpiration of 10.2 mm and 4.4 mm matched quite well with the measured water uptake (heat pulse technique) that was 10 mm and 4.3 mm, respectively.

Under high atmospheric evaporative demand and for water limited-plots, a systematic overestimation of the measured water uptake values were observed in the hottest part of the day (Figure 2), which could be due to the difficulty in correct simulation of the canopy conductance, where the variability of the stomatal conductance tend to increase (Turner, 1991). For the low atmospheric evaporative demand (Figure 3), in the plots under severe stress the model curves of estimation follow closely those obtained for water uptake. Daily totals show correspondence between the measured and estimated values (Figure 3). This shows a good agreement between measured and estimated values of transpiration.

Under condition of stressed plots discrepancy between the model estimated values of transpiration in the high and low atmospheric evaporative demand, is likely due to the minor stomatal control of transpiration which could occur in the low atmospheric demand. In this case a well-decoupled canopy (Jarvis & Mcnaughton, 1986), could be improving model estimation by independence of canopy conductance variability.

Figure 4A shows hourly values of model estimated and measured water uptake for the 1995/96 growing season for the well-watered plots. Estimated transpiration exhibited excellent agreement with the measured values, with R^2 equal to 0.95.

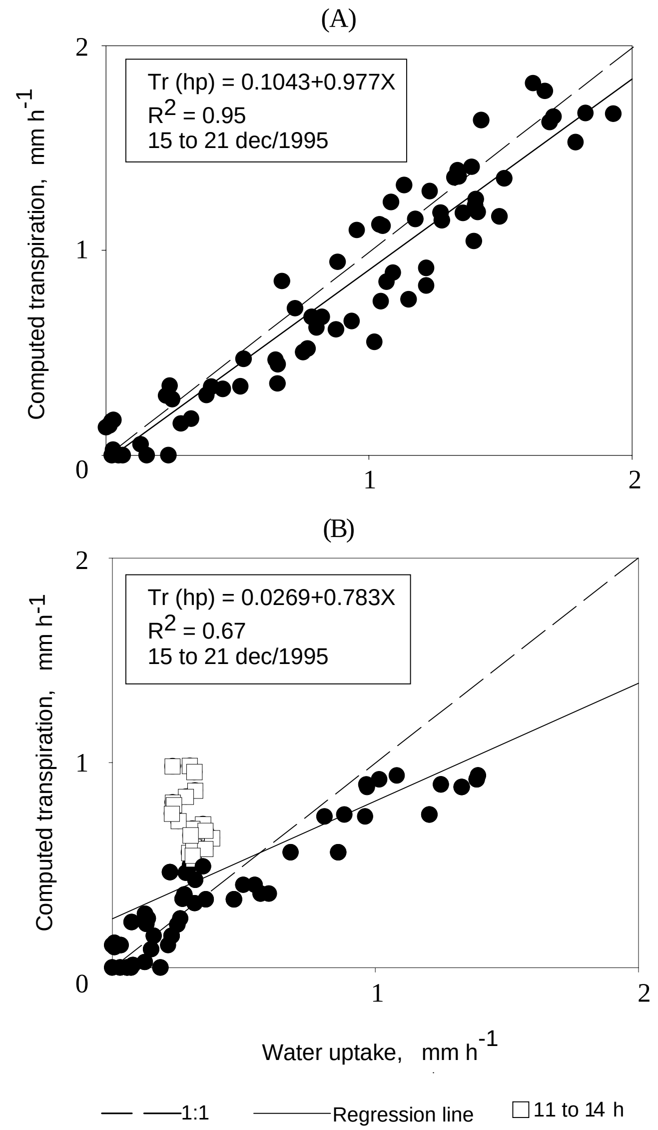

Figure 4. Estimated transpiration with respect to measured water uptake by heat pulse technique, in maize, under non-stress (A) and severe stress conditions (B), during the 1995/1996 growing season. Results from regression analysis are shown

For the plots under severe stress (Figure 4B) linear regression analysis yields a R^2 value of 0.67. The diagram of linear regression shows concentrated points of model overestimation with respect to the measured water uptake. This resulted from the model-computed transpiration in the hottest hour of the day. At this time the stomata could be closed, in response to very low humidity and severe stress that occurred in the plots.

Figure 5 shows daily values of estimated and measured transpiration by the lysimeter and heat pulse for growing season of 1996/97. Forcing the linear regression through zero produced a slope of 0.95 for model and lysimeter comparisons, and 0.87

for model and heat pulse comparisons with a R^2 of 0.80 and 0.91, respectively. Standard error of estimate is 0.5 mm day^{-1} for the first case and 1.03 mm day^{-1} in the second one (Figure 5). This demonstrates that the model estimates are closer to the values of lysimeter measurement rather than to those of heat pulse. Despite the R^2 value being smaller for model and lysimeter comparison, the scatter diagram concerning the relationship between the model and lysimeter outputs, suggests the existence of a stronger correlation between them (Figure 5A).

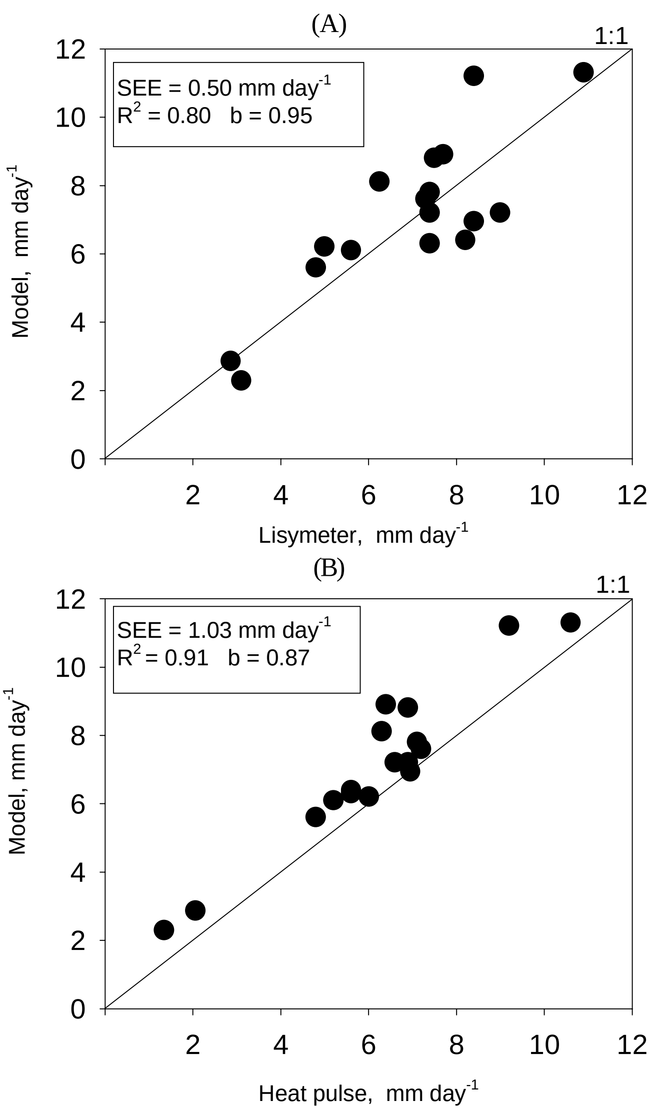

Figure 5. Relationship between estimated transpiration and measured water uptake of maize by lysimeter (A) and heat pulse technique (B), during the growing season of 1996/1997. Results from regression analysis and standard error of estimate (SEE) are shown

Table 2 shows that the modeled contribution of the shaded canopy to overall transpiration represents at least 27% of the crop water loss in the two extreme conditions analyzed. The partitioning of transpiration between the sunlit and shaded fraction of the canopy was influenced by the variation observed in the atmospheric demand and in the soil water availability. The average fraction of shaded/total transpiration decreased from the well-watered to the water-limited condition from 45% to 36% in high atmospheric demand. This was obtained over a typical non-stress to severe stress period. Similar analysis shows that for the normal atmospheric demand the shaded/total transpiration decreased from 30 to 27%.

Table 2. Estimated sunlit and shaded transpiration for maize under two different levels of water availability and atmospheric demand conditions

Atmospheric Evaporative Demand	Water Availability	Daily Total Transpiration mm	Daily Estimated Transpiration* mm		Shaded/ Total
			Sun	Sh	
Normal	Well-watered	6.9	4.8	2.1	0.30
High	Well-watered	13.3	7.2	6.1	0.45
Normal	Severe stress	4.8	3.5	1.3	0.27
High	Severe stress	7.8	5.0	2.8	0.36

* Sun = sunlit; Sh = shaded

DISCUSSION

Expanding the Penman-Monteith to include the shaded leaves, based on Fuchs et al. (1987) and Fuchs & Cohen (1989), may increase the accuracy of simulated transpiration. This is because the transpiration from the shaded fraction of canopy represents a significant contribution for the total transpiration, obtained in the present work in a varied base of atmospheric demand and soil moisture (Table 2). For the crop stages, whenever the soil full coverage is observed and the shaded fraction is very significant the computation of transpiration for this canopy fraction raises its importance.

Furthermore, the inclusion of the shaded fraction in the original equations does not complicate the model, since the computation of shaded transpiration is done with the same meteorological data used for sunlit computation.

The model increases daily estimated shaded transpiration from 2.8 mm to 6.1 mm, when comparing the computation during high atmospheric demand condition with those obtained during normal conditions. A similar comparison shows that daily sunlit transpiration increases from 5 mm to 7.2 mm. The interval is greater in the first case. The results arise from the greater impact of water vapor deficit on foliage with low incident radiation in Eq. (1). The decrease in the average fraction of shaded/total canopy transpiration with intensifying water stress (Table 2) may be due to a significant decrease in the fraction of shaded/sunlit leaf conductance with the development of water stress.

Petersen et al. (1992) have used a similar procedure to compute transpiration of cotton from sunlit and shaded foliage. For a non-stress condition underestimation was reported when model estimates were compared with heat pulse data, mainly in the hottest hours of the day and for normal and high atmospheric demand. Soil evaporation was reported as the source of errors. In this research, the agreement between measured and estimated curves of transpiration for the well-watered plots (Figure 1) was achieved by means of adjusting the leaf boundary layer resistance. It was set to decrease while the high atmospheric demand took place. This was done after systematic underestimation was observed for calculated values regarding high atmospheric demand and for full coverage of the soil. In the case of maize, the soil evaporation in this situation should be minimal. In fact during the growing season of 1996/97, the introduction of a plastic cover over the lysimeter, in the later growth stages of maize did not cause any influence in the comparisons between lysimeter and heat pulse values.

Model estimates for the severe stress condition (Figures 2 and 3) (Table 1), suggest that uncertainty concerning the integration of the stomatal conductance in the canopy can be responsible for decreasing efficiency of estimation, mainly for the hottest hours of the day. In fact the use of leaf stomatal conductance to quantify the canopy conductance (Figure 1) suggests a degree of uncertainty because stomatal conductance has high variability with the increasing level of water stress (Turner & Begg, 1972)

CONCLUSIONS

This study has shown that maize transpiration from the shaded canopy comprises 27 to 45% of the total transpiration, and should therefore be included when modeling crop water loss, moreover with the purpose of monitoring the maize crop in the later stages of development when the crop reaches the most critical stages with regard to water deficit.

Estimated hourly and daily transpiration values were in agreement with the heat pulse and the lysimeter measurement under the non-stress condition and for all atmospheric demand conditions. For plots under severe water stress the difficulties in simulating the canopy conductance decreased estimate efficiency.

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