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Bioclimatology

Experimental verification of a meteorological transpiration model*

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Summary — Automated irrigation which allows frequent watering offers the technical means of matching application to use by the crop. As measurements of evapotranspiration with the accuracy required by frequent irrigations are difficult, a transpiration model is proposed as an alternative. The model uses hourly average measurements of solar radiation, air temperature and humidity and wind speed. Standard electronic meteorological stations collect and transmit these data on a routine basis. Water vapor conductance of the leaves is related to intercepted photosynthetically active radiation flux. Plant inputs are daily updated height and leaf area index. Sunlit leaf area, computed according to canopy geometry and sun angle, is the active coupling surface between the path of water in the plant and in the atmosphere. The model was checked against measurements of the energy balance based on the Bowen ratio and transpiration measured by the heat pulse method, in an irrigated cotton field, during a complete irrigation cycle. The diurnal behavior of modeled transpiration through the test period matched very closely that of the measurements, indicating that the assumptions used to construct the model are good approximations of the natural processes. The modeled consumptive use during the irrigation season was compared with the actual water application in the field to show how the model can improve irrigation management.

irrigation – cotton – evaporation – leaf conductance

Résumé — Vérification expérimentale d'un modèle météorologique de transpiration. *L'irrigation automatisée, qui permet de programmer de fréquents arrosages, fournit le moyen technique de répondre immédiatement aux besoins en eau des cultures. La mesure de l'évapotranspiration, avec l'exactitude requise par l'irrigation à haute fréquence, étant difficile, un modèle évaluant la transpiration a été développé. Il utilise des mesures horaires du rayonnement solaire global et photosynthétiquement actif, de la température, de l'humidité et de la vitesse du vent. Une station météorologique automatique récolte et transmet ces données de façon routinière. La conductance stomatique des feuilles pour la vapeur d'eau est calculée à partir de sa relation linéaire avec le rayonnement photosynthétiquement actif. L'indice foliaire et la hauteur moyenne de la culture sont fournis chaque jour pour l'établissement du modèle. La surface foliaire éclairée directement, calculée à partir de la distribution angulaire du feuillage et de l'angle solaire, établit la surface d'échange entre la culture et l'atmosphère. Le modèle a été vérifié, dans une culture de cotonnier durant un cycle complet d'irrigation, à l'aide de mesures du bilan énergétique par la méthode du rapport de Bowen et des mesures de flux de sève par la méthode des chocs thermiques. L'évolution journalière de la transpiration modélisée suit de très près celle des mesures, indiquant que les hypothèses introduites dans l'élaboration du modèle reproduisent fidèlement les processus naturels. La consommation saisonnière d'eau, calculée par le modèle, a été comparée aux quantités d'eau appliquées pour démontrer comment le modèle peut améliorer le pilotage de l'irrigation.*

irrigation – cotonnier – évaporation – conductance foliaire

INTRODUCTION

Automated irrigation allows frequent applications which decrease the fluctuations of plant water status and considerably enhance the potential productivity of crops. High moisture content of the frequently wetted upper soil layer confines the root system to a small volume of soil. Excess water is applied to avoid the possible damage caused by underestimating consumptive use. However, during periods of high transpiration, the rate of depletion of soil water can be larger than anticipated. Water stress will then appear because roots have not colonized the moist deeper layers of the soil. The corrective action is to shorten the period between applications.

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Increasing the amount is ineffective because excess water leaches into soil layers out of reach of the roots. The basic frequency of application depends on the absolute holding capacity of the soil volume occupied by the roots. In sandy soils it may be several times per day. A correct estimate of evapotranspiration, sensitive to hourly fluctuations, is therefore needed to exploit the advantages of automated irrigation. Stress indicators are useful for deciding on irrigation timing, but they provide only indirect information on the amount of water to be applied.

Several micrometeorological devices measure evapotranspiration (Tanner, 1967). However, despite technological progress in instrumentation (Miyake and Mc Bean, 1970; Perrier *et al.*, 1976; Itier, 1980), these measurements cannot be carried out on an extensive basis to service the requirements of irrigation management. As the complete physical description of evaporation by Penman (1948) uses solely routine meteorological data, we selected this formulation to develop a transpiration model. We followed Monteith (1965), who introduced a canopy conductance to account for the dryness of the plant surface. However, in doing so, we had to integrate single leaf conductance into a canopy conductance and to couple water vapor transport from the leaf to that through the internal boundary layer and through the atmospheric surface layer. The paper presents an experimental validation for cotton of the approximations involved in the development of the model.

Model

Detailed descriptions of the transpiration model have already been published (Fuchs, 1977; Fuchs *et al.*, 1987). The model is based on the observation that stomatal conductance of cotton under field conditions is proportional to the photosynthetic quantum flux (PhAR) intercepted by a green leaf. As more than 90% of photosynthetic radiation is absorbed upon interception, very little of this wave-band impinges on shaded leaves. We therefore assume that their stomatal conductance is small. Leaf conductance measurements in the field using a steady state porometer established that the proportionality constant for non-stressed cotton is 14 $m^3 \cdot E^{-1}$ *or* 14 $m^3 \cdot mol^{-1}$ (photon) (Fuchs and Moreshet, 1985). Water stress sets an upper limit to stomatal conductance at a level which depends on the degree of stress. However, for a frequently irrigated crop managed to avoid water stress this limit does not need to be considered. Similar relationships between absorbed radiation and leaf conductance have been found in maize (Shawcroft *et al.*, 1973), wheat under non-limiting water supply (Denmead and Millar, 1976), and pearl millet (Squire, 1979).

Assuming that the gap frequency in the canopy has a Poisson distribution, the sunlit leaf area index L*, at any depth, is (Lemeur, 1973):

$$L^* = [1-\exp(-fL)] / f \qquad (1)$$

where L is the leaf area index, and f is the mean horizontal shadow of a unit leaf area. For a spherical leaf angular distribution (*e.g.* Ross, 1981):

$$f = 0.5/\cos\eta \qquad (2)$$

with η as the sun zenith angle. The average solar beam radiant flux density impinging on a sunlit leaf is $f\,R_S$. As the horizontal beam radiation flux density R_S is not routinely measured, it is approximated by global radiation. The net absorbed solar radiation, R_{SN}, is (Fuchs, 1977):

$$R_{SN} = 0.74 f R_S \qquad (3)$$

The scattering coefficient of a cotton leaf, weighted for the standard spectral distribution of solar radiation is 0.45 (Moreshet *et al.*, 1979). The coefficient 0.74 was obtained by assuming that sunlit leaves absorb direct plus complementary radiation produced by a single scatter.

The net terrestrial radiation exchange, R_{LN}, is assumed to occur only between sunlit and the cloudless fraction c, of the sky:

$$R_{LN} = 5.67 \times 10^{-8}\, cX\, (1-\varepsilon_A)\, T_A^4 \qquad (4)$$

where the numeric coefficient is the Stefan Boltzmann constant, ε_A is the thermal emissivity of the atmosphere (*e.g.* Brutsaert, 1982), T_A is the Kelvin air temperature, and X is the hemispherical integral of $[1-\exp(-fL)]$. The net radiation R_N is:

$$R_N = R_{SN} - R_{LN} \qquad (5)$$

The turbulent conductance, g_A, is derived from the logarithmic profile, allowing dissimilar sink or source intensities for momentum, parameterized by z_0, the roughness length, and for water vapor, parameterized by $z_E = 0.2z_0$ (Garrat and Hicks, 1973):

$$g_A = k^2\, U/[\ln((z-D)/z_0)\ln((z-D)/z_E) \qquad (6)$$

where U is the wind speed at height z, $k = 0.41$ is the von Karman constant and D is the profile displacement height. The values for D and z_0 are taken as 70% and 13% of the average cotton canopy height (Stanhill and Fuchs, 1968). The diabatic influence on the transport is neglected because temperature gradients over a frequently irrigated field are small. The boundary layer conductance, g_B, of a palmately lobed cotton leaf is approximately (*e.g.* Campbell, 1977):

$$g_B = (U_0)^{0.5}/50 \qquad (7)$$

where U_0 is the wind speed at mean canopy height in ms^{-1}. The total aerodynamic conductance, g_U, is formed by the parallel boundary layer conductance of the sunlit leaf area in series with the turbulent conductance:

$$1/g_U = 1/g_A + 1/(g_B L^*) \quad (8)$$

Potential transpiration, T_P, according to Penman (1948), expressed as a heat flux density, is:

$$T_P = [s/(s+\gamma)]R_N + [\rho\, c_p e_A\, g_U / (s+\gamma)](1-h) \quad (9)$$

where s is the slope of the saturation vapor pressure temperature curve, γ is the psychrometric constant, ρ is the density of air, c_p is its specific heat, e_A is the saturated vapor pressure at air temperature, and h is the relative humidity. Actual transpiration T_R is:

$$T_R = T_P / [1 + g_U / ((s+\gamma)\, g_L L^*)] \quad (10)$$

where $g_L = 14f\,PhAR$, is the conductance of the sunlit leaves. $PhAR$ is the photosynthetic quantum flux density on a horizontal surface above the canopy, and $f\,PhAR$ is the average flux density incident on the sunlit foliage. The canopy conductance, $g_L L^*$, is thus taken as the average parallel conductance of the sunlit foliage. Such averaging of the leaf conductance is permissible only because of the linearity of the relation between leaf conductance and radiation. If the linearity ceases, as a result of water stress for example (Fuchs and Moreshet, 1985), the averaging is no longer valid, leading the model to overestimate transpiration. A similar approach to transpiration modeling has been applied by Sinclair *et al.* (1976), using leaf resistance at the average radiation. However, their procedure is mathematically questionable because of the hyperbolic relationship between leaf resistance and irradiance (Shawcroft *et al.*, 1973).

METHODS

The model was tested in a large cotton (*Gossypium hirsutum* L. "Acala") field in the course of an irrigation, starting 3 d after the passage of a self-propelled sprinkler line, DOY (day of year) 218, until DOY 223, preceding the next passage of the line. The cotton canopy had reached maximum development and its leaf area index, L, was 5.6. Differential ventilated psychrometers, reversing their position every 15 min, measured the Bowen ratio. The fetch in the direction of the prevalent wind was 300 m. An inflated polyethylene shielded pyrradiometer and 4 soil heat flux plates completed the energy balance measurement. Transpiration was determined in 9 plants using the heat pulse method (Cohen *et al.*, 1988). Global radiation, photosynthetic quantum flux, air temperature, humidity, wind speed and direction were recorded at 30-min intervals at an automated weather station 1 000 m west of the cotton field. Plant height was averaged from 20 samples and L was derived from gap frequency measurements (Bonhomme and Chartier, 1972).

RESULTS

The latent flux density obtained from the measurement of the energy balance by the Bowen ratio method includes transpiration, evaporation directly from the soil surface, and occasionally some evaporation of dew collected on the leaves. The LAI during the reported measurements was 5.6. Consequently very little energy reached the ground and evaporation during daytime was low. Energy balance measured during the night showed that dew accumulation did not exceed 0.2 mm. The heat pulse method measures the water uptake, which may lag the diurnal course of transpiration because of water storage in plant tissues. Hence both experimental data represent only approximations of the modeled transpiration. A comparison of the evapotranspiration by the energy balance and the water uptake by the heat pulse was performed to estimate the reliability of these data and their suitability to check the transpiration model. Figure 1 shows 61 hourly water uptake and evapotranspiration measurements, taken on 6 successive days from 2 after sunrise until 1 before sunset. The linear regression fitted to the data has a small positive offset, which does not differ significantly from 0, and a slope close to unity. Evaporation of water directly from the soil surface would have produced a negative offset. Its magnitude should therefore be considered below the sensitivity range of the experimental data. Morning and afternoon data are distinguished to show that water uptake lags behind evapotranspiration. The phase shift could be caused by storage or evaporation of dew in the morning, but later analysis of the heat pulse technique (Cohen *et*

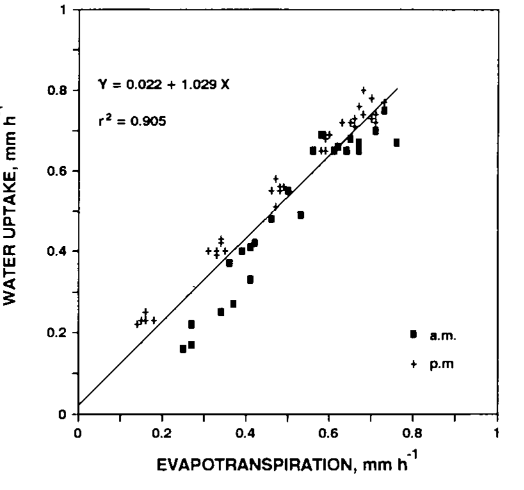

Fig. 1. Comparison of hourly measurements of water uptake and hourly measurements of the evapotranspiration in a cotton field. The data include all measurements taken 2 h after sunrise until 1 h before sunset for 6 successive days.

al., 1988) has shown that morning warming and afternoon cooling of the cotton stems, underestimates sap flow in the morning and overestimates it in the afternoon. Regardless of the cause for the phase lag of the water uptake measurements, its magnitude is small. The excellent agreement between the evapotranspiration and the water uptake establishes that these measurements can be invoked for testing the model.

The diurnal course of evapotranspiration (ET), measured transpiration, modeled and potential transpiration for DOY 219, DOY 220 and DOY 221 are shown in Figure 2. Data for the other days carry similar information. ET derived from the energy balance serves as the reference datum for comparison. As it includes the evaporation from the soil surface it is larger than transpiration. The scatter diagram in Figure 3 part A, of all the hourly data collected 2 h after sunrise and 1 h before sunset, during the 6 days between 2 successive irrigations, shows that the modeled transpiration has a negative offset relative to evapotranspiration. The distribution of data in Figure 3 A shows that the offset is the result of a slightly underestimated transpiration by the model in the late afternoon, possibly because the model neglects vapor loss by

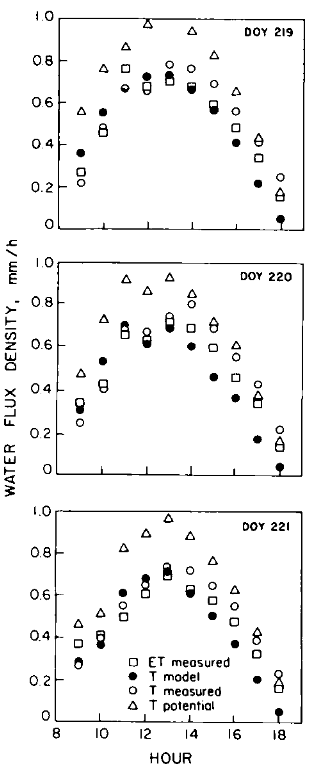

Fig. 2. Diurnal cycles of evapotranspiration and water uptake measurements are compared with potential and modeled transpiration derived from data recorded at a nearby meteorological station. DOY 219: scattered clouds at noon decreased the measured fluxes but did not affect the meteorological station. DOY 220: scattered clouds at noon affected the field and the meteorological station. DOY 221: scattered clouds at 10 a.m. affected the meteorological station only.

shaded leaves, which constitute a higher proportion of the total leaves at low solar elevation. The slope of the linear regression is 1.155. However, the value of this coefficient is the result of the computational artefact produced by the offset. The linear regression forced through 0 indicates that the model underestimates evapotranspiration by 4% on a par with the presumed magnitude of evaporation.

Measured water uptake is smaller than either ET or modeled transpiration during the early part of the day, but is larger in the afternoon (Fig. 2). The daily average measured water uptake is slightly higher than either ET or modeled transpiration (Table I). A small decrease of the evaporative demand at noon on DOY 220 shown in potential transpiration is carried over to the model by computation, but appears also in the measurement of ET and of transpiration by the heat pulse (Fig. 2). A similar weaker fluctuation is found on DOY 219 at noon, but only for ET and measured transpiration, and DOY 221 et 10 a.m. when the variation affects potential and modeled transpiration. The asynchronism is caused by scattered clouds passing at a different time over the weather station and the field. These small fluctuations show the high resolution of the transpiration and of the energy balance measurements. The model appears to be equally sensitive to changes in the environmental inputs.

The modeled transpiration is systematically higher than the measured water uptake during the morning (Fig. 3 B). The differences are reversed in the afternoon. It is tempting to assign this phase shift to water storage in the plants. However, deficiencies of the model in the early morning and late afternoon shown in Figure 3 A, and temperature drift errors in the heat pulse method also cause water uptake to lag behind modeled transpiration. The linear regression has an offset of -0.06 mm h^{-1} and a slope exceeding unity by 7%. On a daily basis, water uptake

Table I. Measured and modeled daily water vapor fluxes normalized with respect to potential transpiration (POT).

DOY	*ET/POT*	*Tmod/POT*	*Tmeas/POT*	*PhAR E/m2*
218	0.68	0.61	0.75	32.4
219	0.71	0.69	0.76	40.0
220	0.74	0.67	0.82	40.2
221	0.72	0.67	0.78	40.8
222	0.72	0.70	0.76	44.5
223	0.71	0.68	0.73	41.8

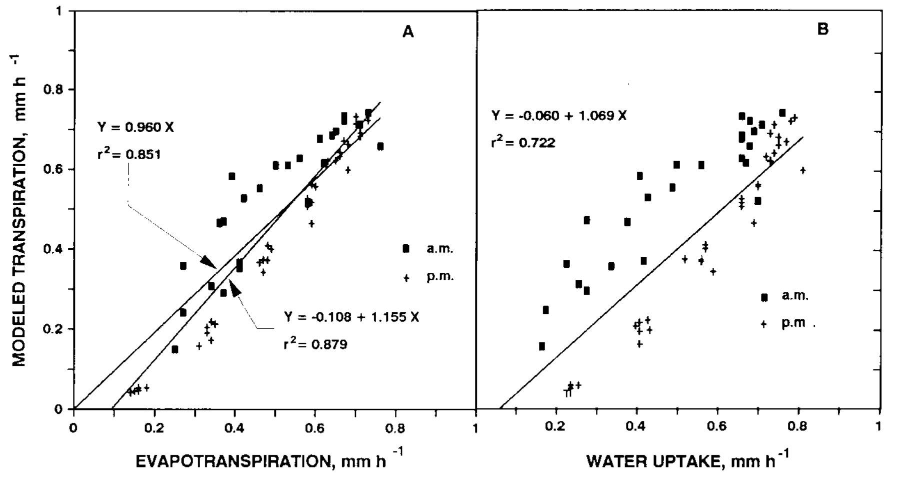

Fig. 3. Comparison of modeled hourly transpiration against measurements of evapotranspiration (A) and water uptake (B) in a cotton field. The data include all measurements taken 2 h after sunrise until 1 h before sunset for 6 successive days.

measurements exceed the modeled transpiration by ≈ 10% (Table I).

DISCUSSION

The transpiration model as applied here assumes that stomatal conductance is not affected by the depletion of soil water during the irrigation cycle. The validity of this assumption is tested in Table I where the measurements and the model prediction are normalized with respect to potential transpiration. If soil moisture depletion lowers stomatal conductance, then the normalized fluxes should decrease towards the end of the irrigation cycle. Table I shows that the normalized daily fluxes remain nearly constant through the drying period. In fact the smallest values are on DOY 218, at the beginning of the cycle. This day stands out as having the lowest incoming P*h*AR. The model links stomatal conductance to P*h*AR, but the measured normalized fluxes are also smaller, indicating that the approximations of the model give a good account of the vapor transport process. It is noteworthy that the measured to potential evapotranspiration ratio is of the order of 0.7, a ratio very close to the Class A evaporation pan factor found for cotton at optimum irrigation regime (Fuchs and Stanhill, 1963). The accuracy and time resolution of the model exceeds the operational requirements of the self-propelled sprinkler line used to irrigate the cotton field. Table II, which compares modeled transpiration with water application, shows how the model could have improved the management of the irrigation. Excessive amounts in the 2 first applications of water logged the bottom of the soil profile, causing a considerable loss by drainage. Consequently the irrigation dose was reduced to compensate for the excess, but warmer weather increased transpiration, inducing a desiccation of the upper soil profile. The good diurnal prediction of the model suits the most demanding irrigation systems such as those of nurseries and vegetable crops grown in sandy soils with low moisture holding capacity.

Table II. Cumulative transpiration between 2 successive irrigations and amount of water applied.

DOY	T_R *model (mm)*	*Water (mm)*
188	59.5	73.5
200	62.0	81.6
214	79.2	69.6
225	60.6	64.3

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