AGRISCIENTIA, 2000, VOL. XVII : 11-19

Improved modeling of maize canopy water loss: a case study in Brazil

Santos, A.O., H. Bergamaschi, J.I. Bergonci, L.M.G. Rosa

SUMMARY

The precise determination of water loss from plant canopies is important for monitoring crop water usage and for many agricultural management operations related to water use planning. The aim of this study was to estimate water loss from sunlit and shaded fractions of a maize (*Zea mays* L.) canopy, under well-watered conditions, using the Penman-Monteith energy balance equation. Estimated values were validated by a heat pulse system, which was used to measure stem sap flow and by a weighing lysimeter. Water loss was corrected to account for the effect of row structure in the early stages of maize. Results showed that estimated transpiration of the shaded canopy ranged from 30% to 45% for total transpiration, under fluctuation of atmospheric demand. Hourly and daily estimations of transpiration showed good agreement with lysimeter and heat pulse measurements.

Keywords: modeling, transpiration, irrigation, maize.

Santos, A.O., H. Bergamaschi, J.I. Bergonci, L.M.G. Rosa, 2000. Modelo de simulación mejorado de la pérdida de agua por el canopeo del maíz: un estudio piloto para Brasil. Agriscientia XVII: 11-19

RESUMEN

La determinación exacta de la pérdida de agua por el canopeo de las plantas es importante para conocer el consumo de agua por los cultivos y para muchas actividades agrícolas relacionadas con la planificación del uso de agua. El objetivo de este estudio fue estimar la pérdida de agua del canopeo del maíz expuesto al sol y parcialmente sombreado, sin restricciones hídricas. Para ello se utilizó la ecuación del balance de energía de Penman-Monteith. Las estimaciones obtenidas fueron validadas por un sistema de pulsos de calor, el cual fue usado para medir el flujo de savia del tallo, y por un lisímetro de pesadas. La pérdida de agua fue corregida para considerar el efecto del surco en los estadios juveniles del maíz. Los resultados logrados mostraron que la transpiración del canopeo sombreado oscilaba entre el 30 y 45 % del total transpirado considerando las fluctuaciones de la demanda atmosférica. Las estimaciones horarias y diarias de la transpiración presentaron una buena relación con las mediciones del lisímetro y los pulsos de calor.

Palabras clave: modelo, pulso de calor, irrigación.

Fecha de recepción: 5/11/99; fecha de aceptación: 28/09/00.

Santos, A.O. Centro de Ecofisiologia & Biofísica, Instituto Agronómico (IAC), ex Postal 28, CEP 13001-970, Campiñas (SP)-Brazil. E-mail: <odairsan@cec.iac.br>. H. Bergamaschi, J.I. Bergonci, L.M.G. Rosa. Departamento de Agrometeorologia, Universidade Federal do Rio Grande do Sul, cx. Postal 776, CEP 91501-970, Porto Alegre (RS)-Brazil.

INTRODUCTION

Progress in automation of meteorological data networks has provided an opportunity for improved management of agricultural systems. Dissemination of information can be used to assist the monitoring of several key operational areas, such as the crop water use. 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 water application is an important aspect for an efficient crop production system and also to maximise the efflciency of crop water use. Losses from deep percolation can be avoided if precise application of water is implemented.

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

Formulae to estimate the actual evapotranspiration of crops from meteorological data have been presented and reviewed (Doorenbos & Pruit, 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 in 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) modified the same models to account for transpiration of the shaded fraction of cotton canopy. Shaded leaves comprise a large fraction of the leaf area in the later stages of the growing season. The 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 *et al.,* (1989), in turn, suggested that their model's systematic underestimation of cotton transpiration may be due to having neglected water loss from the shaded foliage.

In maize, the most critical period related to water stress is from the beginning of flowering to the end of grain filling (Matzenauer *et al.,* 1995), when the crop canopy has covered the soil and therefore the shaded fraction is significant. It is necessariy to investigate the aspects of transpiration during this period in order to achieve precise monitoring of water usage.

The objective of this study was to provide a simple computatation of water loss 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 was adjusted.

MATERIALS AND METHODS

Site of the experiment and description

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° 05' S, 51° 39' W, 46 m above sea leval). The maize was planted in rows of 0.75 m spacing, in mid October in both years, in a typical plinthic soil (Melo *et al.,* 1996). Fertilizer was applied according to soil analysis and weed infestation was controled manualy. Plant population density was close to 67,000 plants/ha. Leaf area index (LAI) and plant height were monitored weekly (França, 1997).

Irrigation

Water was applied by an in-line sprinkler irrigation system installed at the center of the experimental area in the direction E-W, following the maize row. Water was delivered according to the procedure described by Cunha *et al.,* (1994). The plots were maintained at field capacity throughout the experiment. Minimum values of leaf water potential were found to be -1 Mpa, around mid-day.

Crop and weather measurement

A model LI 1600 steady state porometer (LI-COR, Inc. Lincoln, NE, USA) was used to measure stomatal conductance. Porometric data were colected from two separate cloudless days. Measurements were taken every half an hour throughout the day, starting after 09:00 AM, to ensure the complete dryness of the shaded leaves.

Leaf water potential was measured with a pressure chamber (model 3000, Soilmoisture Co., Santa Barbara, CA, USA). Measurements were taken at approximately 12:00 AM on sunlit leaves. To avoid errors in leaf water potential measurement, leaves were wrapped in a plastic bag at the time of excision and placed in a box for immediate measurement.

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 simultaneously.

Wind speed profile was measured in the plot above and inside the maize canopy along the growing seasons, using a A100R anemometer model (Vector Instruments, UK). The anemometer height was changed as the crop developed, keeping geometrical distance between sensors and having one of them always at the top canopy.

Global radiation, air temperature, humidity, and precipitation were measured at 2 meters height above the ground by an automated weather station, (Campbell Scientific, Logan, USA) located closed to the experimental area. Data were averaged every 10-min interval and recorded wlth a battery-powered data logger (CR10, Campbell Scientific).

Model

Transpiration (W/m^2) was calculated separately for sunlit and shaded leaves according to the Penman-Monteith energy balance equation (Monteith, 1965) as:

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

Where Tr is transpiration, *s* being the slope of the saturation vapor pressure curve (KPa/°K), γ the psychometric constant (Kpa/°K), *Rn* the net radiation flow density at the surface of the sunlit or shaded leaves (W/m^2), p the density of air (Kg/m^3), *Cp* the specific heat of air (J/Kg.°K), $e(T_a)$ the saturation water vapor pressure at air temperature(KPa) and e_a the actual water vapor pressure of the air (KPa). Since the Eq. [1] concerns leaves, the flow density into the soil may be neglected (Berlato and Molion, 1981).

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

The boundary layer conductance of a leaf is as follows (Gates, 1980):

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

where *d* is the average width of maize leaf and *U* the wind speed computed at the top of sunlit or shaded canopy.

The turbulent transfer coefficient (g_a) for the crop is computed according to Fuchs *et al.,* (1987):

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

k = 0.41 as the Von Karman constant for turbulent diffusion, *U* is the wind speed (m/s) measured at height z(m), *d* is the displacement height (m), z_0 is the roughness length (m) and z_E the roughness length for sensible heat transfer (m).

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

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

LAI_Δ is either the sunlit or shaded leaf area Index.

Integrated stomatal conductance of the foliage, g_s (m/s) 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.

Leaf conductance was determined in the field and adjusted to PAR (μmol/m^2.s) according to Gates, (1980):

$$gf = \frac{1.39\ PAR}{1+\left(0.0024\ PAR\right)} \qquad [6]$$

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

$$LAI^* = \left[1-EXP\left(-fLAI\right)\right]/f \qquad [7],$$

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

$$f = 0.5 / \cos\theta \qquad [8],$$

where 8 is the sun zenith angle.

Total leaf area index (LAI) was estimated according to equation relating LAI and crop development, established with same density and growing conditions by França (1997), in the experimental area.

The direct components of the global radiation (R_d) at the top of canopy were computed adapting Fuchs *et al.,* (1984) and Santos (1998) models as follows:

$$R_d = \left(\frac{R_{de}}{R_{ge}}\right)\left(R_g\right) \qquad [9]$$

Where R_{de} is the estimated direct radiation , R_{ge} the estimated global radiation (Campbell, 1977) and Rg the measured global radiation. The diffuse component of global radiation was estimated as the difference between measured global radiation and the direct component calculated by Equation [9], The PAR intercepted by the sunlit foliage was computed according to a procedure described by Santos (1998).

Net radiation for the fraction of sunlit canopy included direct and diffuse component (R_{di}) of global radiation while for the shaded fraction only the diffuse component was used, according to the equation:

$$Rn = LAI_\Delta\left[\alpha\left(R_{de} + \chi R_{di}\right) + \chi R_1\right] \qquad [10],$$

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

$$\chi = \left(\frac{1}{\pi}\right)\int_0^{2\pi}\int_0^{\pi/2} \exp\left(-fLAI\right)\sin\theta\cos\theta\, d\theta\, d\phi \quad [11],$$

where ϕ is the sun azimuth angle.

Correcting transpiration for row structure

The model treats the foliage as uniformly distributed over the entire ground. During the early stages, the row structure concentrates the leaves on a fraction of the ground area. Average interception of solar radiation over the empty inter-row and the dense row is less than that of a uniform canopy. Estimation were made on the assumption that the rows are rectangular shapes with height h, width w and planting distance d. LAI was then corrected for the calculation of the sunlit leaf area index (Eq. 7) for the early stages (LAI') as follows, according to Goudriaan (1977):

$$LAI' = (dLAI) / (w + s) \qquad [12],$$

where s is the length of perpendicular shadow cast by the row, and was solved as:

$$s = \tan\theta \sin\varphi \qquad [13],$$

where φ is the smallest horizontal angle between the direction of the sun and that of the row.

As shadow from the rows can overlap on the ground, LAI' was constrained by: $(w+s) \leq d$. For values of (w+s) exceeding this condition, the effect of the row structure disappeared and a uniform canopy was assumed by the model.

Model validation

Stem sap flow was measured simultaneously on 8 maize plants using the heat pulse technique (Cohen *et al.,* 1988) for both growing seasons. 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 radially inserted in the base of the stem in an asymmetric distance from a heating source (Santos *et al.* 1999). During the field measurements the probes were kept 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 data logger (Campbell Scientific, CR21X) was used to monitor the probes, to control the pulse donator and to store the data in the field.

The weighing lysimeter of 5.1 m^2, installed in the center of the experimental area was used to monitor the maize water losses. During the 1995/1996 crop season the lysimeter was operated manually. In the 1996/97 growing season it was monitored by a data logger (CR10, Cambpell, Scientific) and data were recorded by-minute interval throughout the day.

RESULTS

Diurnal course of estimated transpiration and measured water uptake by heat pulse are shown in Figures 1 and 2. Both situations represent typical days of high and low atmospheric demand. Hourly values of the estimated transpiration are very close to the measured values of water uptake all over the day (Fig 1). Daily totals also show to be very close. Meteorological conditions for those particular days were characterized by very low humidity, high air temperatures, and wind, increasing advection of sensible heat into the canopy, causing values of transpiration to be greater than 1 mm/h.

On January 9, 1997 under low atmospheric demand (Fig.2), the computed transpiration and heat pulse measurements also show similar curves throughout the day. The changed inputs of global radiation influenced the model's curve of estimation, which demonstrated that the model responded correctly to the alteration in the radiation regime.

Correlation between transpiration from model estimate and measurement of water uptake for the 1995/96 growing season in hourly values are shown in Fig 3. Estimated transpiration exhibited excellent agreement with the measured values, with r^2 reaching 0.95.

For the comparisons between model estimation and "in situ" measurements, for the shortest intervals of estimates, the heat pulse data were preferred. It proved to be a reliable technique when detecting water uptake from herbaceous plants, in a variable base of atmospheric demand and water stress (Santos *et al* (1999). Nevertheless automation was applied to the lysimeter system by the time of experiment (Bergamaschi *et al.* 1997). As a consequence

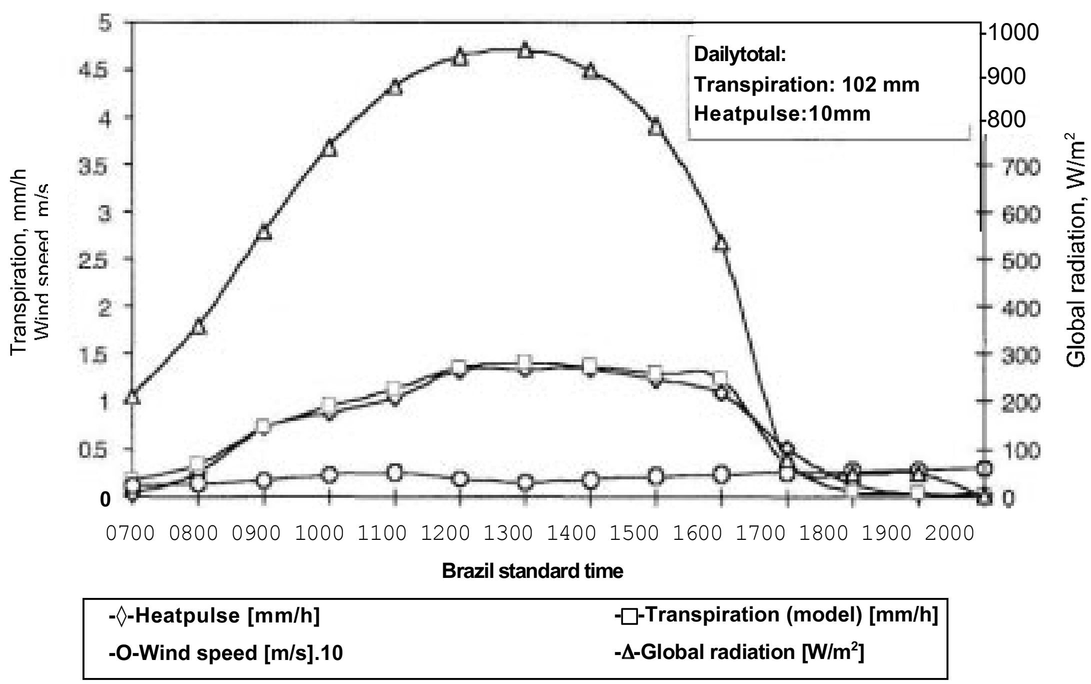

Figure 1. Hourly and daily transpiration estimated by the model and water uptake measured by heat pulse technique in maize, with high evaporative demand, on Dec./17/1995.

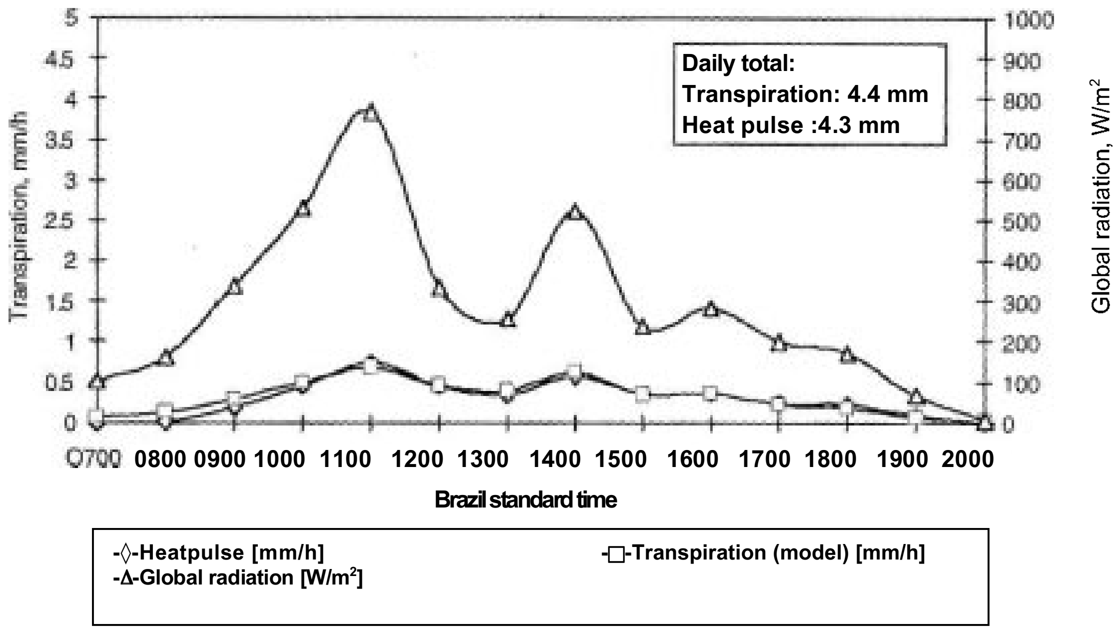

Figure 2. Hourly and daily transpiration estimated by the model and measured by heat pulse technique in maize, with low evaporative demand, on Jan./09/1997.

instability was observed for the readings of short intervals, mainly due to wind pressure.

Figure 4 shows daily values of transpiration estimated by the model vs. measured transpiration from the lysimeter and from heat pulse during the growing season 1996/97. Forcing the linear regression through zero produced a slope of 0.95 for model and lysimeter comparisons, and 1.14 for model and heat pulse comparisons with a r^2 of 0.80 and 0.91, respectively. Standard errors of estimate were 0.5 mm/day for the first case and 1.02 mm/day in the second one (Fig. 4).For a field trial values of r^2 of 0,91 or even 0,80 are enough to characterize a high correlation. In the case of model and the heat pulse comparison less dispersion and better correlation are shown (Fig. 4b). However the standard error of estimate (SEE) is higher is this case, showing less precision of estimate, when compared to the model vs, lysimeter outputs. The model performs some degree of overestimation of the heat pulse values (Fig 4b), which is likely to be caused by the influence of extreme weather conditions observed by the time of experiment. In fact, under very high atmospheric demand conditions the canopy conductance may rises its variability which can imply in dificulties to simulate it (Eq. 5 and 6).

Table 1 shows estimated sunlit and shaded transpiration values for maize in low and high atmospheric demand conditions, during five days analysis. Modeled contribution of the shaded canopy to overall transpiration represented at least 30% of the crop water loss in the analyzed conditions. The partitioning of transpiration between the sunlit and shaded fraction of the canopy was influenced by the variation observed in the atmospheric demand. The average fraction of shaded/total transpiration decreased from 46% to 30% from high to normal atmospheric demand. A similar analysis showed that for the normal to very low atmospheric demand the shaded/total transpiration increased from 30%

Table 1. Estimated sunlit and shaded transpiration for maize, from low to high atmospheric demand conditions.

Date	Daily total transpiration mm	Daily estimated transpiration mm		Shaded/Total
		Sunlit	Shaded	
16/01/97	6.9	4.8	2.1	0.30
19/01/97	2.3	1.44	0.86	0.37
20/01/97	8.8	5.2	3.6	0.41
15/01/95	9.8	5.8	4	0.40
21/12/95	13.3	7.2	6.1	0.46

to 37%. This could be explained by the presence of low irradiance throughout the day, which contributed to the remaining of a more pronounced shaded fraction.

Figure 5 shows the daily performance of the model along the growing season 1996/1997 compared to lysimeter values and potential transpiration (ETp). ETp was calculated according to Penman (1948). The data show good agreement between lysimeter and the model, moreover for lately LAI values. Overestimation by the model can be noted around 40 days after emergence when compared to simultaneous lysimetric values. High temperatures and values of relative humidity as low as 13%, was observed at that time, therefore, stomata closure in the hottest part of the days is likely to be most cause for the overestimation.

DISCUSSION

Expanding the Penman-Monteith model to include the shaded leaves, according to Fuchs *et al.,* (1987) and Fuchs & Cohen (1989), may increase the accuracy of simulated transpiration. Transpiration from the shaded fraction of canopy may represents a significant contribution for the total transpiration, obtained in the present work in a varied base of atmospheric demand. This is important especially during the development stage when maize has full soil coverage and the shaded fraction is significant.

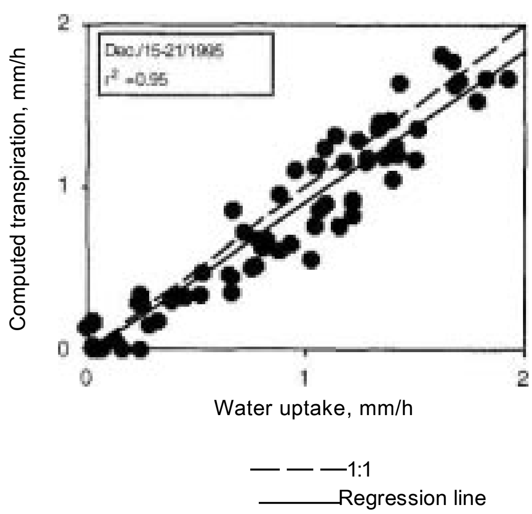

Figure 3. Estimated transpiration vs. measured water uptake by heat pulse technique in maize, during 1995/1996 growing season. Results from regression analisys are shown.

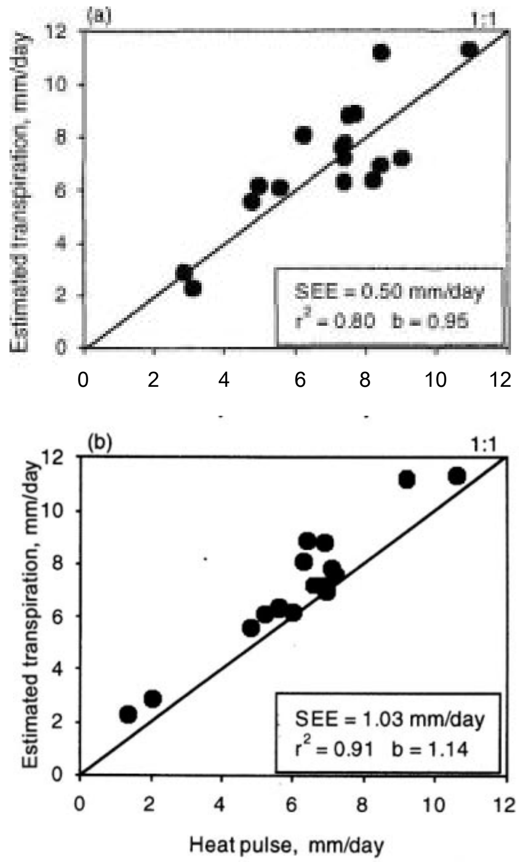

Figure 4. Relationship between estimated transpiration by the model and measured by lysimeter (a) and heat pulse technique (b), during the growing season of 1996/1997. Results from regression analysis and standard error of estimate (SEE) are shown.

Furthermore, including the shaded fraction calculations in the original equations it does not bring an increase in the model complexity, since the computation of shaded transpiration requires the same meteorological data used for sunlit computation.

The model increases daily estimated shaded transpiration from 2.1 to 6.1 mm, from high atmospheric demand conditions to normal conditions. A similar comparison showed that daily sunlit transpiration increases from 4.8 to 7.2 mm. The interval is greater in the first case. This happens as a result of the greater impact of water vapor deficit on foliage with low incident radiation in Eq. [1]. Therefore fluctuation in atmospheric demand influences the partitioning of transpiration between sunlit and shaded fractions of the canopy.

Better results may be expected from the model's performance for a shorter interval of estimate. The

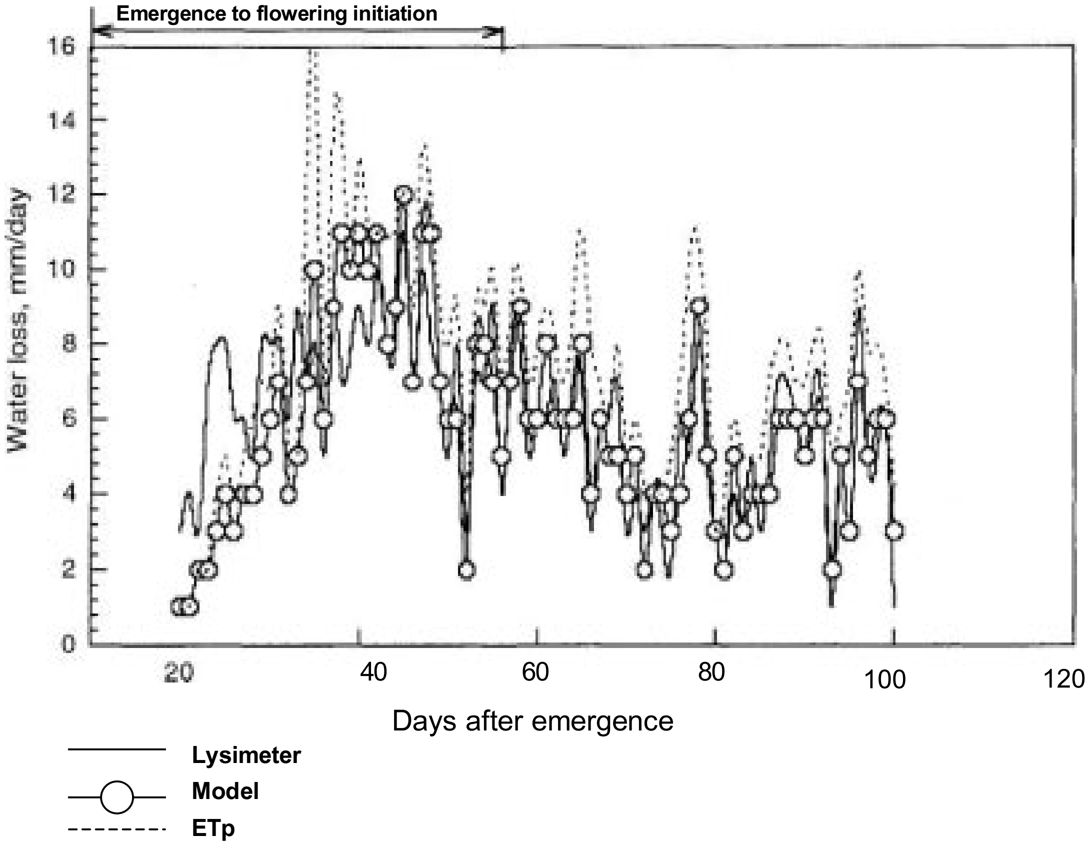

Figure 5. Daily rates of water loss estimated by the model, Penman equation (Etp) and by the lysimeter in maiza, during the growing season 1996/1997.

physical processes described in Eq. [1] have a diurnal cycle. Time concordance creates correlation between the meteorological variables. Therefore precision of estimates can be improved by using short integration periods of the variables.

It must be clarified that any validation of estimations performed by the model, presented in this work, were based on the total computed (sum of computed transpiration from the shaded and sunlit fraction of canopy). No validation was done for the transpiration values resulted from the modeling demonstrated for transpiration of the separate fractions.

Petersen *et al.,* (1992) have used a similar procedure to compute transpiration of cotton 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 conditions. Soil evaporation was reported as a source of errors. In this study, underestimation was observed for calculated values regarding high atmospheric demand and for later stages of maize development (minimal soil evaporation). A better performance of the model was only achieved by means of adjusting the leaf boundary layer resistance. It was set to decrease while the high atmospheric demand took place.

CONCLUSIONS

a) Under well-watered conditions, maize transpira tion estimated by the model, from the shaded canopy accounted for 30% to 46% of the total transpiration, and should therefore be included when modeling crop water losses.

b) Estimated hourly and daily transpiration were in agreement with the heat pulse and the lysimeter measurement, under fluctuated atmospheric demand conditions.

REFERENCES

Bergamaschi, H., L.M. Rosa, A.O. Santos, J.I. Bergonci, 1997. Automação de um lisímetro de pesagem através de estação meteorológica automática, a campo. In: Congresso Brasileiro de Agrometeorologia, 10, 1997, Piracicaba,. Anais... Piracicaba: Sociedade Brasileira de Agrometeorologia, pp. 222-225.

Berlato, M.A.; L.C.B Molion, 1981. Evaporação e evapotranspiração. IPAGRO: Porto Alegre (RS). (Boletim Técnico, 7).

Campbell, G.S., 1977. An Introduction to Environmental Biophysics. Springler Verlag, New York, 320pp.

Cohen, Y., M. Fuchs, V. Falkenflug and S. Moreshet, 1988. Calibrated heat pulse method for determining water uptake in cotton. Agronomy Journal 80 : 398-402.

Cunha, G.R., J.R.F. Paula, H. Bergamaschi, J.C. Saibro and M.A. Berlato, 1994. Evapotranspiração e eficiência no uso da água em alfafa. Revista Brasileira de Agrometeorologia 2 : 23-27.

Doorenbos, J. and W. Pruitt, 1977. Las necessidades de água de los cultivos. FAO: Rome. (FAO publication N° 33).

França, S., 1997. Modelagem do crescimento de milho em função da radiação solar e da temperatura do ar, com e sem irrigação. MSc. Diss. Universidade Federal do Rio Grande do Sul, Brazil

Fuchs M., C. Asrar, E.T. Kanemasu and CE. Hipps, 1984. Leaf area estimates from measurements of photosynthetically active radiation in wheat canopies. Agricultural and Forest Meteorology 32 : 12 - 22.

Fuchs, M., Y. Cohén and S. Moreshet, 1987. Determining transpiration from meteorological data and crop characteristics for irrigation management. Irrigation Science 8 : 91-99.

Fuchs, M. and Y. Cohen, 1989. Experimental verification of a meteorological transpiration model. Agronomie 9 : 827-832.

Gates, D.M., 1980. Biophysical Ecology. Springer-Verlag, New York, 609 pp.

Goudriaan, J., 1977. Crop Micrometeorology: A simulation study. Wageningen Centre for Agricultural Publishing and Documentaron, Wageningen, 349 pp.

Lemeur, R., 1973. A method for simulating the direct solar radiation regime in sunflower, jerusalen artichoke, corn and soybean canopies using actual stand structure data. Agricultural Meteorology 12 : 229-247.

Matzenauer, R., H. Bergamaschi, M.A. Berlato and J. Riboldi, 1995. Relações entre rendimento de milho e variáveis hídricas. Revista Brasileira de Agrometeorologia 3 : 85-92.

Melo, O., R.C. Lemos and C. Abraão, 1996. Levantameto dos solos do centro agronômico. Revista da Faculdade de Agronomía e Veterinária da UFRGS 8 : 7-155.

Monteith, J.L., 1965. Evaporation and environment. Symposia of the Society for Experimental Biology 19 : 205-234.

Monteith, J.L., 1975. Principles of Environmental Physics. Edward Arnold Publishers, London, 215 pp.

Penman, H.L., 1948. Natural evaporation from open water, bare soil and grass. Proceedings of Royal Society of London,-193: 120-145.

Petersen, K.L., M. Fuchs, S. Moreshet, Y. Cohen and H.Sinoquet, 1992. Computing transpiration of sunlit and shaded cotton foliage under variable water stress.Agronomy Journal 84 : 91-97.

Petersen, K.L., S. Moreshet and M. Fuchs, 1991. Stomatal response of field-grown cotton to radiation and soil moisture. Agronomy Journal 83 : 1059-1065.

Santos, A.O., 1998. Simulação da perda d'água dos estratos ensoralado e sombreado de um dossel de milho *(Zea mays* L), sob diferentes condições de disponibilidade hídrica. (1998). Doctoral Thesis. Universidade Federal do Rio Grande do Sul, Brazil.

Santos, A.O., Bergamaschi, H., Rosa, L.M.G., Bergonci, J.I., Radin, B., 1999. Assessment of corn water uptake based on sap heat tracing under water-stressed conditions. Revista Brasileira de Engenharia Agrícola e Ambiental. Campina Grande (PB) v. 3, n.2, pp. 145-149.

Smith, M., 1992. Report on the expert consultation on revision of FAO methodologies for crop water requirements. FAO, Rome.

Thom, A.S., 1975. Momentum, Mass and Heat Exchange of Plant Communities. In Vegetation and the Atmosphere(Ed. J.L. Monteith) Academic Press, London, pp. 57-109.

Zeiger, E. and C. Field, 1982. Photocontrol of the functional coupling between photosysthesis and stomatal conductance in the intact leaf. Plant Physiology 70 : 370-375.