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Evapotranspiration models for a maize agro-ecosystem in irrigated and rainfed conditions

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Abstract

A high level of accuracy in the estimation of crop evapotranspiration (ET) may lead to significant savings of economic and water resources in irrigated agriculture. Although ET is a fundamental process in many applications, it cannot be directly measured but it has to be estimated by monitoring the exchange of energy/water above the vegetated surface (micrometeorological methods), or as a residual term of the hydrological balance (lysimeters, soil water budget). The techniques to be adopted are often complex, costly and require specific equipment. Thus, since the ‘50s, many researchers have devoted their activity to the development of models for its estimation. The available approaches can be classified in “direct” methods, based on the original Penman-Monteith (PM) equation, in which the canopy resistance r_c is modelled, and “indirect” methods, based on the preliminary calculation of ET for a well-watered reference grass (ET_0) with a constant r_c, which is then multiplied by a crop coefficient K_c and, in case, by a stress coefficient K_s to obtain ET. Even if the latter approaches are more widely adopted for their practical simplicity, many authors show that the former often provide better ET estimates in absence of calibration of crop parameters. In this study the performances of different direct and indirect methods were evaluated in the case of a surface irrigated and of a rainfed maize grown in the Padana Plain (Northern Italy). The following models were considered: the “one-layer” original PM equation with three different models for r_c (Monteith, Jarvis, Katerji-Perrier), the “two-layers” PM model proposed by Shuttleworth and Wallace, the “single” and “double” crop coefficient models illustrated in the Paper FAO-56. Latent heat fluxes measured in 2006 and 2011 in an experimental maize field by eddy-covariance were used to evaluate the models accuracy. Crop, soil and meteo data monitored contextually were used for the implementation of the different models. Results confirm that direct methods are more performing for both irrigated (2006) and rainfed (2011) conditions, with the SW model providing the best results and the FAO-56 models with generalized crop coefficients overestimating ET, especially during the middle growth stage.

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Introduction

As the water resources available for agriculture become limited due to population growth, competition among different water uses, droughts, and water quality degradation, the importance of quantifying evapotranspiration (ET), which is the major component of water use in agriculture, grows (Farahani *et al.*, 2007). ET cannot be directly measured but it has to be estimated by monitoring the exchange of energy/water above the vegetated surface (micrometeorological methods), or as a residual term of the hydrological balance (lysimeters, soil water budget). The techniques that can be adopted are often complex, costly and require specific equipment, thus they are generally applied only in scientific research.

In most practical situations where crop ET rates are required, the available economic and human resources are not sufficient to allow use of the ET measurement techniques mentioned above, and models are used instead. Since the ‘50s, many researchers have devoted their activity to the development of models that seek to estimate crop ET from near surface climate data. Early ET models were based on the perception that surface atmosphere exchange was a simple physical phenomenon little influenced by any overlying vegetation cover. This led to empirical relationships between climatic data and the potential rate of evaporation (or evapotranspiration) (*e.g.*, Thornthwaite, 1948; Blaney and Criddle, 1950). In this context, the equation of Penman (1948, 1963) was a benchmark. Penman’s contribution was to derive a “combination equation” by combining two terms, one of which accounted for the energy required to maintain evaporation (“available energy” term), and the second for the atmosphere’s ability to remove water vapour (“aerodynamic” or “sink”term) (Farahani *et al.*, 2007). After that, the modification of Monteith (1965) to the previous equation of Penman moved the axis of the research from a representation of the phenomenon by purely physical laws to one where physiological controls play a fundamental role (Ziemer, 1979). Subsequently, further progress was made in building compartment models based on two or more combination equations, allowing the description of sparse canopies and the partitioning of ET (*e.g.*, Shuttleworth and Wallace, 1985).

Difficulties in applying combination formulas (particularly related to a lack of consolidated information on the required aerodynamic and surface resistances for different crops and to the need of meteorological data measured above the canopy) led researchers towards an alternative "indirect" approach to estimate the crop evapotranspiration (ET_c). This approach is based on a "two-step" procedure: in the first step, the rate of ET was estimated for a reference crop (ET_0) in well-watered conditions. This rate was then multiplied by a crop specific coefficient with the objective of estimating ET_c for different crops. The ratio of ET_c to the ET_0 for a reference crop (short grass or alfalfa), called crop coefficient, K_c (Jensen, 1968), was then experimentally determined for different growth stages for many crops as the basis for this now long established two step approach for estimating crop water use. The use of ET_0 (estimated using local climate data) and associated crop coefficients, K_c, became an accepted way to estimate ET_c for well watered crops, and the K_c methodology was adopted by the UN's Food and Agriculture Organization (FAO) in the 1970s (Doorenbos and Pruitt, 1977). Its subsequent worldwide promotion was a significant step forward in irrigation engineering and water management (Farahani *et al.*, 2007). Later, in the 1980s and 1990s, there was further rapid progress in data acquisition, remote data access, automation, and in eddy correlation and other measurement techniques. Transfer of technology made available daily values of ET_0, facilitating early computer applications for irrigation scheduling (Martin *et al.*, 1990). The superior realism and value of combination equations was recognized, and the PM equation was adopted to estimate ET_0 in the K_c approach (Allen *et al.*, 1994; Allen *et al.*, 1998).

Despite the practical simplicity of using the "indirect" approach is indisputable, many authors in the last fifteen years demonstrated that the adoption of generalized crop coefficient curves can lead to relevant errors in the estimation of ET, since the differences between the K_c values reported in the FAO-56 Paper (Allen *et al.*, 1998) and the values obtained from locally observed data are up to ± 40%, especially during the middle growth cycle (Katerji and Rana 2006). This is mainly due to the complexity of the crop coefficient, which actually integrates several physical and biological factors. On the contrary, many researchers assessed the validity of "direct" approaches (Kato *et al.*, 2004; Farahani and Bausch, 1995; Lafleur and Rouse, 1990), concluding that their ability to simulate the processes is good, provided that the resistances involved are calculated appropriately (Brisson *et al.*, 1998). In order to adopt these models for operational uses, however, the main problems limiting their practical application must be solved.

Both the "direct" and "indirect" methods have their merits and demerits, but certainly very few experiments were conducted applying the different models jointly to the same dataset.

The objective of this study was the investigation of the performance of the most popular "direct" and "indirect" ET methods for a maize agro-ecosystem under well-irrigated and under water-stressed conditions in Northern Italy. In particular, the exercise was conducted using the datasets collected in two agricultural seasons: the first in which the field was irrigated, and the second in which no irrigation event was applied. This allowed to compare the models' performance under different soil water conditions and, at the same time, in conditions ranging from bare to full covered soils. Latent heat fluxes measured by an eddy-covariance tower placed in the field were used to test the models performance at the daily time step.

Materials and methods

The Landriano experimental site

Data used in this work were collected during the cropping seasons 2006 and 2011 in a 10 ha maize field located in Northern Italy (Landriano), in an experimental farm of the State University of Milan (45°19' N, 9°15' E, 88 m a.s.l.). Long-season Zea Mays varieties (FAO class 600–700) were seeded both years. The crop in 2006 was for silage, seeded after ryegrass and harvested green (emergence: DoY=157, harvesting: DoY=283). In 2011 maize was for forage as well, but it was harvested at the dough stage (maize silage with cobs; emergence DoY=110, harvesting: DoY=244). Maize was chosen for the study since it is the main crop in Northern Italy, covering more than 30% of the arable land.

Instruments for detailed monitoring of water and energy fluxes were installed in 2005. A micrometeorological eddy covariance (EC) station was located in the centre of the field. Instruments for the monitoring of soil water content and potential were positioned at different depth in a soil profile. Due to the presence of a shallow water table (90-120 cm below the topographic surface), a shallow piezometer with a pressure transducer device was also installed. Data were averaged and registered on half an hour basis. Several campaigns were carried out to monitor crop biometric parameters (leaf area index, crop height, rooting depth) and soil properties in both agricultural seasons. Standard meteorological variables were measured on hourly time step by an agro-meteorological station installed in a grass parcel located at 200 m distance from the experimental field.

The site has a humid subtropical climate according to the Koppen classification system.

During the cropping season 2006 the field was irrigated twice: at DoY=159 with the sprinkler method to promote crop emergence, and at DoY=195 with the border method. The water amount applied was estimated to be respectively 25 mm and 140 mm in the two events (Baroni *et al.* 2010). No irrigation was applied in 2011.

Eddy covariance data were post-processed using the TK2 software (Mauder and Foken, 2004). The energy balance closure for daytime (R_n>0) 30-min data was equal to 83% for 2006 and 92% for 2011. The gap-filling of missing/eliminated daytime data was conducted determining a regression between half-hourly values of ET and both available energy (R_n-G) and vapour pressure deficit (VPD), only for the days in which at least the 80% of daytime data were available. Daily ET values were finally calculate summing up the 30-min data. More information about the experimental site and the processing of eddy covariance data are illustrated in Facchi *et al.* (2013).

Direct methods

One-layer Penman-Monteith (PM) model

The Penman Monteith (1965) "one-layer" model (PM) schematizes the vegetation cover as a single "big leaf" placed at a certain height within the vegetation. The vegetation is taken into account through the canopy and the aerodynamic resistances. The aerodynamic resistance (r_a) is a function of wind and vegetation height. The canopy resistance (r_c) is a "bulk" resistance describing the resistance of vapour flow through stomata openings, through the canopy total leaf area and within the soil to the soil surface.

A problem with the PM "one-layer" approach is that areas with partial or sparse vegetation cover don't satisfy completely the hypothesis of "big leaf". The difficulty of providing accurate ET estimates using the PM model in partial canopy conditions (LAI<1.5-2) has been underlined by several authors (Farahani and Bausch, 1995; Lafleur and

Rouse, 1990).

In this study, the following three approaches for estimating r_c have been selected: a) Monteith, b) Jarvis and c) Katerji and Perrier.

Canopy resistance following Monteith

For a thick crop canopy it can be assumed that all the leaves behave as resistances in parallel and r_c is computed from the ratio between the minimal stomatal resistance (r_s) and the leaf area directly involved in the energy exchange (LAI_{eff}):

$$r_c = \frac{r_s}{LAI_{eff}} \tag{1}$$

Several earlier studies fixed the value of the minimal stomatal resistance r_s at 100 s m^{-1} for grass type fields (Monteith, 1965; Szeicz and Long, 1969). Subsequently, many authors demonstrated that this variable ranges between 100 and 300 s m^{-1} as a function of the crop type. In this study a value of 252 s m^{-1}was adopted, as suggested by Howell *et al.* (1997) for maize.

In a fully developed canopy only a fraction of the leaf area index effectively contributes to transpiration, since the photosynthetically active radiation varies through the canopy. A functional relationship between LAI and LAI_{eff} suitable for all crops has not yet been found. For a maize crop, Gardiol *et al.* (2003) reported LAI_{eff}=LAI for LAI≤2, LAI_{eff}=0.5 LAI for LAI≥4 and LAI_{eff}=2 for intermediate LAI values (2<LAI<4). In this paper an update of this formula is proposed. The PM model with r_c by Monteith applies only to well watered soil conditions, since this resistance does not take into account of soil or crop water status.

Canopy resistance following Jarvis

For more than thirty years, the most widespread approaches to parameterize the effect of environmental factors on stomatal behaviour have been the Jarvis-type models, in which the canopy resistance is expressed as a function of the minimal stomatal resistance r_s and a series of independent stress functions F_i combined in a multiplicative way (each function representing the influence of one factor and providing values ranging from 0 to 1). In particular, the Jarvis-type model proposed by Noilhan and Planton (1989) is set as follows:

$$r_c = \frac{r_s}{LAI\ F_1 F_2 F_3 F_4} \tag{2}$$

In this study, for consistency with the r_c modelled following the Monteith approach, LAI=LAI_{eff} and r_s=252 s m^{-1} (Howell *et al.*, 1997) were adopted. F_1, F_2, F_3 and F_4 represent respectively the influence on r_c of photosynthetically active radiation, vapour pressure deficit, air temperature and effective soil water content, and they were modelled as reported in Gharsallah *et al.* (2013). In particular, the F_4 factor was modified with respect to the original version of Noilhan and Planton (1989), becoming:

$$F_4 = \begin{cases} 1, if\ \theta > \theta_t \\ \dfrac{\theta - \theta_{wilt}}{\theta_t - \theta_{wilt}} & , if\ \theta_{wilt} \le \theta \le \theta_t \\ 0, if\ \theta < \theta_{wilt} \end{cases} \tag{3}$$

where θ is the effective soil water content (m^3 m^{-3}), θ_{wilt} is the soil water content at the wilting point (m^3 m^{-3}) while θ_t is set at the critical soil water content under which the evaporative stress begins following what proposed by Allen *et al.* (1998). Due to the F_4 function, the PM equation with r_c following Jarvis is expected to provide good results both under well-watered and water-stressed conditions.

Canopy resistance following the Katerji and Perrier approach

According to Katerji and Perrier (1983), the latent heat flux is governed by three resistances: the aerodynamic resistance r_a, the climatic resistance r*, depending only on weather variables, and the canopy resistance r_c. Through dimensional analysis the authors demonstrated that the resistances r_c and r* are linked as follows:

$$\frac{r_c}{r_a} = a\frac{r^*}{r_a} + b \tag{4}$$

where a and b are calibration parameters which vary with the crop type, its phenological stage and its water status, but, according to the authors, they are not site-specific (Rana *et al.*, 1997a). Parameters values for a few crops in different growth stages (active development and senescence) and water conditions (different intervals of leaf water potential) were provided by Rana *et al.* (1997a, 1997b, 2001). Unfortunately, maize is not among those crops, thus in this study the two parameters were derived from the available data. This is the only calibration operation in the study, performed using some days of the dataset collected at Landriano in 2011. In particular, the dataset was divided into three periods: active development in the absence of crop water stress conditions, active development under crop water stress conditions and senescence. Three representative days for each period were selected, the daytime (R_n>0) 30-min canopy resistance r_c was determined from the corresponding eddy covariance data by the inversion of the PM equation, a linear regression between the ratio r_c/r_a and r^*/r_a was then fitted and the parameters a and b were identified. Obviously, r_c from the eddy covariance data, r* and r_a were calculated starting from the half-hourly data acquired in the selected days. The a and b values found for the first period of 2011 agricultural season (*i.e.* active development with absence of water stress) were used for the whole 2006 season, since maize was well-watered and harvested very early that year. Instead, for the agricultural season 2011, a e b values found for the three periods where respectively used. Data used for the a and b calibration were eliminated from the 2011 eddy covariance dataset used for the models' validation. Since the a e b parameter values were identified even under water-stressed conditions, the model is expected to work properly for all soil water status.

Two-layers Shuttleworth (SW) model

The SW model (Shuttleworth and Wallace, 1985; Shuttleworth and Gurney, 1990) combines two PM type equations for crop transpiration and soil evaporation. Canopy and surface resistances regulate the heat and mass transfer at the plant and soil surfaces and aerodynamic resistances regulate those between the two surfaces and the atmospheric boundary layer. The two terms are computed by the following equations:

$$\lambda ET = \lambda T + \lambda E = C_c \lambda T0 + C_s \lambda E0 \tag{5}$$

where λET is the sum of the latent heat flux from the crop (λT) and the soil (λE) (W m^{-2}). λT0 and λE0 are the terms similar to the PM model and C_c and C_s are respectively the canopy resistance and soil surface resistance coefficients.

Different resistances play they role in the model. The soil surface resistance r_{ss} is interpreted as the resistance for the water vapour to diffuse through the top layer of the soil. Shuttleworth and Wallace (1985) proposed values respectively of 0, 500 and 2000 s m^{-1} for r_{ss} in various soil water conditions. The canopy resistance r_{sc} was calculated following Eq. 1, while the aerodynamic resistances r_{aa} and r_{as} as well as the soil surface resistance coefficients C_c and C_s were computed as reported by Shuttleworth and Gurney (1990) and Kato *et al.* (2004). The SW model is expected to provide affordable results for bare to full covered soils under water stressed and well-watered conditions.

Indirect methods

The FAO-56 "single crop coefficient" model

In the FAO-56 "single crop coefficient" approach (Allen *et al.*, 1998), crop evapotranspiration ET_c in optimal water conditions is estimated multiplying the reference evapotranspiration ET_0 (calculated applying the PM equation to a "reference grass" having fixed crop parameters) and the crop coefficient K_c, specific for the crop type and its stage of development. Crop development stages (L_{ini}, L_{dev}, L_{mid}, L_{late}) and the corresponding K_c values ($K_{c\ ini}$, $K_{c\ mid}$, $K_{c\ end}$) are tabulated in the Paper FAO-56 for different crops grown in various regions.

For the case study, K_c curves for years 2006 and 2011 were built considering the length of the crop growth stages observed in the field and adjusting the tabulated crop coefficients with the local data following the procedures indicated by Allen et al (1998). Since maize in 2006 was harvested green and FAO-56 does not provide $K_{c\ end}$ value for silage maize, K_c was kept constant and equal to $K_{c\ mid}$ till harvesting. Crop stages length and adjusted K_c values for 2006 and 2011 are reported in Table 1. More details can be found in Facchi *et al.* (2013).

To estimate the evapotranspiration in water-stressed condition $ET_{c\ adj}$, ET_c must be multiplied by a stress coefficient K_s, which depends on the average soil water content in the root zone as calculated by a daily water balance (Allen *et al.*, 1998).

Since the simple balance model proposed by FAO-56 does not take into account adequately the capillary rise, the "single crop coefficient" approach was applied in this study only for 2006 (for which $ET_{c\ adj}=ET_c$). As a matter of fact, the capillary rise is very important in soil water-stressed conditions when the water table depth is very shallow, as for the experimental site.

The FAO-56 "double crop coefficient" model

In the FAO-56 "double crop coefficient" approach (Allen *et al.*, 1998) the separation between the soil evaporation and the crop transpiration fluxes is achieved by splitting the K_c in two different coefficients: the basal crop (K_{cb}) and the soil evaporation (K_e) coefficients, the latter being calculated as a function of the basal crop coefficient and other variables. As for the "single crop coefficient", crop development stages and the corresponding K_{cb} ($K_{cb\ ini}$, $K_{cb\ mid}$, $K_{cb\ end}$) values are tabulated in FAO-56. In the case of soil water stress, $ET_{c\ adj}$ is calculated from ET_c considering the two stress coefficients K_s and K_r respectively computed from the average water content in the transpirative and in the evaporative zone by daily water balances (Allen *et al.*, 1998).

In this study, K_{cb} curves for 2006 and 2011 were built by considering the growing periods length observed in the field and the tabulated K_{cb} values after the adjustments suggested by Allen *et al.* (1998). The resulting values are reported in Table 1.

The calculation of daily K_r and K_s values was carried out with the support of the ALHyMUS model (Gandolfi *et al.*, 2006; Baroni *et al.*, 2010), computing ET_c on the basis of the "double crop coefficient" proposed by FAO-56. In this model, capillary rise is simulated following Liu *et al.* (2006).

Time step and performance indicators

Eddy covariance ET measurements were used to test the models performance for the two datasets at the daily time step. The PM and SW models were applied at the hourly time step, to determine the daily ET amount the sum of hourly daytime outputs (R_n>0) was then carried out. Since the FAO-56 "single" and "double crop coefficient" models were implemented using daily ET_0 estimates, they provided directly the daily ET values.

The statistical evaluation of the models' performance was carried out evaluating the linear correlation between observed and measured data (slope of the regression, M, and regression coefficient, R^2, were considered) and calculating the root mean square error (RMSE), the mean relative error (MRE) and the Nash-Sutcliffe Efficiency (NSE) indices.

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(C_i - M_i)^2\right]^{\frac{1}{2}} \tag{6}$$

$$MRE = \frac{1}{N}\sum_{i=1}^{N}\frac{(C_i - M_i)}{M_i}100 \tag{7}$$

$$NSE = 1 - \frac{\sum_{i=1}^{N}(C_i - M_i)^2}{\sum_{i=1}^{N}(M_i - M_{avg})^2} \tag{8}$$

Results and discussion

Development of a new LAIeff function for maize crop

With the aim of identifying a new and more general equation for LAI_{eff} for maize crop, five ET data series measured by the eddy covariance technique were considered. Alongside the data series measured at Landriano in 2006 and 2011, also the one (incomplete) acquired in 2010 at the same site and the two measured in 2010 and 2011 at the Livraga experimental site (45°11' N, 9° 34' E, 60 m a.s.l.) were used. For more information about the datasets refer to Facchi *et al.* (2013). The need to identify a new function emerged because the Gardiol *et al.* (2003) model, which showed to work well for the 2006 dataset (Gharsallah *et al.*, 2013), led to an unacceptable LAI_{eff} pattern for 2011, characterized by a fast increase in the LAI_{eff} value for LAI≥4. As a matter of fact, the maximum LAI value measured in 2006 was around 4 $m^2\ m^{-2}$, while in 2011 this parameter reached a value of about 6 $m^2\ m^{-2}$.

Once daily ET data were obtained for the five eddy covariance datasets, ET values for days characterized by soil water stress conditions were eliminated. Soils were considered in water conditions preventing the occurrence of evapotranspirative stress when the average water content in the rooting depth is higher than 0.15 m^3m^{-3} and 0.22 m^3m^{-3} respectively for the Landriano and Livraga sites (Facchi *et al.*, 2013).

Crop resistance r_c was obtained for each day by inverting the PM equation following the Monteith approach for r_c. The obtained r_c, as well as the measured LAI values, were then plotted in function of the cumulative ground degrees days (GDD) starting from the seeding date

Table 1. Crop stages length observed in the field and K_c and K_{cb} adjusted considering local data.

Parameter	2006	2011
L_{ini}	25	29
L_{dev}	26	40
L_{mid}	56	51
L_{late}	27	26
$K_{c\ ini}$	0.29	0.28
$K_{c\ mid}$	1.16	1.14
$K_{c\ end}$	1.16*	0.57
$K_{cb\ ini}$	0.15	0.15
$K_{cb\ mid}$	1.11	1.09
$K_{cb\ end}$	1.11*	0.52

* crop was harvested green

(Facchi *et al.*, 2013). The use of GDD instead of the number of days reduces the data dispersion due to the different climatic conditions, and allows to consider data of a second crop maize (Landriano 2006) together with those of a first crop maize. The obtained data are shown in Figure 1.

Two approaches for the estimation of LAI_{eff} are proposed. The first one can be applied when measured LAI values are available. In that case, the Gardiol *et al.* (2003) model is modified as follows: $LAI_{eff}=LAI$ for $LAI\leq 2$, $LAI_{eff}=2$ until the end of the middle season stage, LAI_{eff} linearly decreasing from 2 to 0.3 in the case of a complete senescence, to 0.35 for a dough stage harvesting, to 0.5 for silage maize.

The second approach can be adopted when measured LAI data are not available: $LAI_{eff}=0.2$ for initial stage (L_{ini}), LAI_{eff} between 0.2 and 2 for the crop development stage (L_{dev}), $LAI_{eff}=2$ for the middle season stage (L_{mid}), and LAI_{eff} as in the first approach for the late season stage (L_{late}).

Comparsion of ET models under well-watered conditions (2006)

Results of the models application and performance indices are reported in Figure 2 and Table 2.

All the "direct" approaches for ET estimation provide a very good agreement with the observations during the entire agricultural season. In particular, as expected given the lack of soil water stress conditions, the result provided by the model of PM with r_c by Jarvis is very close to that obtained with r_c by Monteith. Slightly lower performances are provided by the PM model with r_c by KP, even if the result is very satisfactory considering that the parameters a and b were calibrated using an independent data set (*i.e.* 2011). The SW model shows the best performance, behaving well also for days with sparse canopy and peak evaporation rate following irrigation and rainfall events. ET values estimated with the "single" and "double crop coefficient" approaches are higher than the observed, probably because of the excessively high values of K_c and K_{cb} obtained following the methodology FAO-56 when compared with those obtained from experimental observations in Northern Italy (Facchi *et al.*, 2013).

Comparsion of ET models under water-stressed conditions (2011)

Figure 3 and Table 3 show the performances of ET models under water-stress conditions, which basically confirm the results obtained

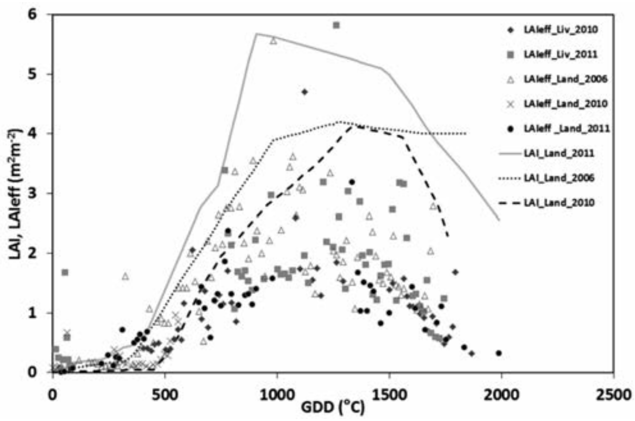

Figure 1. LAIeff derived from field measurements, measured LAI and average LAI_{eff}.

Table 2. Performance indices calculated for the ET models at Landriano in 2006.

ET models	M	R2	RMSE	MRE	NSE
PM (rc Monteith)	0.98	0.86	0.52	-1.25	0.87
PM (rc Jarvis)	0.96	0.86	0.53	-3.20	0.86
PM (rc KP)	1	0.73	0.69	9.56	0.76
SW	1.05	0.93	0.42	7.43	0.91
FAO-56 "single crop"	1.12	0.82	0.79	16.8	0.68
FAO-56 "double crop"	1.24	0.82	1.17	23.53	0.31

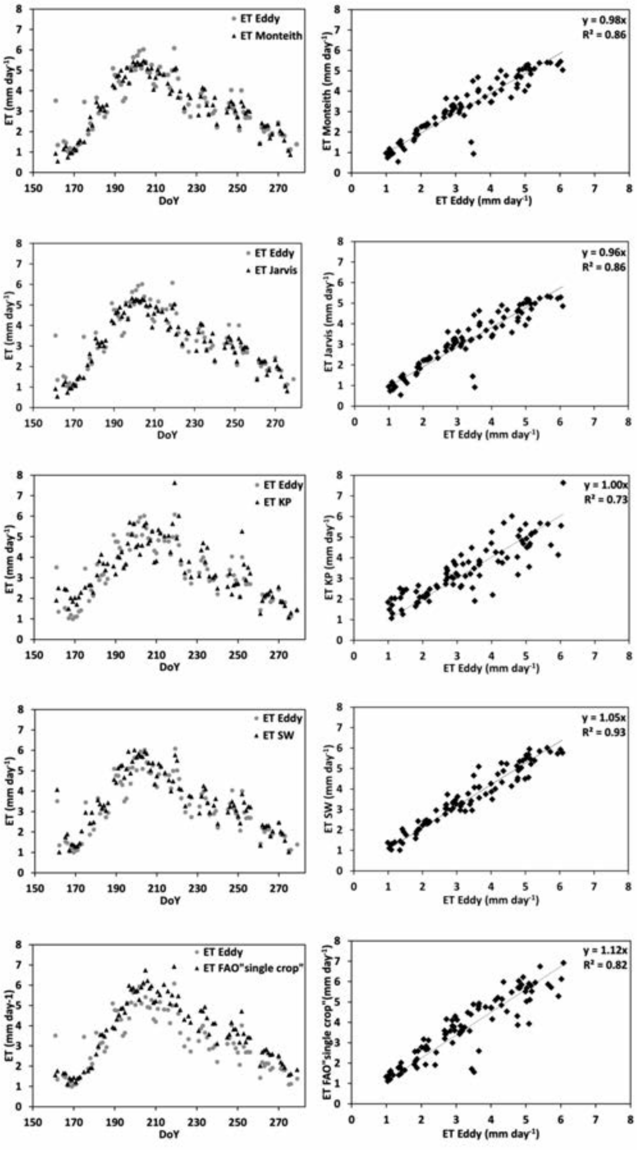

Figure 2. On the left: daily ET estimated by the different ET models and measured by the eddy covariance technique at Landriano in 2006. On the right: correlation between the measured and estimated data series.

Table 3. Performance indices calculated for the ET models at Landriano in 2011.

ET models	M	R^2	RMSE	MRE	NSE
PM (r$_c$ Jarvis)	0.97	0.56	0.65	2.75	0.72
PM (r$_c$ KP)	1.01	0.74	0.51	7.89	0.78
SW (r$_c$ Jarvis)	0.99	0.67	0.56	6.78	0.73
FAO-56_adj“double crop”	1.16	0.68	1.05	267.43	0.04

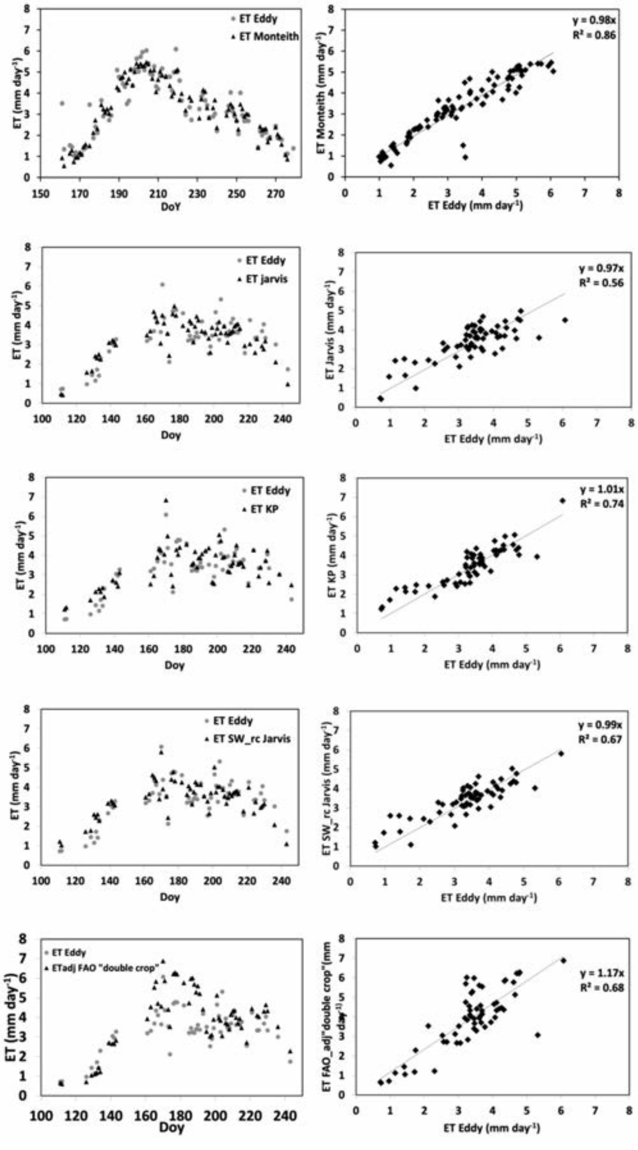

Figure 3. On the left: daily ET estimated by the different ET models and measured by the eddy covariance technique at Landriano in 2011. On the right: correlation between the measured and estimated data series.

under well-watered conditions, with the “direct” approaches giving the best results. It can be noted that the PM equation with r$_c$ modelled following KP gives the best results, outperforming the PM with r$_c$ by Jarvis, probably because the parameters a and b were calibrate using data of the 2011 dataset. Anyway, the performances for the three “direct” methods are comparable. As in the well-watered case, the performance of the FAO-56 model is the poorest.

A comparison between indices in Table 2 and Table 1 shows that in water-stressed conditions, even if the index values indicate good performances for all the “direct” models, these are slightly lower than those found for the well-watered case. In particular, the dispersion around the regression line increases, especially - but not only - at lower ET values (with a decreasing of R^2), and the NSE values are higher. This can be explained by the fact that in water-stressed condition ET deviates from its potential value, becoming more difficult to estimate, since it starts to depend from a higher number of factors.

Conclusions

The main findings of this study are: i) in absence of calibration of the crop parameters, direct methods provide better performances than the indirect methods, confirming the findings of several authors in the literature; ii) the use of a new and simple function for estimating LAI$_{eff}$ for a maize crop in the different growth stages, proposed in this study, improves the performances of direct models at high values of LAI, compared to the most widely used functions reported in the literature; iii) the SW model is a robust model providing very good performance for the entire agricultural season under different soil water status conditions, but it requires complex procedures to estimate the various resistances involved; iv) the one-layer PM equation also provides good results in well-watered and water-stressed conditions with r$_c$ by Jarvis and KP; v) the “single” and “double crop coefficient” FAO-56 models overestimate ET for the entire agriculture season; this is due to the fact that the crop coefficients, even if adjusted with local data, are overestimated, pointing to the necessity of determining site-specific crop coefficients ; vi) the main obstacle to the routine use of direct approaches, such as both PM and SW models, is the need of micrometeorological measurements taken above the crop (*e.g.*, R$_n$, VPD, wind speed) and the lack of consolidated information on surface resistances for the different crops, which call for further research to make these methods more applicable operatively.

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