ELSEVIER

Agricultural and Forest Meteorology 86 (1997) 215–224

AGRICULTURAL AND FOREST METEOROLOGY

Validation of a model of actual evapotranspiration for water stressed soybeans

G. Rana [a,*], N. Katerji [b], M. Mastrorilli [a], M. El Moujabber [c], N. Brisson [d]

[a] *Istituto Sperimentale Agronomico, via C. Ulpiani, 5-70125 Bari, Italy*
[b] *INRA Unité de Bioclimatologie, 78850 Thiverval-Grignon, France*
[c] *C.I.H.E.A.M., via Ceglie-Valenzano (BA), Italy*
[d] *INRA Unité de Bioclimatologie, 84149 Avignon Cedex 9, France*

Received 13 March 1996; accepted 4 January 1997

Abstract

In this paper a model for estimating actual evapotranspiration (*ET*) is tested at two experimental sites in Europe (southern Italy and southern France), using data for soybean crops temporarily stressed, grown under a typical Mediterranean climate. The present *ET* model is based on the Penman–Monteith approach, but uses a canopy r_v value that takes account of both stomatal resistance and canopy architecture. In this model, r_v appears only as r_v/r_a, where r_a is aerodynamic resistance. r_v/r_a is set to a fraction of the ratio r^*/r_a (with r^* called the critical resistance, similar to the isothermal resistance). The function $r_v/r_a = f(r^*/r_a)$ depends on crop water status as specified by the predawn leaf water potential. The model gives very good results for both sites on hourly, daily and seasonal time scales. © 1997 Elsevier Science B.V.

Keywords: Evapotranspiration; Water stress; Canopy resistance; Soybean; Penman–Monteith

1. Introduction

Evapotranspiration (*ET*) estimates are required for many applications in agricultural and environmental management, from hydrological applications to crop models and irrigation scheduling. In the last few decades attention has focused on theoretical and applied analysis of this biophysical phenomenon and most of the scientific papers on the subject are devoted to the evaluation of *ET* models that use readily available data (for example, Kanemasu et al., 1976; Jamieson, 1982; Hatfield, 1988; Heermann, 1988; Saxton and Cordery, 1988). In these studies, crops grown under non-limiting soil water conditions were considered. In semi-arid and arid regions and, in particular, in the Mediterranean area, water resources are always limited. Supplying good quality irrigation water has become a major problem, since the annual rainfall cannot meet the potential *ET* demand (see, among others, Biswas, 1994; Hamdy, 1994). Hence, good management of irrigation water in these regions must evaluate as precisely as possible the *ET* losses. This evaluation is useful in order to analyse the impact of water stress on the production and define the optimum restoration of the soil water conditions.

* Corresponding author.

0168-1923/97/$17.00
PII S0168-1923(97)00009-9

Jensen et al. (1990) reviewed single level models for estimating *ET* and recommended the Penman–Monteith model (Monteith, 1965) as presented by Allen et al. (1989) as the preferred method for predicting reference *ET* (*ET* from grass maintained under optimum soil moisture and nutritional conditions) on a daily basis.

Several authors have applied the Penman–Monteith to field crops: for example, Perrier et al. (1980) tested the model on alfalfa, Steiner et al. (1991) evaluated it for grain sorghum, Howell et al. (1994) for winter wheat, sorghum and corn. In all these papers the canopy resistance, r_c, was taken as a fixed value over the growing season, derived from stomatal resistance measurements (as indicated by Allen et al., 1989) or estimated by models applicable to well watered crops (for example, Idso, 1983).

Many authors have studied canopy or stomatal resistance as a function of environmental and plant factors. A comprehensive review can be found, among others, in Jarvis et al. (1981), Turner (1991) and El Moujabber (1995).

A milestone in the modeling of canopy resistance is the work of Jarvis (1976), in which r_c is taken as function of environmental variables and crop water status which is related to the availability of soil moisture. This last r_c formulation is comparable with the model described by Katerji and Perrier (1983) for alfalfa, in which they suggest taking r_c as function of crop water status, fixed for a given climatological situation. Such a model was adapted by Rana et al. (1997) to crops experiencing water stress. In this paper, the plant factor that takes crop water status into account is the predawn leaf water potential, Ψ, instead of the 'Jarvis' soil water availability. Ψ, measured at predawn, expresses the crop water status when the plant is in equilibrium with the soil and is thus only a characteristic of the species and not of the soil type (Katerji and Hallaire, 1984; Tardieu et al., 1990; Itier et al., 1992).

Previously (Rana et al., 1997), the model presented here was tested successfully on grain sorghum and sunflower grown in a Mediterranean region, where the soil is submitted alternately to humid and dry conditions. In this paper, we propose to generalize the model to make it applicable to different sites.

To meet this target we calibrated the model on soybean and tested it in southern Italy. The model was then used on soybean grown in southern France, without further calibration. The results are presented for various time scales (hourly, daily and seasonal).

2. Model description

2.1. For hourly scale

The combination Penman–Monteith model represents a basic general description of the evaporative process from a vegetative surface. This process is supposed to be stationary, i.e. applicable on a temporal scale from a few minutes to 1 h. It can be written:

$$\lambda E = \frac{\Delta(R_n - G) + \left[\rho c_p(e^* - e)\right]/r_a}{\Delta + \gamma(1 + r_c/r_a)} \qquad (1)$$

where E is crop evapotranspiration (kg m^{-2} s^{-1} or mm s^{-1}), Δ is the slope of the saturated vapour pressure curve (Pa K^{-1}), R_n is the net radiation (MJ m^{-2} s^{-1}), G is the soil heat flux (MJ m^{-2} s^{-1}), ρ is air density (kg m^{-3}), c_p is the specific heat of moist air (MJ kg^{-1} K^{-1}), e^* is the saturated vapour pressure of the air (Pa), e is the actual vapour pressure of the air (Pa), γ is the psychometric constant (Pa K^{-1}), r_a is the aerodynamic resistance (s m^{-1}), r_c is the canopy resistance (s m^{-1}) and λ is the latent heat of vaporisation of water (MJ kg^{-1}). r_a is the resistance to the turbulent transfer of vapour between the source and the reference level. The source of vapour is at height $z = (d + z_{0m})$, the latter is taken to be the effective crop surface (i.e. Monteith, 1963), where d (m) is the zero plane displacement and z_{0m} (m) is the roughness length for momentum. r_c is the integrated stomatal resistance for the canopy considered as a 'big leaf', taken as the parallel sum of the stomatal resistances.

Following the approach described by Perrier (1975a,b), the canopy is considered a porous medium; therefore, the mechanism of vapour transport from the crop level is influenced by both the architecture of the canopy and the stomatal regulation of the leaves. Thus, canopy resistance can be defined as

$$r_v = r_s + r_0 \qquad (2)$$

where r_s depends only on the mean stomatal regulation of leaves and r_0 depends on the canopy structure; the latter resistance can be calculated, for a given crop, using *ET* measures for a well watered canopy (Perrier, 1975a).

In this case the energy conservation boundary condition is applied to the top of the canopy, so that aerodynamic resistance is experienced between this plane (level h_c (m), height of the crop) and the reference level; this aerodynamic resistance is defined, under neutral stability conditions, by the relationship

$$r_a = \frac{\ln\left(\frac{z-d}{z_{0m}}\right)\ln\left(\frac{z-d}{h_c-d}\right)}{k^2u(z)} \quad (3)$$

where z (m) is the reference level where the wind speed $u(z)$ (m s^{-1}) has been measured and z_{0m} (m) is taken equal to 0.123 h_c (Brutsaert, 1982).

The Penman–Monteith formula contains two terms: (i) the radiative and (ii) the aerodynamic term. To clearly separate these two terms, Eq. (1), taking into account Eq. (2), can be written in the following form:

$$\lambda E = \frac{\Delta}{\Delta+\gamma}(R_n - G)\frac{1+\frac{\rho c_p(e^*-e)}{\Delta(R_n-G)r_a}}{1+\frac{\gamma}{\Delta+\gamma}\frac{r_v}{r_a}} \quad (4)$$

From the above relation it can be argued that there are only two cases in which *ET* is equal to the radiation term (i.e. independent of the aerodynamic term): (i) when $r_a \gg 0$, that is, if the surface is very smooth and/or the wind speed is very low; (ii) when r_v takes the particular value (Monteith, 1965):

$$r_v = \frac{\Delta+\gamma}{\Delta\gamma}\frac{\rho c_p(e^*-e)}{(R_n-G)} = r^* \quad (5)$$

This last parameter, in s m^{-1}, is linked to the isothermal resistance introduced for the first time by Monteith (1965). It has also been called the 'critical resistance' (Daudet and Perrier, 1968) because it represents a threshold between one situation, when $r_v < r^*$, in which λE increases with wind speed and another situation, when $r_v > r^*$, in which λE decreases with wind speed.

If we substitute Eq. (5) into Eq. (4), the Penman–Monteith formula can be written in the more legible form:

$$\lambda E = \frac{\Delta}{\Delta+\gamma}(R_n - G)\frac{1+[\gamma/(\Delta+\gamma)](r^*/r_a)}{1+[\gamma/(\Delta+\gamma)](r_v/r_a)} \quad (6)$$

The second fraction is a dimensionless quantity which provides a weighting on the equilibrium evaporation (McNaughton, 1976) and can be seen as a crop-climatological coefficient (Katerji and Perrier, 1983; Katerji et al., 1987); it modulates part of the available energy transformed by the soil–canopy–atmosphere system during evapotranspiration.

Eq. (6) relates r_v, r^* and r_a. Perrier et al. (1980) showed experimentally that r_v/r_a was a function of r^*/r_a and this relationship depends on phenological stage and soil water status. In sorghum and sunflower crops, r_v/r_a increases, for a given value of r^*/r_a, as a function of plant water status (Rana et al., 1997). Moreover, from a mathematical point of view, a linear link between r_v/r_a and r^*/r_a can be argued from a dimensional analysis on the basis of the Buckingham theorem (i.e. Kreith, 1973). Therefore, Katerji and Perrier (1983) proposed the following linear relation

$$r_v/r_a = a(r^*/r_a) + b \quad (7)$$

with a and b as empirical coefficients. These coefficients were determined for several crops (see Table 1). In this paper, we demonstrate that in the relation given by Eq. (7), a and b depend on the crop water status as expressed by the predawn leaf water potential (Ψ). In this manner, the dependence of r_v on soil moisture (and its dependence on soil type) is

Table 1
Coefficients a and b for several crops

Crop	a	b	Ref.
Grass (tropical climate)	0.18	0	Gosse, 1976
Grass (Mediterranean climate)	0.16	0	Rana et al., 1994
Alfalfa	0.24	0.43	Katerji and Perrier, 1983
Sorghum	0.94	1.1	Rana et al., 1997
Sunflower	0.53	1.2	Rana et al., 1997

avoided, making Eq. (7) more general than the r_c function of water stress as suggested by Jarvis (1976).

When Eq. (7), with experimentally determined values of a and b, is substituted into Eq. (6) the Penman–Monteith model contains only standard climatological parameters.

2.2. *For daily scale*

Theoretically, the daily estimation of ET by combination models based on daily mean values will not be correct according to the hypothesis of stationarity, unless the daily value is calculated as a sum of hourly data. Nevertheless, having a daily expression of the Penman–Monteith model can be very useful for practical purposes. In this case, daily evapotranspiration (E_d; mm day^{-1}) can be written, following our model, as:

$$E_d = C_d \frac{\Delta}{\Delta + \gamma} (R_n - G)_d \qquad (8)$$

where $(R_n - G)_d$ is the daily integral of the available energy and C_d can be considered as a sort of 'crop-climatological coefficient' and can be calculated as:

$$C_d = \frac{1 + [\gamma/(\Delta + \gamma)](r^*/r_a)_d}{1 + [\gamma/(\Delta + \gamma)](r_v/r_a)_d} \qquad (9)$$

with $(r^*/r_a)_d$ and $(r_v/r_a)_d$ the daily averages of these ratios. C_d depends on the growth stage: C_d values have been found to range from 0.92 to 1.38 for wheat (Perrier et al., 1980), 1.14–1.37 for rice and 0.69–1.1 for peanuts (Peterschmitt and Perrier, 1991). A linear relation has been found experimentally between C_d and (r^*/r_a) for reference crops such as alfalfa (Katerji and Perrier, 1983) and grass (Rana et al., 1994), such that:

$$C_d = a(r^*/r_a)_d + b \qquad (10)$$

For crops under water stress, C_d is related to the predawn leaf water potential as:

$$C_d = a \cdot \Psi + b \qquad (11)$$

In this case, the coefficient a has the same units as Ψ^{-1} (here MPa^{-1}). Rana et al. (1997) found the coefficients a and b for sunflower and grain sorghum under different levels of water stress in a Mediterranean region.

3. Sites description and field measurements

3.1. *Experimental conditions*

The study was carried out at two European sites. The first, southern Italy (SI) (Rutigliano-Bari, 41°01′N, 14°E, altitude 122 m a.s.l), is characterized by a typical Mediterranean semi-arid climate. The soil is shallow (0.6 m) clay (43%), well drained due to a fissured rocky subsoil, with 96 mm total available soil water. Soybean (*Glycine max* cv. 'Hodgson') was sown on 14 May 1989 (DOY 134). At the second site, southern France (SF) (Avignon, 43°54′N, 4°48′E, altitude 10 m a.s.l.), soybean (*Glycine max* cv. 'Labrador') was planted on 2 July 1990 (DOY 183) and grown on an homogeneous silty clay loam, deep (2 m) soil. The measurements were made when the crop completely covered the soil: 79 days after sowing in SI and 10 days after planting in SF. At both sites, measurements began when LAI was about 2.

For SI the experimental field was maintained with good soil moisture conditions until canopy closure, when it was divided into two plots: one (about 5000 m^2) well watered and the other (about 10000 m^2, where the measurements took place) submitted to three successive cycles of soil drying and rewetting (through rainfall or irrigation).

For SF, during the first month of the growing season the crop was irrigated and, once the leaf area index reached a value of 2, water supplies depended only on rainfall.

3.2. ET *reference measurements*

For the SI site, actual ET calculated by the model was compared with ET measured by the energy balance/Bowen ratio ($ET_{measured}$). For the SF site, $ET_{measured}$ was determined by the energy balance above the canopy, using the eddy correlation method to estimate the sensible heat flux and the calorimetric method to estimate the heat flux through the soil surface. Net radiation was measured directly.

3.3. Measurements

3.3.1. SI site

Net radiation was determined using two Fritschen-type net radiometers (model Q*6; Radiation Energy Balance System, Seattle, WA, USA) placed 1.2 m above the crop. Air humidity was determined from wet and dry bulb air temperatures, which were measured using aspirated, sheltered, platinum resistance (PT100) sensors, 1.5 m above the canopy for the model inputs and 0.2 and 1.2 m for the Bowen ratio measurements. The Bowen ratio psychrometers were exchanged automatically every 6 min with 3 min interval of stabilization, so that the humidity gradient was the mean of 15 min for each sensor. The final gradient was the hourly average of 4 (measurements each hour) × 2 (sensors) = 8 means of 15 min. Wind speed was measured using a cup anemometer (model A100, Vector Instruments, Clwyd, UK) mounted 1.5 m above the canopy. Soil heat flux was measured by three heat flux plates (Campbell Scientific, Logan, UT, USA) at 5 mm and corrected using the calorimetric method with four thermocouples in the soil. All transducers were measured every 10 s by a Campbell Scientific CR7X data logger, signals were averaged for 15 min, and four 15-min means were composited into 1-h means. All sensors were placed 150 m from the edge of the plot in the predominant wind direction, which is usually constant at the site during summer.

Crop water status was evaluated from the leaf water potential (Katerji and Hallaire, 1984; Tardieu et al., 1990), measured, by sampling ten young fully developed trifoliate leaves, immediately after cutting, and just before dawn, using a pressure chamber (Scholander et al., 1965).

3.3.2. SF site

Evapotranspiration was measured as the residual in the energy balance ($R_n = \lambda E + G + H$). Net radiation was measured directly by a net-radiometer (model Q*6) and soil heat flux was estimated by the calorimetric method using four thermocouples in the soil. Sensible heat flux was measured with the eddy correlation method using a sonic anemometer and fine thermocouple (CA27, Campbell Scientific) placed 0.5 m above the canopy; the data were acquired at 8 Hz and averaged every 15 min. Further

Table 2
Water stress classes for soybean

Class	Ψ interval (MPa)
No stress	$\Psi > -0.5$
Weak stress	$-0.5 \geq \Psi \geq -1$
Strong stress	$-1 \geq \Psi$
Senescence + water stress	$-1 \geq \Psi$ + senescence

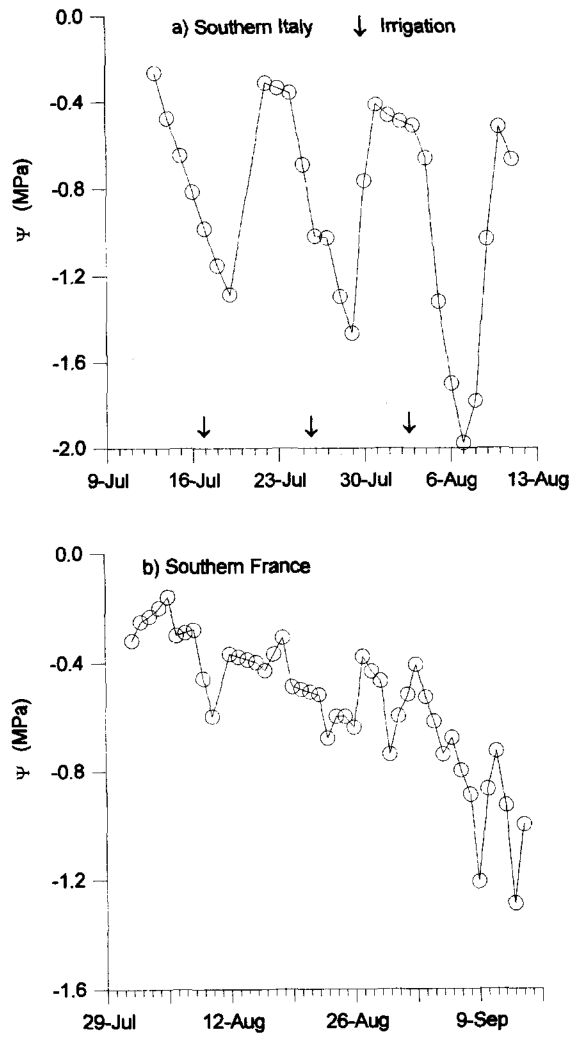

Fig. 1. Variations in predawn leaf water potential Ψ during the growth season of soybean for sites in (a) southern Italy (SI) and (b) southern France (SF).

details of the energy balance and micrometeorological parameter measurements are described in Olioso (1992). The Ψ measurements were taken on the uppermost expanded leaves (five replicates) using a pressure chamber.

3.4. Test method

Several 'stress levels' of soybean were chosen, so that Ψ was divided into stress classes as shown in Table 2, according to Mastrorilli et al. (1993). During the last part of the growing season, stress occurs due to the senescence stage of the crop growth as well as the soil water conditions: thus, it can be termed 'senescence + water' stress. When a plant becomes senescent, large molecules are hydrolyzed, contributing to a decrease of Ψ by osmotic pressure. When this occurs, the equilibrium between soil and plant at predawn no longer exists.

To validate the model on an hourly scale, for the different stress classes, the coefficients a and b in Eq. (7) were experimentally calculated for the SI site only, using data from certain days (two or three for each stress class). In this case, r_v/r_a was considered the unknown in Eq. (6) with λE measured by the Bowen ratio method. The ratio r^*/r_a was derived from climatological data. The model was calibrated for every stress class and the derived relationships for each stress class substituted r_v/r_a in Eq. (6). Hourly validation of the model was done with data not used for the calibration.

On a daily scale, a relationship between C_d and Ψ was found for certain days during the entire crop growing season using data from the SI site only. The model was validated by replacing C_d in Eq. (8) for each site with days not used in the calibration.

4. Results and discussion

4.1. Stress cycles

In Fig. 1 the seasonal course of soybean daily Ψ is shown for both sites. For SI (Fig. 1(a)), three well defined stress cycles are shown, with minima of -1.29, -1.47, and -1.98 MPa. In SF (Fig. 1(b)), the climate was slightly different and the crop experienced only one long stress cycle. A slow decrease of Ψ is noticeable up to a minimum of about -1.3 MPa. For the SF site, conditions of strong stress, as defined in Table 2, were never attained, because the most severe stress, present in the last part of the growing season, was an example of senescence + water stress.

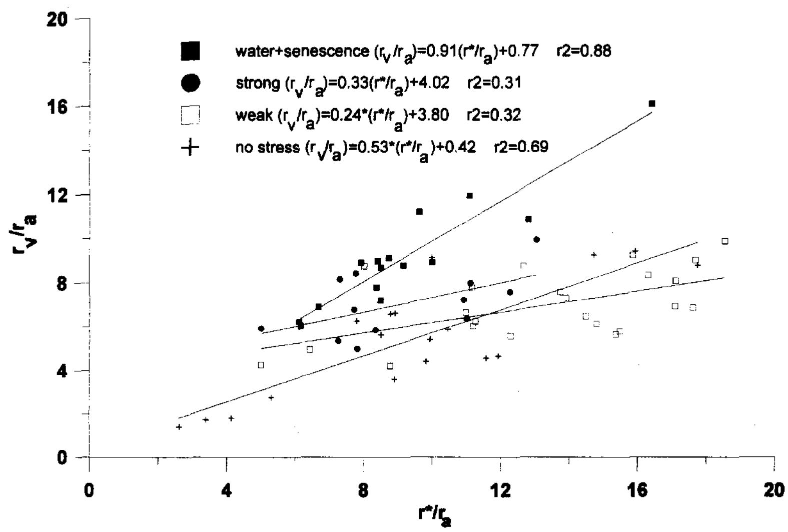

Fig. 2. Relation between (r_v/r_a) and (r^*/r_a) on a hourly basis for several water stress classes.

4.2. Hourly scale

In Fig. 2 the experimental relationships between (r_c/r_a) and (r^*/r_a) for each stress class are shown, using data from the SI site only. The dates used for this calibration were 20, 21 and 22 July for no stress, 14 and 19 July for weak stress, 18 and 26 July for strong stress, 4, 5 and 6 August for senescence + water stress. Although the correlations between the above parameters are well established for every stress class, some points in the graph could belong to two adjacent classes. The slope of each relation increases with the increase in the level of stress, as the stomatal resistance increases with the depletion in soil water.

The comparison between calculated and measured λE is shown in Figs. 3 and 4 for SI and SF, respectively. The correlation is very good when soybean has a plentiful supply of soil moisture, when the stomata are almost completely open. It is also satisfactory when the crop is under senescence + water stress, when many leaves are becoming yellow and the stomata are almost completely closed. In the statistical comparison between measured and calculated ET the t-test indicated that, in all cases, the intercept is significantly not different from zero at

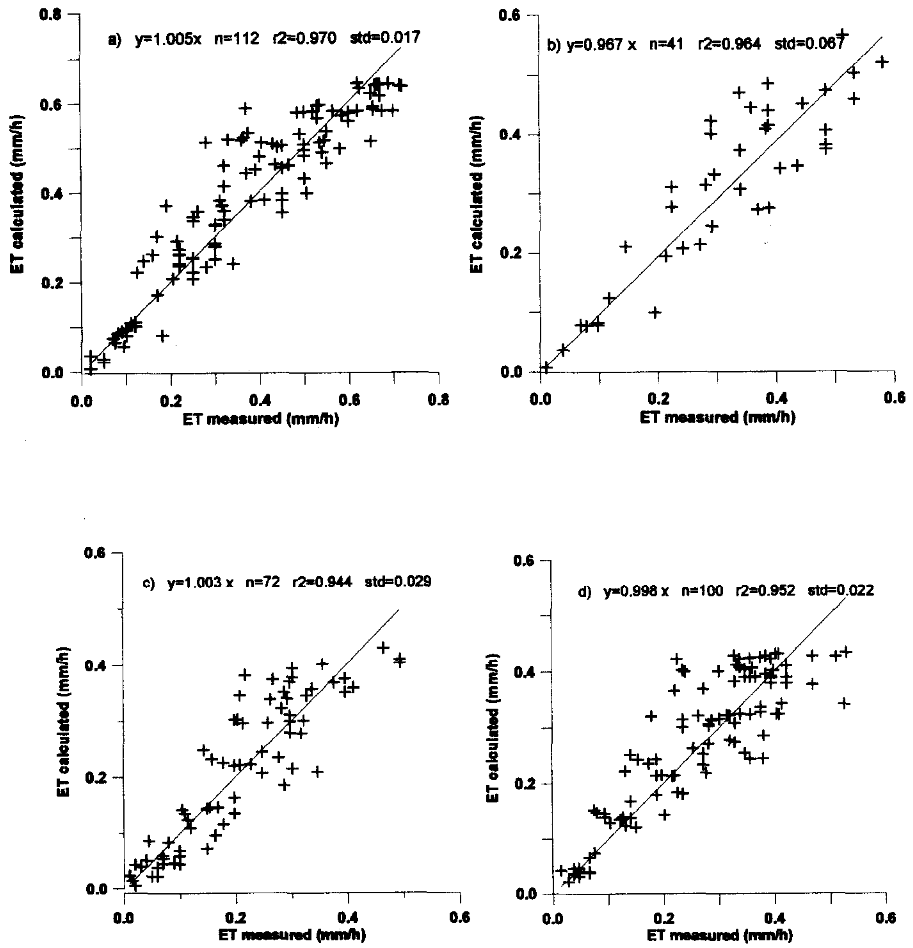

Fig. 3. Hourly comparison between calculated and measured evapotranspiration (ET) for the site in southern Italy: (a) no stress; (b) weak stress; (c) strong stress; (d) senescence + water stress (STD, standard deviation).

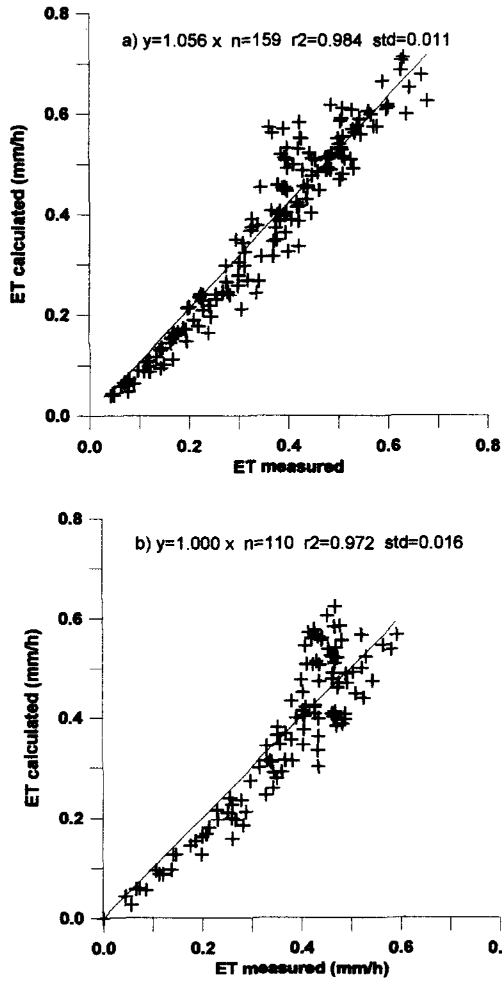

Fig. 4. Hourly comparison between calculated and measured evapotranspiration (ET) for the site in southern France: (a) no stress; (b) weak stress (STD, standard deviation).

the 95% significance level. The analysis was done forcing the linear regression model through zero. In these cases, r^2 is very high (0.970 and 0.984 for no stress in SI and SF, respectively and 0.952 for senescence + water stress in SI). In the other circumstances the model also works well, with r^2 equal to 0.964 and 0.962 for weak stress in SI and SF, respectively, and 0.944 for strong stress in SI. In the last two cases, the points are a little more spread out than in the other cases, due, as above, to the range of the stress class interval.

Hourly data for senescence + water stress were not available for the SF site.

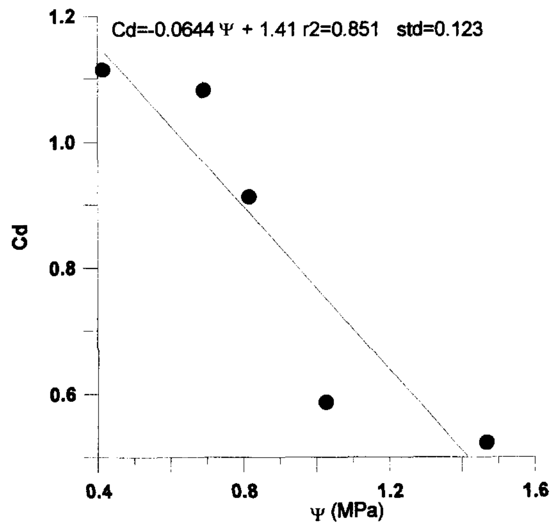

Fig. 5. Relationship between the crop coefficient C_d and predawn leaf water potential Ψ for the site in southern Italy.

4.3. Daily scale

To calibrate the relationship between C_d and Ψ (Fig. 5) we used data from the SI site only, using data for 15, 24, 26, 28, and 30 July to cover the range of Ψ in different crop water situations.

A comparison between measured and calculated ET is shown in Figs. 6 and 7 for SI and SF, respectively. Here, the seasonal course of ET

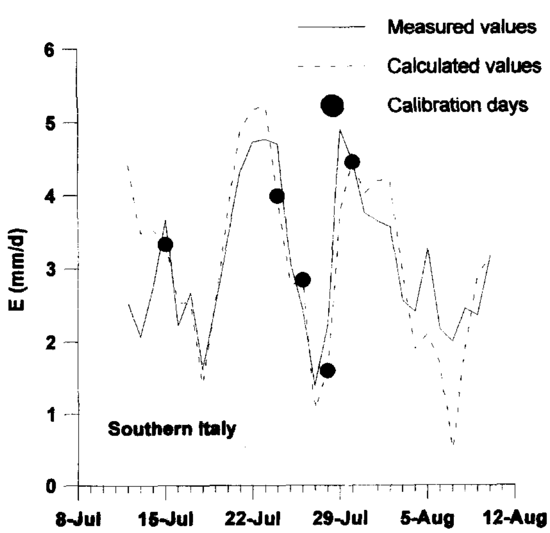

Fig. 6. Comparison between daily calculated and measured evapotranspiration (ET) for the site in southern Italy.

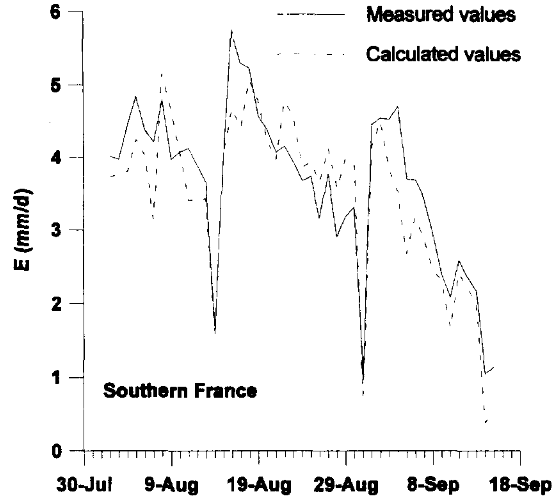

Fig. 7. Comparison between daily calculated and measured evapotranspiration (*ET*) for the site in southern France.

demonstrates that *ET* ranged between very low values before irrigation and high values afterwards. Daily *ET* values are presented in time. The linear regression statistical analysis between the model and measured *ET* gives: $a = 0.979$, $b = 0.01$, $r^2 = 0.869$, RMSE = 0.769 (25% of *ET* daily average) for SI and $a = 0.944$, $b = 0.012$, $r^2 = 0.811$, RMSE = 0.521 (14% of *ET* daily average) for SF.

Seasonal model performance was evaluated by comparing cumulated *ET* (as a sum of the daily values in mm) for the model and Bowen ratio method; for SI the model overestimates by about 1% (81 mm and 80 mm for the model and the reference, respectively), for SF the model underestimates by about 5% (152 mm and 160 mm for the model and the reference, respectively). The estimation error is of the same order of measurement errors, i.e. classically ± 10% (i.e. Rosenberg et al., 1983).

5. Conclusions

The evapotranspiration model presented here is based on the Penman–Monteith formula, with the introduction of a new concept for canopy resistance. Canopy resistance is estimated daily from climatological data and plant water status, so that it is a variable parameter, assuming a specific value at each moment and, consequently, for each day.

This method is applicable to field crops completely covering the soil, both in well watered and stress conditions. It has been tested at two different sites in the Mediterranean region, the first with a semi-arid climate and the second with a semi-humid climate. On a hourly scale, it seems to work well in various soil water situations: when the crop is well watered, weak, strong and senescence + water stressed, the last situation occurring during the final stage of the growing season.

The performance of the model could be improved by the use of more than four water stress classes; in this case each interval would be smaller but the model loses practical applicability.

On a daily scale hourly overestimations are counterbalanced by underestimations so the model works very well throughout the entire crop growing season at the two sites in all soil water conditions.

These results confirm that this method does not need a local calibration, like other Penman and Penman–Monteith based models, but only a 'per crop' calibration. If the coefficient C_d, a function of the crop water condition specified by the predawn value of Ψ is known, the model would be valid at another site. It must be emphasised that in the present study, model calibration for soybean was carried out at the SI site and model validation was made at both SI and SF sites.

Nevertheless, application of the model does entail certain difficulties. Further developments are necessary to make it more applicable, in particular using estimates of soil water balance instead of measurements of Ψ. Predawn leaf water potential, despite its independence of soil characteristics, is difficult to measure daily, hence relationships between soil water content and Ψ will be required to generalize the applicability of the model.

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