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Evaluation of the Penman-Monteith model for estimating soybean evapotranspiration

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Abstract The Penman-Monteith model with a variable surface canopy resistance (r_{cv}) was evaluated to estimate hourly and daily crop evapotranspiration (ET_c) over a soybean canopy for different soil water status and atmospheric conditions. The hourly values of r_{cv} were computed as a function of environmental variables (air temperature, vapor pressure deficit, net radiation) and a normalized soil water factor (F), which varies between 0 (wilting point, θ_{WP}) and 1 (field capacity, θ_{FC}). The performance of the Penman-Monteith model (ET_{PM}) was evaluated using hourly and daily values of ET_c obtained from the combined aerodynamic method (ET_R). On an hourly basis, the overall standard error of estimate (SEE) and the absolute relative error (ARE) were 0.06 mm h^{-1} (41 W m^{-2}) and 4.2%, respectively. On a daily basis, the SEE was 0.47 mm day^{-1} and the ARE was 2.5%. The largest disagreements between ET_{PM} and ET_R were observed, on the hourly scale, under the combined influence of windy and dry atmospheric conditions. However, this did not affect daily estimates, since nighttime underestimations cancelled out daytime overestimations. Thus, daily performances of the Penman-Monteith model were good under soil water contents ranging from 0.31 to 0.2 (θ_{FC} and θ_{WP} being 0.33 and 0.17, respectively) and LAI ranging from 0.3 to 4.0. For this validation period, calculated values of r_{cv} and F ranged between 44 s m^{-1} and 551 s m^{-1} and between 0.19 and 0.88, respectively.

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Introduction

An accurate estimation of evapotranspiration is very useful for appropriate water management both at the farm and the irrigation project level. Nowadays, the most usually recommended method consists of estimating the crop evapotranspiration (ET_c) for a crop canopy using a reference evapotranspiration (ET_r) and a crop coefficient. The Penman-Monteith equation has been recommended for predicting ET_r over a grass kept under optimum soil moisture and nutritional conditions (Allen et al. 1998, FAO-56 method). Under these conditions, the grass canopy behaves like a single big leaf and, therefore a constant value of the surface canopy resistance is used to estimate ET_r (Jensen et al. 1990).

The FAO-56 method may not be accurate for non-optimum soil moisture and nutritional conditions. Moreover, the surface canopy resistance may vary according to weather conditions such as available radiation or vapor pressure deficit (Jarvis 1976; Alves and Pereira 2000). Due to variations in atmospheric conditions during the day, it may also be necessary to compute ET_r with an hourly time step instead of a daily time step (Ortega-Farias et al. 1995). In all these cases, several authors have shown that the Penman-Monteith equation with a variable canopy resistance (r_{cv}) could be used to compute ET_c directly. This has been tested with or without water stress, over several crops such as grass, lettuce, soybean, cattails, maize, tomato, wheat, and cotton (Ortega Farias 1993; Abtew and Obeysekera 1995; Farahani and Bausch 1995; Rana et al. 1997; Alves and Pereira 2000; Anadranistakis et al. 2000; Ortega-Farias et al. 2000). In all these cases, the Penman-Monteith equation requires an adequate parameterization of the surface canopy resistance. Several empirical models have been developed to explain the nonlinear influences of both atmospheric conditions and soil water content on the behavior of stomatal resistance or surface canopy resistance (Jarvis 1976; Noilhan and Planton 1989; Ortega-Farias 1993; Taconet et al. 1995; Olioso et al.

1996; Rana et al. 1997). These models usually account for the effects of incident radiation, vapor pressure deficit and, in some cases, of temperature. The effect of soil moisture may be introduced directly by using the response curve of resistance to soil water content in the root zone (Noilhan and Planton 1989) or to pre-dawn leaf water potential (Rana et al. 1997). Other studies found it preferable to relate resistance to leaf water potential (Jarvis 1976, Olioso et al. 1996). In this case, the determination of ET_c was more complex to implement, since it required an explicit simulation of water transfer through the plants in order to simultaneously compute leaf water potential, surface resistance, and transpiration (Olioso et al. 1996). The computation of surface resistance is also required to account for the quantity of evaporative surfaces, mostly the leaves, either by introducing a simple response function to LAI (Noilhan and Planton 1989), or by integrating the stomatal conductance response to microclimate over the canopy (Olioso et al. 1996). An alternative method, proposed by Ortega-Farias (1993), was based on a dimensional analysis of the surface resistance without referring directly to integration of stomatal resistance. It considered the response of surface resistance to the available energy at the canopy level. This last approach is very attractive for users of the Penman-Monteith equation since it requires similar inputs (net radiation, vapor pressure deficit), is very simple to implement and may include the effect of soil water content if required. It was applied with success to wetted and non-wetted grass canopies (Ortega-Farias 1993; Ortega-Farias and Cuenca 1998, Ortega-Farias et al. 1999) and to a tomato crop under optimum soil moisture conditions (Ortega-Farias et al. 2000).

The objective of this study was to evaluate the Penman-Monteith equation with a variable surface canopy resistance, using the bulk formulation proposed by Ortega-Farias (1993), for estimating hourly and daily ET_c for a soybean crop, which was grown under moderate water stress conditions.

Theoretical background

The essential physics and biology of evapotranspiration from a crop canopy are represented in the following mathematical expression (Monteith and Unsworth 1990):

$$ET_{PM} = \frac{\Delta \cdot (R_n - G) + \gamma \cdot E_a}{\Delta + \gamma \cdot \left(1 + r_{cv} \cdot r_a^{-1}\right)} \qquad (1)$$

where ET_{PM} = crop evapotranspiration computed from the Penman-Monteith model on an hourly basis (mm h^{-1}); R_n = net radiation (mm h^{-1}); G = soil heat flux (mm h^{-1}); γ = psychrometric constant (kPa °C^{-1}); E_a = aerodynamic vapor transport term (mm h^{-1}); Δ = slope of the saturation vapor pressure curve as a function of hourly average air temperature (kPa °C^{-1}); r_{cv} = surface canopy resistance (s m^{-1}); r_a = aerodynamic resistance (s m^{-1}).

The aerodynamic vapor transport term, which represents the combined effect of wind speed, air temperature, and vapor pressure deficit over the water losses from the crop canopy, can be defined as (Brutsaert 1982):

$$E_a = \frac{L_v \cdot \varepsilon \cdot \rho_a \cdot D_{pv}}{P \cdot r_a \cdot C_F} \qquad (2)$$

where D_{pv} = water vapor deficit (kPa); L_v = latent heat of vaporization (J kg^{-1}); ρ_a = air density (kg m^{-3}); ε = ratio of molecular weight of water vapor to that of dry air (0.622); P = atmospheric pressure (kPa); C_F = conversion factor [680 W m^{-2} (mm $h^{-1})^{-1}$].

The aerodynamic resistance between the top of the canopy and a reference level is defined, under neutral stability conditions, by the following relationship (Jensen et al. 1990):

$$r_a = \frac{\ln\left((Z - d) \cdot Z_{om}^{-1}\right) \cdot \ln\left((Z - d) \cdot Z_{ov}^{-1}\right)}{K^2 \cdot u} \qquad (3)$$

where Z = wind speed and air temperature measurement height (m); Z_{om} = surface roughness length for momentum transport (m); Z_{ov} = surface roughness length for heat transport (m); K = von Kármán constant (0.41); u = horizontal wind speed (m s^{-1}); d = zero plane displacement (m). The aerodynamic properties of the soybean crop could be computed as d = 0.67 h_c, Z_{om} = 0.10 h_c, and Z_{ov} = 0.14 Z_{om}, where h_c = soybean canopy height (m).

The surface canopy resistance, which depends on climatic factors and available soil water, is defined as the resistance to water transfer from the soil and plant to the atmosphere. The combined effect of atmospheric and soil moisture conditions on r_{cv} can be expressed as follows (Ortega-Farias 1993):

$$r_{cv} = \frac{\rho_a \cdot C_p \cdot D_{pv}}{\Delta \cdot (R_n - G) \cdot C_F} \cdot F^{-1} \qquad (4)$$

where C_p = specific heat of dry air (1,013 J kg^{-1} °C^{-1}) and F = normalized soil water (from 0 to 1). This formulation was developed by using a dimensional analysis over a wetted and non-wetted grass canopy (Ortega-Farias 1993). In this case, the Penman-Monteith model with a variable canopy resistance (Eq. 4) was able to predict latent heat flux with errors less than 6.0%. A similar approach has been applied by Alves and Pereira (2000) over a well-irrigated lettuce crop (*Lactuca sativa* var. *capitata* cv Saladin).

The F value can be estimated as (Noilhan and Planton 1989):

$$F = \frac{\theta_i - \theta_{WP}}{\theta_{FC} - \theta_{WP}} \qquad (5)$$

where θ_{FC} = volumetric soil moisture content at field capacity (fraction); θ_{WP} = volumetric soil moisture content at wilting point (fraction); θ_i = volumetric soil moisture content in the root zone (fraction). Equation 5 has been widely used in models to study the effect of soil water stress on r_{cv}, ET_c and photosynthesis, such as soil–vegetation–atmosphere transfer (SVAT) models (Noilhan and Planton 1989; Calvet et al. 1998). The factor F varies between 0 and 1 when θ_i varies between θ_{FC} and θ_{WP}, respectively.

Materials and methods

Data to evaluate the Penman-Monteith equation were collected over a soybean (*Glycine max* cv. Labrador) crop located at the INRA Research Center near Avignon, France (43°54′N, 4°48′E). The region is characterized by a typical Mediterranean climate (Fig. 1a–c). The soybean crop was grown on a silty clay loam at a density of 55 plants per square meter from the beginning of July [sowing on day of year (DOY) 185] to mid-October 1990.

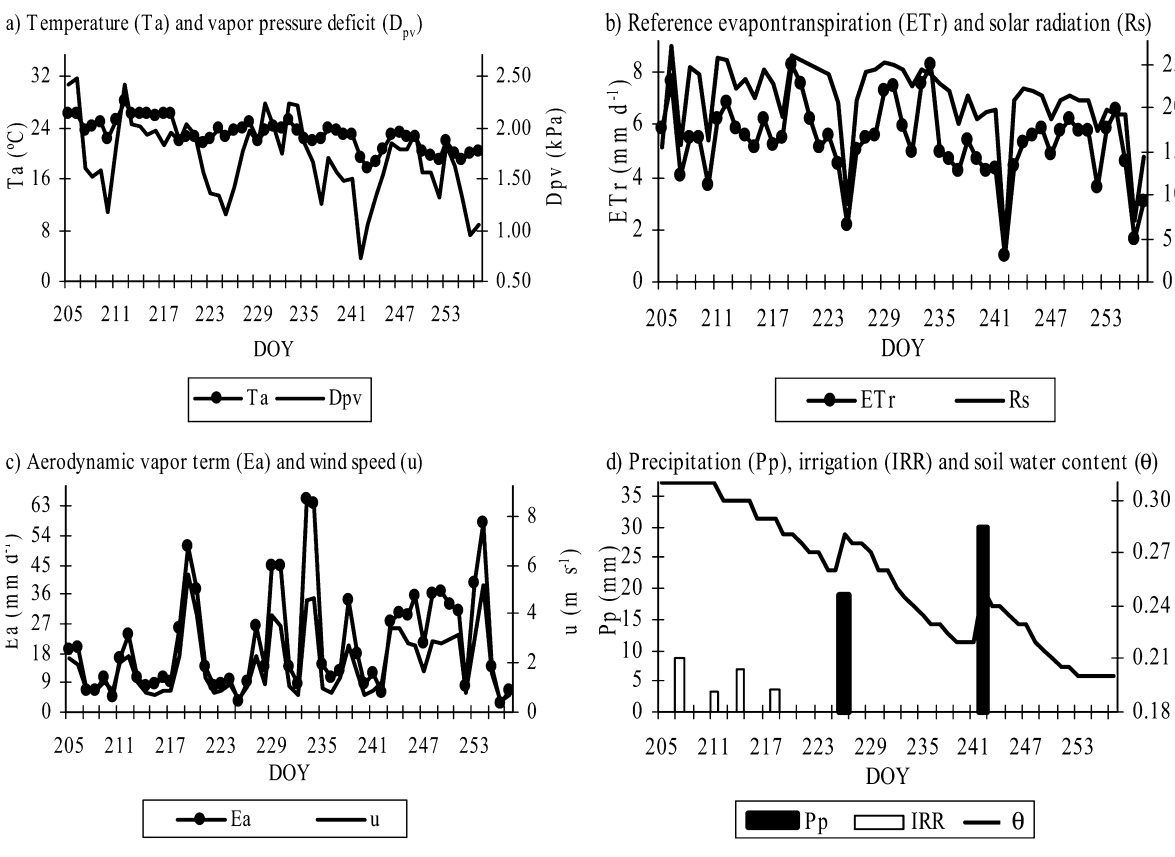
During the experiment, conducted from DOY 205 to DOY 258, the crop received about 22.6 mm of water from a sprinkler irrigation system (Fig. 1d). Once the leaf area index (LAI) reached a value of 2 (DOY 219), irrigation was withdrawn until harvesting, but two rainy days resulted in LAIs 19 mm (DOY 226) and 30 mm of precipitation (DOY 242), respectively. In this experiment, soil water content steadily decreased from 0.31 to 0.20 and mayor peaks were due to water supply by rains (Fig. 1d). The volumetric soil moisture content at field capacity and wilting point were 33% and 17%, respectively.

The LAI was measured twice a week with a LICOR 3000 planimeter from three samples collected on an area of 0.25 m^2. Vegetation height (h_c) was estimated twice a week as the average height of 15 individual plants. The LAI and h_c reached nearly 4 and 0.65 m, respectively, when the canopy was fully developed after DOY 235. Root density profiles were observed weekly using a grid method with three replicates [a detailed description of these measurements was given in Brisson et al. (1993)]. Maximum rooting depth reached 1.20 m

Soil moisture was measured every 2 or 3 days with three replicates using a neutron probe from 0.2 to 1.80 m depth in the soil. These measurements were complemented by collecting gravimetric samples from 0 to 0.20 m in three layers (0 to 0.05 m, 0.05 to 0.10 m and 0.10 to 0.20 m). The gravimetric sampling was performed daily at the beginning of the crop cycle and less frequently after a complete crop cover was attained (every 2 or 3 days). Soil water potential was measured daily, using manual tensiometers, to a depth of 1.55 m at 20 cm intervals with two replicates, the starting depth being 0.05 cm. Soil water potential measurements made it possible to determine the zero-flux plane, which was always lower than the root depth, and never lower than 1.6 m. It was then possible to use soil measurements to derive the crop evapotranspiration from the water balance using the calculation of water fluxes below the root zone (see Bertuzzi et al. 1994). In this case, water storage variation was computed for the soil layer between 0 and 1.20 m at the beginning of the crop cycle (i.e. before the zero flux level reached 1.2 m) and between 0 and 1.6 m when the canopy was well developed, adding water supplies and subtracting the deep percolation (at 1.2 or 1.6 m). The deep percolation was computed from the difference of water potential measured at two depths around 1.2 m (1.15 and 1.35 m) and 1.6 m (1.55 and 1.75 m) and an estimation of the unsaturated hydraulic conductivity from soil moisture. The unsaturated hydraulic conductivity – volumetric water content was derived by Bertuzzi et al. (1994) on the same field, using the expression by Van Genuchten (1980) according to Mualem's model (Mualem 1976). Deep percolation was always low, around 0.05 mm day^{-1}, in agreement with the high clay content of the soil.

Energy balance measurements were implemented in order to derive ET_c at an hourly time step from several methods: Bowen ratio (ET_B), combined aerodynamic (ET_R) and combined fluctua-

Fig. 1 Daily values of air temperature (T_a), vapor pressure deficit (D_{pv}), solar radiation (R_s), reference evapotranspiration (ET_r), wind speed (u), aerodynamic vapor transport term (E_a), precipitation (P_p), irrigation (IRR), and volumetric water content (θ) in the root zone (depth 1.2 m)



tion (ET_F) methods. Net radiation (R_n) was measured using a net radiometer 1 m above the canopy. Soil heat flux (G) was calculated from the temperature profile down to 1 m depth. Two profiles were used between rows and on rows. Soil heat capacity was estimated from soil humidity and soil density. The Bowen ratio was determined from measurements of air temperature (T_a) and air vapor pressure (e_a) at two levels above the canopy (approximately two and three times the vegetation height) using the alternate sampling system described by Cellier and Olioso (1993). The Bowen ratio, together with R_n and G measurements, made it possible to derive latent heat flux (LE). Horizontal wind speeds (u_a), measured at the two same levels as air temperature were used to compute the sensible heat flux (H) following the Monin-Obukhov theory as modified by Brutsaert (1982). Eddy correlation measurements of H using mono-dimensional sonic anemometers (Campbell CA27) were also performed at selected periods. Two sonic anemometers were set at 2.5 times the vegetation height.

In the combined aerodynamic method, values of LE (ET_R) were computed as the residual of the energy balance equation ($LE = R_n - G - H$). This method was the only one to provide continuous latent flux measurements during the validation period. A comparison among the three methods indicated that hourly values of ET_R were very close to those of ET_B and ET_F, with errors less than 3%.

As the field size was not very large (1 ha), the positions for atmospheric measurements were optimized in order to reduce advective effects by considering the directions of major wind regimes and by setting the instruments no higher than three times the canopy top. A footprint analysis indicated that 90% of the fluxes originated from the field, accounting for more than 90% of the data acquired in diurnal conditions (Hsieh et al. 2000). At night, because of the stable conditions, footprints were often larger than the field (60% of the data). However, less than 15% of the cumulated latent heat fluxes in the flux data did not originate from the field.

In order to assess the validity of the estimation of ET_c, as computed from the Penman-Monteith equation (ET_{PM}), our calculations were compared to latent heat flux obtained from the combined aerodynamic method (ET_R). This comparison included the ratio (b) between ET_{PM} and ET_R, the Z test to check whether the value of b was significantly different from unity, the standard error of estimate (SEE), and the absolute relative error (ARE). Cumulated values of ET_{PM} were also compared to the cumulated evapotranspiration obtained from soil water balance calculation (ET_{WB}). Also, the FAO-56 Penman-Monteith equation was used to estimate the daily ET_r during the validation period (Fig. 1b) (Allen et al. 1998).

Results and discussion

The results, summarized in Table 1, indicate that there was good agreement between both daily and hourly soybean evapotranspiration measured by the combined aerodynamic method (ET_R) and that computed by the Penman-Monteith equation with a variable surface resistance (ET_{PM}). On an hourly basis, the overall value of ARE was 4.2% with a SEE equal to 0.06 mm h^{-1} (41 W m^{-2}). Results of the Z test suggest that the overall value of b was significantly greater than 1 at the 95% confidence level, indicating that the ET_{PM} tended to be larger than ET_R on an hourly basis. The hourly comparison between both methods (Fig. 2) indicates that ET_{PM} values tended to be greater than ET_R for values above 0.4 mm h^{-1}. However, the Penman-Monteith model tended to underestimate evapotranspiration for ET_R values ranging between 0.1 and 0.3 mm h^{-1}.

Table 1 Statistical results of hourly and daily evapotranspiration over a soybean canopy estimated by the Penman-Monteith equation

	SEE[a]	b (ET_{PM}/ET_R)[a]	ARE (%)[a]	Z test[b]
ET_{PM} (hourly)	0.060 mm h^{-1}	1.04	4.2	F
ET_{PM} (daily)				
LAI ≤ 3	0.35 mm day^{-1}	1.01	1.5	T
LAI > 3	0.52 mm day^{-1}	0.95	4.6	F
Total	0.47 mm day^{-1}	0.97	2.5	T

[a] SEE = standard error of estimate, b = ratio between the ET_R (combined aerodynamic method) and ET_{PM} (Penman-Monteith equation), ARE = absolute relative error
[b] T = true hypothesis ($b = 1$), F = false hypothesis ($b \neq 1$)

The largest disagreements between ET_{PM} and ET_R were observed under the combined influence of windy and dry atmospheric conditions. These conditions were characteristic of the "Mistral" event, a strong and dry wind occurring in the south-east of France. The hourly difference between ET_{PM} and ET_R as a function of the aerodynamic vapor transport term (Eq. 2) indicates that the largest disagreements between ET_{PM} and ET_R were observed for values of E_a greater than 2.5 mm h^{-1} (Fig. 3) or 1,700 W m^{-2}. These conditions were found on DOY 219, 220, 229, 230, 233, 234, and 254, which presented daily values of wind speed, vapor pressure deficit, and aerodynamic vapor transport between 3.5 and 5.6 m s^{-1}, 1.63 and 2.25 kPa, and 38 and 65 mm day^{-1}, respectively (Fig. 1a–c). On the other days, the largest daily values of the aerodynamic vapor transport term were less than 35 mm day^{-1}.

For E_a values larger than 2.5 mm h^{-1}, SEE computed for each day ranged between 0.1 mm h^{-1} (69 W m^{-2}) and 0.17 mm h^{-1} (115.6 W m^{-2}). However, the frequency distribution of hourly difference between ET_{PM} and ET_R (Fig. 4) illustrates that differences greater than ± 0.060 mm h^{-1} (41 W m^{-2}) were found in less than 21% of the total observations. This analysis indicates that the hourly agreement between ET_{PM} and ET_R was good in spite of the departures observed under very windy and dry atmospheric conditions. Under mistral conditions, it was possible that advection of heat had a significant influence on sensible heat flux measurements or that instruments, such as the anemometer, were not sufficiently accurate because of the very gusty winds of the mistral.

Comparison of ET_{PM} and ET_R for some selected days is presented in Fig. 5. Best agreements between ET_{PM} and ET_R at the experimental site were observed on DOY 214 (Fig. 5a). On this day, the value of b (0.98) was not significantly lower than one with SEE equal to 0.017 mm h^{-1} (11.9 W m^{-2}). The greatest disagreements were found on a mistral day, DOY 219 (Fig. 5b), which presented the largest b value (1.98) and highest SEE (0.17 mm h^{-1}). On this day, the daily value of E_a was 6.5 times larger than that observed on DOY 214 (Fig. 1c). Maximum values of E_a were 3 and 0.8 mm h^{-1} for DOY 219 and 214, respectively. On DOY 219, Fig. 5b, also illustrates that the Penman-Monteith model tended to overestimate evapotranspiration during daytime and underestimate evapotranspiration during nighttime. It must be noted that measured evapotranspiration rates at

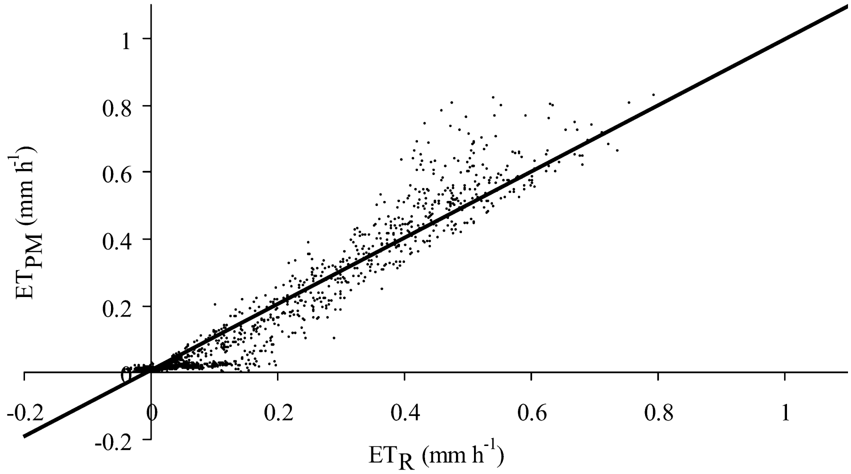


Fig. 2 Hourly comparison between actual evapotranspiration obtained by the combined aerodynamic method (ET_R) and Penman-Monteith (ET_{PM}) over a soybean canopy

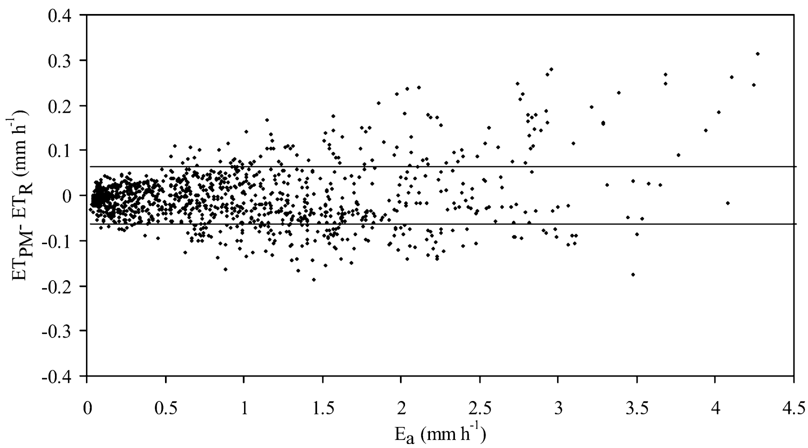


Fig. 3 Difference between hourly values of actual evapotranspiration obtained by the combined aerodynamic method (ET_R) and Penman-Monteith (ET_{PM}) as a function of aerodynamic vapor transport (E_a)

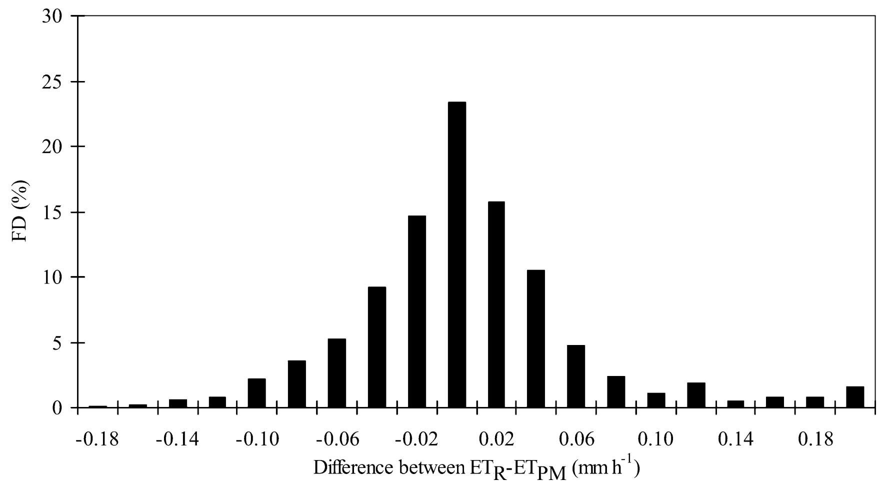


Fig. 4 Frequency distribution (*FD*) of hourly difference between hourly values of actual evapotranspiration obtained by the combined aerodynamic method (ET_R) and the Penman-Monteith equation (ET_{PM})

night were very large on DOY 219. This phenomenon was previously noticed under similar conditions of very windy and very dry atmospheric conditions in other experiments in the south of France (Bernard Seguin, INRA-Avignon, personal communication). However, considering on one hand the potential problem of advection of heat in stable atmospheric conditions (usually at night) due to large footprint size (reinforced by an irrigation event that occurred the day before), and on the other hand, the fact that experimental estimation of ET_c was derived as the residual of the energy balance, the use of ET_c measurements in these conditions should

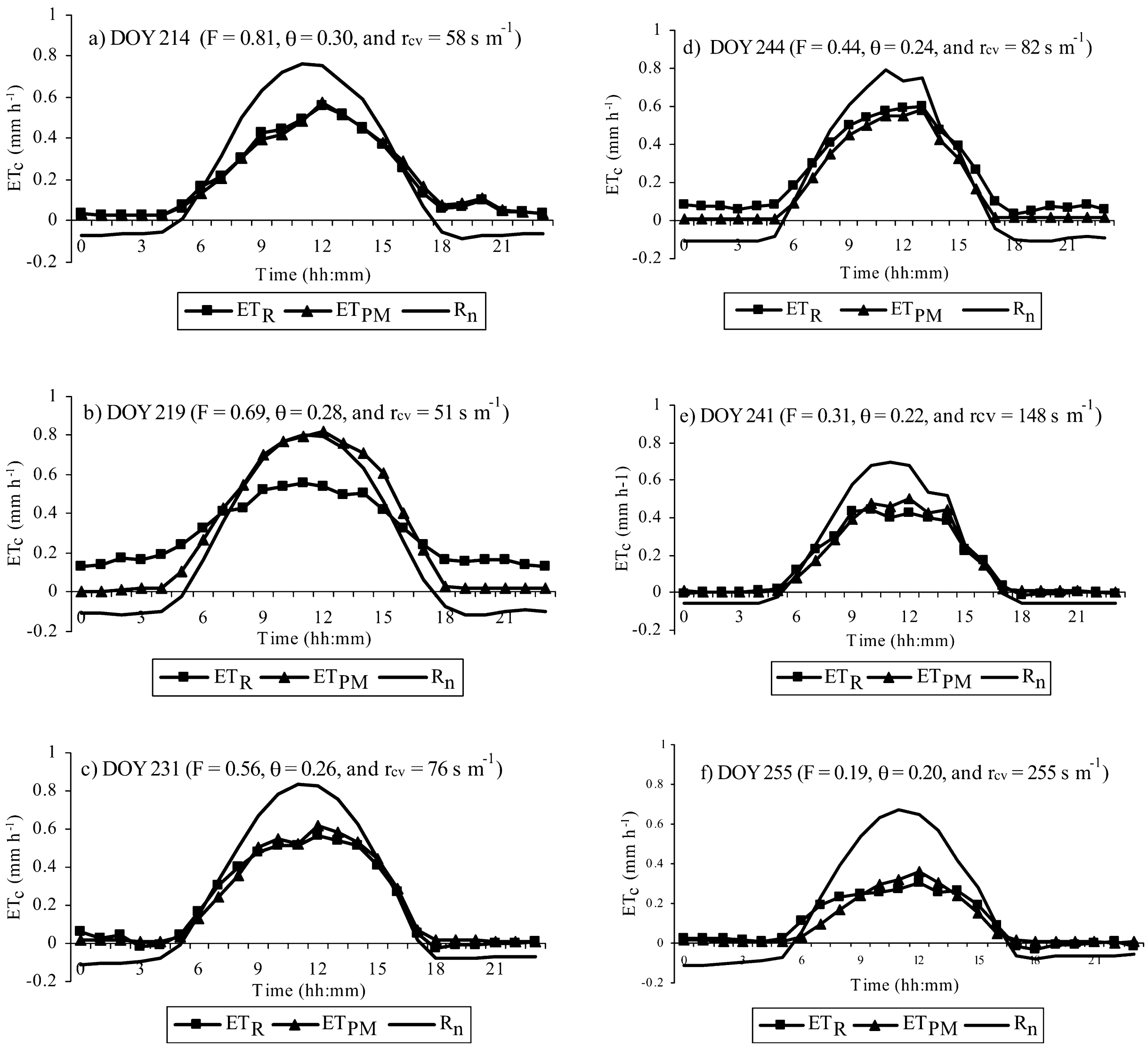


Fig. 5 Hourly values of crop evapotranspiration (ET_c) obtained by the combined aerodynamic methods (ET_R) and the Penman-Monteith equation (ET_{PM}) over a soybean crop, where θ is the volumetric soil water content, F is the normalized soil moisture and r_{cv} is the surface canopy resistance (average values from 10.00 to 15.00 hours). The net radiation (R_n) is included as reference

be treated with caution. The same behavior occurred on other days, particularly on DOY 220, 229 and 230, and to at a lesser extent on the other days with mistral (DOY 233, 234, and 254).

The performance of the Penman-Monteith model to estimate ET_c over a soybean crop under different soil moisture conditions is also shown in Fig. 5a–f, which indicate that hourly values of ET_{PM} and ET_R were usually close during the day for most soil water conditions (except for DOY 219). For the soybean crop under a soil moisture content near field capacity ($F=0.81$ and $\theta=0.3$), maximum differences between ET_{PM} and ET_R were less than 0.05 mm h^{-1} (35 W m^{-2}). In this case, daily values of ET_{PM} and ET_R were 96% and 97% of the R_n, respectively (Fig. 5a). When the water supply was limited and the volumetric soil moisture content was less than 20% ($F=0.19$ and $\theta=0.2$), daily values of ET_{PM} and ET_R were about 69% and 71% of the R_n, respectively (Fig. 5f). The decrease in these percentages is related to an increase in surface canopy resistance: the averaged values of r_{cv} (Eq. 4) were 58 and 255 s m^{-1} for DOY 214 and 255, respectively. For this experiment, the averaged surface resistance ranged between 44 and 551 s m^{-1}. The normalized soil moisture (F) and the ratio between ET_R and ET_r (K_e) ranged from 0.19 to 0.88 and from 0.36 to 1.21, respectively (Fig. 6). It is worth noting that before DOY 230, the average surface resistance had a value lower than 100 s m^{-1}, usually close to 50 s m^{-1}, while F was higher than 0.5. During this period, variations in F, from values close to 0.9 to 0.5, only slightly affected the K_e ratio.

To evaluate the ability of the Penman-Monteith model to reproduce the seasonal evolution of ET_c over a soybean crop under different soil water contents and various atmospheric conditions, daily comparisons were made from DOY 205 to DOY 255 (beginning of

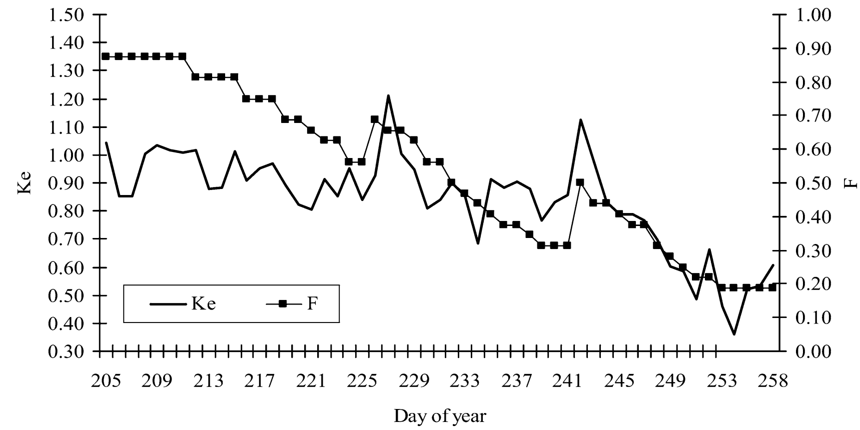


Fig. 6 Ratio (K_e) of the reference evapotranspiration (ET_r) to crop evapotranspiration (ET_c) and normalized soil moisture (F) in the root zone (depth 1.2 m)

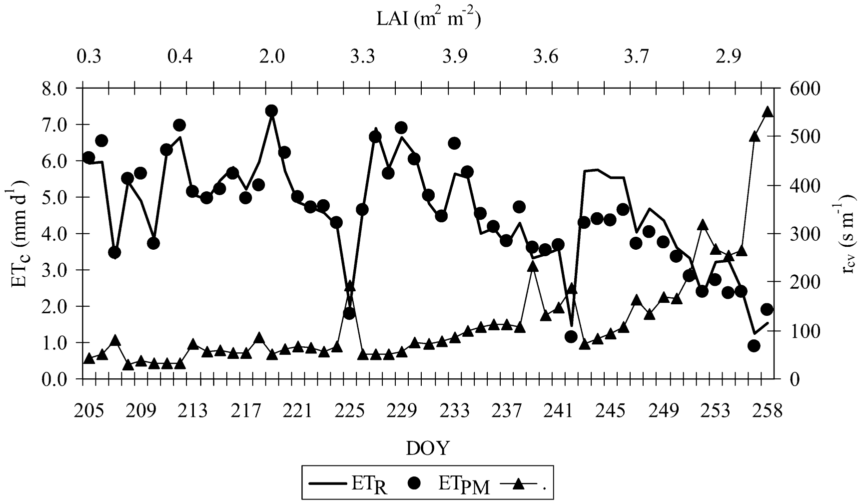
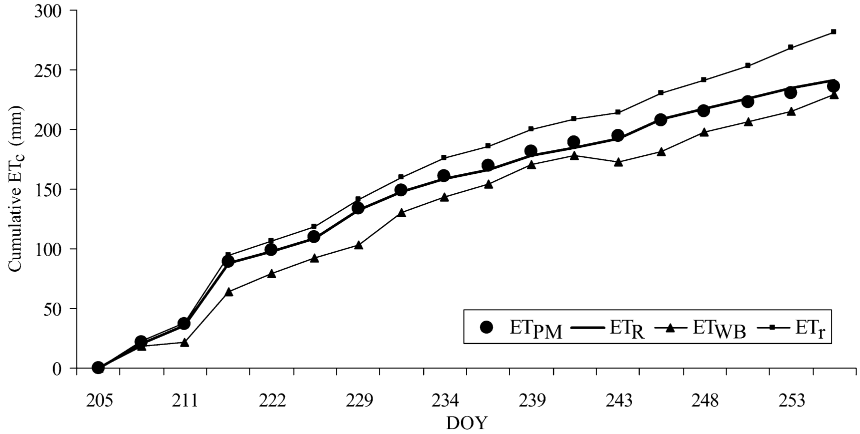


Fig. 7 Crop evapotranspiration (ET_c) obtained by the combined aerodynamic method (ET_R) and the Penman-Monteith equation (ET_{PM}), and surface canopy resistance (averaged values from 10.00 to 15.00 hours). The leaf area index (*LAI*) is included as a reference

senescence). Figure 7 shows a good agreement between daily values of ET_{PM} and ET_R, with SEE and ARE values equal to 0.47 mm day^{-1} and 2.5%, respectively (Table 1). The Z test indicated that the b value was not statistically different from unity, suggesting that values of ET_{PM} and ET_R were similar. It is very important to note that model performances were similar for a large range of LAI (from 0.26 to 3.9). In this case, ARE values were 1.5% and 4.6% for LAI ≤ 3 and LAI > 3, respectively (Table 1). This result is very interesting, since when other models (SVAT models) were applied to the same dataset, systematic underestimation of evapotranspiration were always obtained at low LAI (Olioso et al. 1999, 2002). These other models were more complex than the Penman-Monteith equation and used surface resistance models based on the integration of stomatal conductance over the canopy together with a separate calculation of the evaporation at the soil surface: ALiBi (Olioso et al. 1996, 2002), ISBA (Noilhan and Planton 1989; Noilhan and Mafhouf 1996) and Si-SPAT (Braud et al. 1995). For instance, results of the ALiBi model presented by Olioso et al. (1999) resulted in a value of b significantly lower than that obtained in the present study with the Penman-Monteith model (0.92 instead of 1.01; see Table 1). The good behavior of the Penman-Monteith model at low LAI may be linked to the 'bulk' formulation of the surface resistance (Eq. 4), while the simulation of evapotranspiration by SVAT models, based on a detailed description of water vapor and heat exchanges, required more parameters and use of exchange formulations, which may be difficult to apply in partial canopies.

The seasonal model performance was also evaluated by comparing cumulative ET_c (as the sum of daily values in millimeters) for the Penman-Monteith (ET_{PM}) and for combined aerodynamic (ET_R) methods (Fig. 8). The cumulated ET_{PM} almost perfectly followed the measured ET_R. Over the whole crop cycle, ET_{PM} tended to underestimate ET_R by only 2.2% (236 mm and 241 mm for the Penman-Monteith model and ET_R method, respectively). On the other hand, cumulative values of ET_{PM} and ET_R were 3.0% and 5.3% larger than those obtained from the water balance (ET_{WB}), respectively. Along the crop cycle, these differences were larger (Fig. 8), usually around 10%. However, a large part of this difference may be linked to the difficulty in accounting for the water supply in water-balance calculations: measurements of rain and irrigation

Fig. 8 Cumulative crop evapotranspiration (ET_c) obtained by the combined aerodynamic method (ET_R), water balance (ET_{WB}) and the Penman-Monteith (ET_{PM}) methods. The reference evapotranspiration (ET_r) computed from FAO-56 Penman-Monteith is also included



amount may be inaccurate; some water may be lost through runoff or because of the interception of water by the plants. If periods with water supply were not accounted for in the calculation of water balance, differences with cumulated ET_{PM} and cumulated ET_R were usually lower than 5%. Furthermore, cumulative ET_r (281 mm) was 45, 52, and 39 mm greater than ET_{PM}, ET_{WB}, and ET_R, respectively.

Conclusions

The estimation of actual evapotranspiration presented here was based on the Penman-Monteith equation, with a variable surface canopy resistance. Canopy resistance was estimated on an hourly basis from climatological data and soil moisture measurements, so that it was a variable parameter, assuming a specific value at each moment and, consequently, for each day.

The Penman-Monteith model calculations were compared with combined aerodynamic measurements of latent heat flux at hourly, daily, and seasonal time scales and also to soil water balance measurements at seasonal scale. Model performance was good at the hourly scale in various soil water situations, since volumetric soil moisture decreased from 31% ($F=0.88$) to 20% ($F=0.19$). However, under windy and dry atmospheric conditions (E_a larger than 2.5 mm h^{-1}) the Penman-Monteith model tended to overestimate hourly values of evapotranspiration during the day and to underestimate them during the night. It was possible that advective conditions were responsible for such behavior (this happened only 7 days out of more than 50 days). For these conditions, hourly overestimation during the daytime was counterbalanced by underestimation during the night, thus the model still produced good results on a daily scale. Consequently the Penman-Monteith model worked very well at the daily scale throughout the entire crop-growing season in all soil water and atmospheric conditions. It was very interesting to see that the Penman-Monteith model was also worked very well at all stages of crop development including periods with a very low LAI. This may be because the bulk formulation of the surface resistance parameterization used in combination with the Penman-Monteith model is more useful on a daily scale than the more complex models that were used on the same dataset in previous studies. On the other hand, cumulative values of ET_{PM} and ET_R were 3.0% and 5.3% larger, respectively, than those obtained from the water balance (ET_{WB}).

In order to increase our confidence in the accuracy of the model proposed in the present study, we will perform new evaluations on other crops and situations. Its application to complex canopies, such as those found in a vineyard, and to various irrigation systems, including drip and furrow irrigation systems, will be assessed in future studies.

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