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Performance evaluation of evapotranspiration estimations in a model of soil water balance

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ABSTRACT: Soil water content models have huge applications from an agronomic point of view and they are usually used as a sub-model for weather and climate modelling. They are also useful tools for efficient water management irrigation practices. The aim of this investigation is to evaluate the performance of two different parameterizations of evapotranspiration when applied to a soil water balance model. Experimental data of a maize crop is used to evaluate model accuracy. The first methodology proposes a parallel resistance arrangement to represent the latent heat fluxes of the soil surface and the leaves in the canopy layer considering the leaf area index (LAI). The second methodology uses the parameterization proposed by the United Nations Food and Agriculture Organization (FAO), based on the crop coefficient (K_c) and the potential evapotranspiration obtained from the Penman–Monteith equation. The crop was divided into five plots with different irrigation systems according to their phenological stages. The model suitably predicts daily soil water content in five different irrigation systems. Predictions of soil water content using the LAI or K_c methodology tend to overestimate observations. In addition, the model has better predictions using the LAI methodology than the K_c methodology. The root mean square error and the determination coefficient were 0.059 and 0.92, respectively, with the LAI methodology and 0.063 and 0.87, respectively, using the K_c methodology. Copyright © 2010 Royal Meteorological Society

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1. Introduction

The necessity of increments in crop productivity implies that it is essential to analyse the limiting factors for improving yields. Water stress affects a crop depending on its phenological stage. Many experimental studies have been conducted to identify its impact on corn yield. Water stress occurring between about 2 weeks before and 2 weeks after corn silking (R1 stage – female flowering according to the phenological classification expressed by Ritchie and Hanway, 1982) will result in larger grain yield reduction than similar stress at any other period during the growing season (Ritchie and Hanway, 1982; Grant *et al.*, 1989; Rhoads and Bennet, 1990). This is because water stress may cause a lag between pollen shedding and ovule development, with a consequent reduction in the fertilized ovules to generate grains (Hall *et al.*, 1981; Otegui *et al.*, 1995; Andrade *et al.*, 1996). Although not as severe as at R1, stress during grain filling (R3 and later stages) can still have some effect on yield by shortening the period of dry matter accumulation in the grains (Andrade *et al.*, 1996). During ripening, the reduction of potential yield caused by water stress is diminished (Ritchie and Hanway, 1982).

The Argentinean Pampas is one of the most important temperate areas of South America for crop production and grain production is conducted there predominantly without irrigation (Hall *et al.*, 1982). However, crop evapotranspiration exceeds rainfall during a major part of the growing cycle in summer crops (Stewart and Nielsen, 1990). This means that the crop yield depends on the stored water in the soil and the capacity of the roots to extract it. Experimental studies in the southeast of Buenos Aires Province (Argentina) revealed that maize plots exposed to water stress suffered a yield loss of 20–40 kg ha^{-1} *per* mm of reduction of water extracted from soil (Otegui *et al.*, 1995; Andrade and Sadras, 2000). The highest yield losses occurred when severe water stress was imposed around silking.

Several agrometeorological experiments have been conducted in this region. The experimental field is

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divided into several plots, each with different irrigation systems. Effects of these treatments on yield (Della Maggiora *et al.*, 2000) and soil hydraulic properties (Serio *et al.*, 2004) have previously been reported. Della Maggiora *et al.* (2000) found that different water availabilities alter the phenological evolution of the crop. Water stress around flowering means that physiological maturity is reached 7 days later compared to reference treatments. Water stress during grain filling means that physiological maturity is reached 6 days earlier than in well-watered treatments. The transpiration rate decreased between 35 and 55% depending on the severity and the period of water deficit. Most importantly, a reduction in grain yield of 34% occurred after severe water stress around flowering. Serio *et al.* (2004) applied empirical functions to estimate the vertical and temporal distribution of soil matric potential and hydraulic conductivity and the effects of water stress on these properties. Distribution patterns of both variables indicated that roots extracted water from deeper layers of soil. Therefore, water stress is related to soil water content.

Models of soil water content are useful for obtaining a greater productivity and to improve soil and water management practices. A continuously well-watered crop will give a better yield. Knowledge of the soil water status during the growing season is required to determine the optimal management practices to maximize yield with minimum impact on soil and water resources.

Measurement of soil water content can be very costly and time consuming, and the utility of observational data presents limitations by its inherent temporal and spatial variability (de Jong and Bootsma, 1996). Consequently, monitoring soil water content is often replaced with estimation methods. There are two main methodologies for modelling soil water content: volumetric balance models (Rao, 1987; Rao *et al.*, 1988, 1990; George, 1997; Hajilal *et al.*, 1998) and dynamic models (Lee and Abriola, 1999; Wilderotter, 2003). The first model is the most widely used since it has the advantage of being simpler, needing fewer input variables and can be used at the local scale, but it offers spatially averaged information and temporal resolution is as high as a day. Volumetric balance models are based on the principle of mass conservation within a soil thickness that acts as a water reservoir whose bottom limit is the maximum depth of the roots. Dynamic models, on the other hand, have the advantage of offering a greater amount of spatial and temporal information, but they also need a greater amount of initial data to solve the equations, with greater computational cost (Stockle and Nelson, 1998; Vieux, 2004).

Irrigation, precipitation and evapotranspiration (ET) are the main variables for determining soil water content. The amount of precipitation is determined by weather conditions. Weather also has a great influence on evapotranspiration. The largest component in the loss of water content in the soil-plant system is often evapotranspiration (Critchfield, 1983). The demand of water by the atmosphere in terms of climatic characteristics is the potential evapotranspiration (PET). It represents the maximal evaporation rate at which the atmosphere is capable of extracting from a well watered field with a reference crop (short grass), usually referred to as 'potential conditions'.

The daily rate of actual evapotranspiration (AET) from an annual crop could seldom equalize PET. Soil water availability, crop density and growth stage affect AET. Even in well-watered soil, in the case of an annual crop, the seasonal total AET will not equal total PET, being around 0.6–0.9 of it. AET in a soil-plant system without limiting water availability is known as maximum evapotranspiration (MET). During the different stages of growth MET can be greater or lower than PET. To obtain the highest possible yields of many agricultural crops, water could be provided through irrigation systems to prevent it acting as a limiting factor. The seasonal total AET can vary between 0.5 and 1.0 of total MET, depending on the soil water content (Allen *et al.*, 1998).

ET is difficult to measure in the field. This component of the hydrological cycle is usually obtained in cropping systems through indirect methodologies such as the Penman–Monteith (P–M) equation (Allen *et al.*, 1998; Foken, 2008), the crop coefficient methodology (Allen *et al.*, 1998) or some physical models (Shuttleworth and Wallace, 1985; Gardiol *et al.*, 2003).

The aim of the present study is to evaluate the performance of two different types of ET models coupled with a volumetric soil water balance model (Panigrahi and Panda Sudhindra, 2003). Field data were used to simulate soil water content in a maize plot with five different water management systems. Daily values of soil water content during the most important stages of the crop cycle were calculated using the two different parameterizations of ET. The model is validated with observational data of soil water content for a layer of approximately 1.0–1.2 m depth.

2. Experimental site

A field campaign was conducted in a maize crop in the area of Balcarce, Buenos Aires province (Argentina) during the 1998/1999 summer season. Data were collected during the field experiment at the Unidad Integrada Facultad de Ciencias Agrarias UNMdP - EEA INTA Balcarce (37°45′S, 58°18′W; 130 m a.m.s.l.). Mean annual precipitation in Balcarce is around 910 mm. Maize (Dekalb 639) was planted on 16 October with a density of 85 714 pl ha^{-1} at a 0.7 m row spacing on a loam soil (illitic thermic loam petrocalcic Paleudoll). The crop was controlled to be pest and disease free. The simulation was performed between 27 November 1998 and 1 March 1999 (94 days).

The plot was split into five sections, each with different irrigation systems and four replications were made for each section. The phenological classification for maize of Ritchie and Hanway (1982) is used to classify different growing periods of maize plants. The division of the plot was carried out to study the behaviour of the

Table I. Humidity percentage lower limits required for soil water potential conditions (% of AW) in the 0–0.6 m soil depth during different sub-periods of the growing season.

Treatment	Sub-period		
	Vegetative (before V12)	Flowering (V12–R2)	Grain filling (after R2)
IIIU	50	70	50
IIIC	50	70	50
I01IC	50	50	50
I02IC	50	30	50
II01C	50	70	30

IIIU, uncovered well-watered treatment; IIIC, covered well-watered treatment; I01IC, covered treatment with water stress period during flowering; I02IC, covered treatment with water stress period during flowering; II01C, covered treatment with water stress period during grain filling.

V12 and R2, phenology classification according to Ritchie and Hanway (1982).

crop when subjected to water deficiencies during different stages of the maize cultivation (Serio *et al*., 2004). In each section of the plot, different quantities of water were distributed to maintain the soil's humidity within the prefixed limits during the three specific periods of the crop's development: the vegetative phase (V1–V12), the flowering phase or the first reproductive phases (V12–R2) and the growth or filling of fruits and ripening stage (R2 onwards). The flowering phase is the one in which the plant has the greatest water requirements (Serio *et al*., 2004). Three plots were used to achieve water stress during one of the three periods considered. The soil was covered with black polyethylene of 100 µm thickness in order to insulate it from rainfall. In two of these plots water stress was applied during the flowering phase (second period) with two different types of irrigation treatment (I01IC and I02IC). The third plot was used to achieve water stress during the grains' growth and ripening stage (third period) (II01C). Two plots with (IIIC) and without (IIIU) polyethylene film cover received irrigation to maintain the soil humidity in potential or reference conditions during the three respected periods. Table I shows the required humidity percentage lower limits in the soil for each treatment in each one of the three periods of development. Covered plots were irrigated using the sprinkle method.

Maize was fertilized with 150 kg ha^{-1} nitrogen when plants were in the V6 phenological stage. Dates of phenological stages for the different treatments are shown in Figure 1. During the experimental period, the rainfall in IIIU was 93.1 mm and it was supplemented with 225.3 mm of irrigated water. Covered plots were irrigated with 320.0 mm (IIIC), 217.5 mm (I02IC), 216.5 mm (I01IC) and 129.1 mm (II01C) of water.

Soil water content was measured at 2–5 day intervals using the gravimetric method in the 0–0.1 m layer and using a neutron probe (Troxler 4300 Neutron Probe, Troxler E. L. Inc., Res. Triangle Park, NC) at seven depths from 0.1 to 1.2 m in the five plots. Meteorological data were collected at the INTA Balcarce agrometeorological station, located 300 m from the plots. The biomass of plants was also measured six times at selected phenological stages during the growing season. The total green leaf area of the sample was estimated from the green leaf area of a subsample measured with an area meter (model LI-3000, Li-Cor Inc., Lincoln, NE), multiplying the measured leaf area by the ratio between the dry weight of leaves of the sub and total samples. The green leaf area index was obtained by multiplying the mean green leaf area *per* plant by the number of plants *per* square metre. The dry weight of the leaves was determined using the gravimetric method.

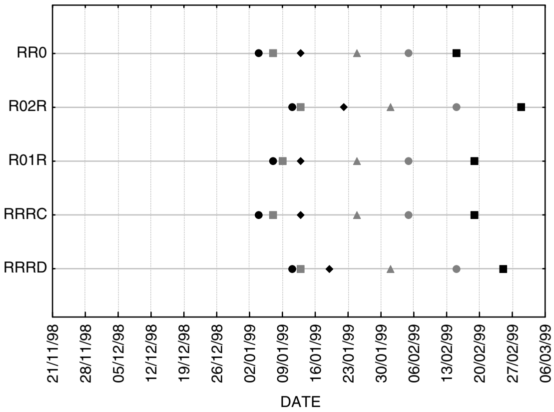

Figure 1. Phenology stage for the five plots with different water treatments (according to Ritchie and Hanway, 1982). Vegetative (V) and reproductive stages (R): (VT) (●), R1 (■), R2 (◆), R3 (▲), R4 (●) and R5 (■).

3. Soil water balance model description

The model considers a soil depth divided into two layers. The upper layer is the active root zone, where the plants have already grown. The limits of the passive root zone are the bottom of the active root layer and the maximum depth that roots can grow to. In the first layer the water balance is calculated taking into account the inputs (precipitation and irrigation) and the outputs (runoff, ET and percolation) of water in the system. In the second layer only percolation and deep percolation act as input or output of water through the layer. Effects of upward capillary flow into the root zone are not considered. The daily value of soil water content was simulated as:

$$\begin{aligned} SWC_i Ra_i &= SWC_{i-1} Ra_{i-1} + P_i + Ir_i \\ &\quad + \Delta Ra_i SWC0_{i-1} - Pe_i - AET_i - Rf_i \end{aligned} \tag{1}$$

where i is the sub index meaning days after seeding, SWC is the soil water content in the active root zone (mm cm^{-1}), SWC_0 is the soil water content in the passive root zone (mm cm^{-1}), Ra is the active root depth (cm), P is precipitation (mm), Ir is irrigation (mm), ΔRa is the daily increase of the active root depth (cm), Pe is the

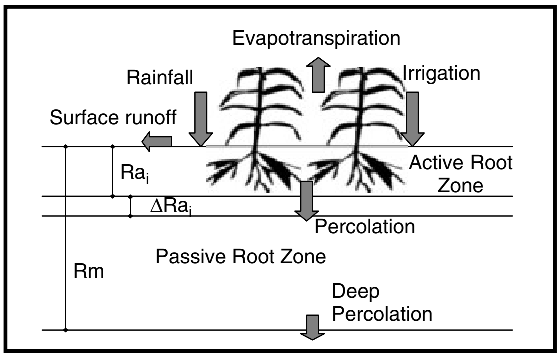

Figure 2. Representation of the soil–plant–atmosphere system and water balance components.

amount of water percolated from the active to the passive root depth (mm), AET is measured in mm and Rf is the surface runoff (mm) (Figure 2). A brief description of the model is presented.

3.1. Active root depth

The thickness of the active root layer is estimated with a sinusoidal function of time measured starting at seeding (t_i):

$$Ra_i = Rm\,(0.5 + 0.5\ \sin(3.03\,(t_i/tm) - 1.47)) \quad (2)$$

where Rm is the maximum depth of roots and tm is the number of days needed for full root growth, which was considered to be the date that the plants are in bloom. According to field observations the values of tm varied between 83 and 88 days for the different treatments. The maximum root depth (Rm) for maize was considered up to 1.2 m (mean depth of the caliche level in Balcarce).

3.2. Percolation and deep percolation

Percolation is calculated as the difference between the amount of incoming water in the layer and field capacity:

$$Pe_i = (P_i + Ir_i - Rf_i) - [(FC - SWC_{i-1})Ra_{i-1} + (FC - SWC0_{i-1})\Delta Ra_i] \quad (3)$$

where FC is the field capacity (mm cm^{-1}). Negative values of Equation (3) were assumed as no percolation and therefore the soil water content in the passive root layer remains unchanged with the time step. An increase in $SWC0$ is caused by positive percolation:

$$SWC0_i = \begin{cases} SWC0_{i-1} & Pe_i \le 0 \\ SWC0_{i-1} + \dfrac{Pe_i}{Rm - Ra_i} & Pe_i > 0 \end{cases} \quad (4)$$

If the amount of water in the passive root layer exceeds the field capacity, then deep percolation will occur. In those cases, the value of $SWC0$ is corrected to field capacity and the excess of water simply leaves the system.

3.3. Surface runoff

The Curve Number (CN) technique (Chow *et al.*, 1988) from the Natural Resources Conservation Service (NRCS) (USDA, 2004) provides an approximated methodology to estimate the volume of precipitation that the system loses through surface runoff. Land use, soil texture, agricultural and hydrological conditions and management practices are taken into account. Soil Hydrological Groups are assigned to soil series using the criteria found in the NRCS National Engineering Handbook. The CN associated to the complex soil cover are median values, roughly representing the average conditions in a field. It was assumed that this methodology could be applied in the area of the Buenos Aires province. The runoff estimation is given by:

$$Rf_i = \frac{(P_i - 0.2s)^2}{P_i + 0.8s} \quad (5)$$

where s is the maximum potential retention at the initial time of the storm (mm) and is related to CN through the following expression:

$$s = 254\left(\frac{100}{CN} - 1\right) \quad (6)$$

The CN value used was obtained from the available tables. Soil hydrological group was assigned by considering texture, depth, slope and land cover. Straight row crops and good hydrological conditions were considered upon determining the curve number. Soils with moderate infiltration rate with wet conditions correspond to group B of the USDA (2004) soil classification. Water movement through these soils is moderately rapid. The corrections proposed by Sharpley and Williams (1990) were applied according to the available water. Days with precipitation lower than $0.2 \times s$ (initial abstraction of water) were considered to be without runoff. Maximum potential retention of the soil has not been studied in this area of Argentina. Therefore, it is supposed that the parameterization provided by Equation (6) is valid in the region.

3.4. Actual evapotranspiration

AET was estimated on the basis of the MET of the crop using two different methodologies to perform an evaluation of them in the soil water balance model.

The model suggested by Gardiol *et al.* (2003) was used to calculate soil maximum evaporation and plant transpiration separately. This is a double-layer model based on the resistance theory (Monteith, 1976). It proposes a parallel resistance arrangement to represent the latent heat flux from the soil surface and plant leaves in the canopy:

$$ET = \alpha E + T \quad (7)$$

where α is a weighting factor for soil evaporation (E) according to vegetation density and T represents the plant's transpiration. E and T were obtained according to Gardiol *et al.* (2003):

$$\lambda T = \frac{\Delta\left(R_n - R_n^s\right) + \rho c_p D\left(r_a^a + r_a^c\right)}{\Delta + \gamma\left(1 + r_s^c/\left(r_a^a + r_a^e\right)\right)} \tag{8}$$

$$\lambda E = \frac{\Delta\left(R_n^s - G\right) + \rho c_p D\left(r_a^a + r_a^s\right)}{\Delta + \gamma\left(1 + r_s^s/\left(r_a^a + r_a^s\right)\right)} \tag{9}$$

where λ is the latent heat of water vapourization (J kg^{-1}), ρc_p the volumetric air heat capacity (J K^{-1} m^{-3}), γ the psychrometric constant (hPa K^{-1}), Δ the slope of saturation water vapour pressure/temperature curve (hPa K^{-1}), D the air water vapour pressure deficit (hPa), R_n the net radiation flux above the canopy (W m^{-2}), R_n^s the net radiation flux at the soil surface (W m^{-2}), G the soil heat flux (W m^{-2}), r_a^c the bulk boundary layer resistance of a representative canopy element (s m^{-1}), r_s^c the bulk stomatal resistance of the canopy (s m^{-1}), r_a^a the aerodynamic resistance between the canopy and the reference height (s m^{-1}), r_a^s the aerodynamic resistance between the soil and mean canopy height (s m^{-1}) and r_s^s the surface resistance of the soil (s m^{-1}). Resistances were parameterized as functions of micrometeorological variables (surface roughness, zero-displacement plane height) and the leaf area index (LAI). The application of these equations is referred to in this paper as the 'LAI methodology'.

Maximum evapotranspiration was modelled using the standard reference crop evapotranspiration methodology based on the P–M equation (Allen *et al.*, 1998):

$$PET = \frac{\Delta(R_n - G) + \rho c_p D/r_a^a}{\Delta + \gamma(1 + r_s^c/r_a^c)} \tag{10}$$

The values of resistances were those suggested by Allen *et al.* (1998). There were no limitations on evapotranspiration from water of the reference crop and on crop's growth due to salinity stress, crop density, pests and diseases or low soil fertility. MET was subsequently determined using the crop coefficient approach, where the effect of weather conditions are incorporated into PET and the crop characteristics into the crop coefficient (K_c):

$$MET = K_c PET \tag{11}$$

Crop coefficients for a corn crop in standard conditions for Balcarce were developed by Della Maggiora *et al.* (2003). This method will be referred from now on as the 'K_c methodology'.

AET of the crop is obtained from MET using the following equation:

$$AET_i = \frac{(SWC_i - WP)}{(1 - pa)AW} MET_i \quad \text{if} \quad SWC_i - WP < (1 - pa)AW \tag{12a}$$

$$AET_i = MET_i \quad \text{if} \quad SWC_i - WP \geq (1 - pa)AW \tag{12b}$$

where WP is the wilting point of the crop (mm cm^{-1}) and the available water is defined as $AW = FC - WP$. Equation (12a) represents AET with water stress condition while Equation (12b) represents conditions without water stress. The coefficient pa is the average fraction of total available soil water that can be extracted from the root zone before moisture stress occurs (reduction in evapotranspiration), which differs by crop, soil and root system. The fraction pa is a function of the potential of evaporation of the atmosphere. A constant value is often used for a specific growth period of plant, rather than vary the value by day (Allen *et al.*, 1998). Nevertheless, it is a factor that has great complexity when applied at different stages of the crop, since it provides information about the minimum proportion of the available water to maintain the crop in water potential conditions. The atmospheric conditions during the cycle of cultivation play an important role in the variability of the development and growth of crops from 1 year to another. The stage of development, the available nutrients and the phytosanitary state of the crops are variables that intervene on a larger or smaller scale to define the most appropriate value of pa. Two different values of pa were used during the simulation period (Figure 3). It was considered that during the initial and final stages of the crop, field conditions will be maintained until 50% ($pa = 0.5$) of AW, while during the period of maximum growth rate (around bloom stage) the value changes to 65% ($pa = 0.35$). These values were selected taking into account values of soil humidity considered in Table I.

3.5. Model evaluation

A detailed set of statistical parameters was used to analyse the model results against observed data (Fox, 1981; Willmott, 1982) and was also used to test the agronomical models (Ferrer *et al.*, 2000; Singh *et al.*, 2008). The proposed statistics are a measurement of the model errors. In many cases, a summary of statistics and graphical analyses are the best tools to evaluate the model performance with predicted (P) and observed (O) values.

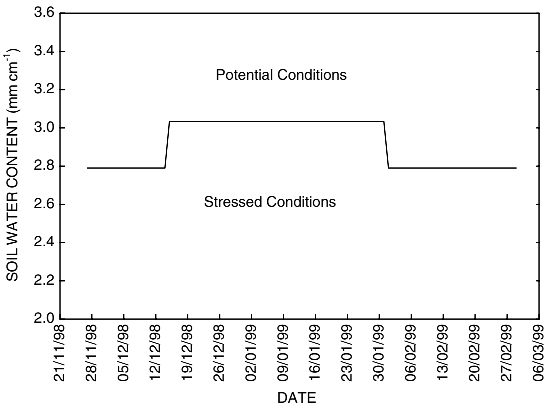

Figure 3. Box function proposed for determining soil water content potential conditions.

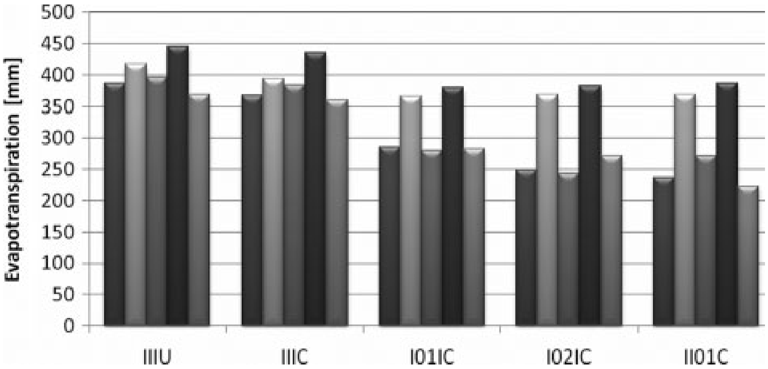

Figure 4. Comparison of AET and MET, LAI and K_c methodologies for MET estimation, and values of AET observed with neutron probe (AETo) in all treatments. For each treatment bars in order represent: AET(LAI), MET(LAI), AET(K_c), MET(K_c) and AETo.

The coefficient of determination is defined as:

$$r^2 = \frac{\mathrm{cov}^2(O, P)}{{\sigma_O}^2{\sigma_P}^2} \tag{13}$$

where cov(O,P) is the covariance between O_i and P_i, and σ_O, σ_P are the standard deviation of the observed and predicted data. A value near 1 indicates a good prediction.

The average of the predicted ($\overline{P}$) and observed ($\overline{O}$) values of the soil water content are needed for the estimation of this statistic.

Mean Bias Error (*MBE*) or the first moment of the distribution of differences shows the general bias of the model predictions:

$$MBE = \frac{\sum_{i=1}^{n}(P_i - O_i)}{n} \tag{14}$$

This statistic is very sensitive to extreme values.

The Root Mean Square Error (*RMSE*) represents the mean value of the residuals:

$$RMSE = \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}\right]^{0.5} \tag{15}$$

The Fractional Bias (*FB*) describes the underestimation or overestimation of a predicted variable in relation to the observed value:

$$FB = \frac{\overline{O} - \overline{P}}{0.5(\overline{O} + \overline{P})} \tag{16}$$

If $FB < 0$, the model underestimates the real values, while if $FB > 0$, the model produces overestimations. In addition, these statistics have the same absolute numerical value for an overestimation of n times the mean value (positive) or an underestimation of 1/n times this value (negative). A model with good performance should have small error values.

4. Discussion

4.1. Simulations of evapotranspiration

Actual evapotranspiration is overestimated by both methodologies in good hydrological conditions (IIIU and IIIC). The accumulated values of evapotranspiration (both actual and maximum) estimated along the study period are presented for both methodologies (Figure 4). The measured values of actual evapotranspiration were: 368.9 mm (IIIU), 360.2 mm (IIIC), 283.4 mm (I01IC), 271.5 mm (I02IC) and 222.5 mm (II01C). The difference between AETo for IIIU and IIIC represents the amount of soil evaporation during the experimental period (~6.7 mm).

Estimated values of AET were, on average, 1.2% (LAI) and 5.0% (K_c) greater than the observed ones. For systems with water stress conditions, the LAI and Kc methodologies produce greater (II01C) (6% LAI and 22% K_c), equal (I01IC) and less (I02IC)(8% LAI and 10% K_c) values of accumulated AET in the period studied than the observations (Table II). K_c methodology estimated greater values of MET than the LAI methodology.

4.2. Soil water balance model

Daily values of soil water content were calculated for a 1 m depth layer for the non-stressed treatments (IIIU and IIIC) and 1.2 m layer for the stressed ones (I01IC, I02IC

Table II. Estimated relative values of actual evapotranspiration (AET) and maximum evapotranspiration (MET) applying the LAI and K_c methodologies.

	IIIU	IIIC	I01IC	I02IC	II01C
AET (LAI)	1.05	1.02	1.01	0.92	1.06
MET (LAI)	1.13	1.09	1.29	1.36	1.66
AET (K_c)	1.07	1.07	0.99	0.90	1.22
MET (K_c)	1.21	1.21	1.34	1.41	1.73

Reference value: observed actual evapotranspiration (AETo). IIIU, uncovered well-watered treatment; IIIC, covered well-watered treatment; I01IC, covered treatment with water stress period during flowering; I02IC, covered treatment with water stress period during flowering; II01C, covered treatment with water stress period during grain filling.

Table III. Observed values or precipitation and irrigation (mm day^{-1}) for the five treatments.

Date	IIIU			IIIC	I01IC	I02IC	II01C
	PP	Irrigation	Runoff	Irrigation	Irrigation	Irrigation	Irrigation
3 December 1998	4.5	12.5	–	12.5	–	–	–
12 December 1998	–	–	–	13.5	–	–	13.5
13 December 1998	12.0	10.0	0.7	–	–	–	–
14 December 1998	–	–	–	17.0	–	10.0	–
15 December 1998	3.8	–	–	–	–	–	–
16 December 1998	–	–	–	–	21.0	–	–
19 December 1998	–	–	–	9.5	–	–	9.5
21 December 1998	–	–	–	21.0	–	–	–
22 December 1998	–	–	–	5.0	–	–	–
23 December 1998	–	–	–	3.0	–	3.0	18.0
24 December 1998	–	20.0	–	7.0	5.0	–	5.0
25 December 1998	–	–	–	–	–	7.0	–
27 December 1998	5.5	–	–	13.0	–	13.0	–
28 December 1998	7.3	13.0	–	9.5	13.0	–	13.0
29 December 1998	0.3	–	–	–	–	23.0	9.5
31 December 1998	–	6.0	–	6.0	2.0	–	6.0
1 January 1999	1.4	–	–	–	–	–	–
3 January 1999	1.7	–	–	–	–	–	–
5 January 1999	–	8.5	–	8.5	–	–	–
7 January 1999	–	7.0	–	7.0	–	–	7.0
8 January 1999	4.5	5.5	–	5.5	5.5	–	5.5
11 January 1999	–	–	–	–	13.0	13.0	–
12 January 1999	–	4.0	–	4.0	–	–	–
13 January 1999	–	–	–	8.0	–	2.7	–
14 January 1999	–	–	–	5.0	5.0	–	–
15 January 1999	–	–	–	–	7.0	–	–
16 January 1999	–	14.5	–	14.5	–	–	–
19 January 1999	–	–	–	12.0	–	–	12.0
20 January 1999	–	12.0	–	–	–	–	–
22 January 1999	–	6.0	–	6.0	6.0	35.0	–
23 January 1999	29.6	–	1.9	9.0	9.0	–	–
24 January 1999	–	9.0	–	–	–	–	–
28 January 1999	–	–	–	12.0	–	–	–
29 January 1999	–	10.0	–	–	12.0	–	–
30 January 1999	7.5	–	–	–	–	–	–
1 February 1999	–	–	–	6.0	4.0	–	–
2 February 1999	–	–	–	6.0	6.0	4.0	–
3 February 1999	–	–	–	7.0	–	6.0	–
4 February 1999	–	–	–	–	15.0	25.0	–
5 February 1999	–	–	–	9.0	–	5.0	–
6 February 1999	–	9.0	–	–	5.0	–	4.0
8 February 1999	–	–	–	7.0	–	7.0	–
9 February 1999	–	7.0	–	–	7.0	–	3.0
10 February 1999	–	6.0	–	9.0	–	4.0	–
11 February 1999	–	–	–	8.0	4.0	8.0	4.0
12 February 1999	–	4.5	–	–	8.0	–	–
13 February 1999	–	–	–	–	–	–	4.5
14 February 1999	–	–	–	12.0	–	7.0	–
15 February 1999	3.7	7.0	–	–	12.0	–	–
17 February 1999	5.5	–	–	5.0	5.0	5.0	–
18 February 1999	–	–	–	3.5	–	–	–
19 February 1999	–	–	–	3.5	–	3.6	3.5
20 February 1999	–	3.6	–	–	3.6	–	1.6
22 February 1999	0.6	–	–	–	–	4.5	–
23 February 1999	–	9.0	–	20.5	4.5	10.5	1.7
24 February 1999	–	6.5	–	–	10.5	–	4.0
25 February 1999	–	–	–	–	–	6.4	–
26 February 1999	–	8.0	–	20.0	6.4	10.0	3.6
27 February 1999	–	7.2	–	–	10.0	–	2.7
28 February 1999	0.4	–	–	–	–	5.0	–
1 March 1999	–	12.0	–	–	–	–	–

Values of runoff (mm day^{-1}) were estimated by the model. IIIU, uncovered well-watered treatment; IIIC, covered well-watered treatment; I01IC, covered treatment with water stress period during flowering; I02IC, covered treatment with water stress period during flowering; II01C, covered treatment with water stress period during grain filling; PP, daily precipitation value.

and II01C). The difference in soil depth analysed for the different treatments is based only on data availability. Data of irrigation, precipitation (Table III) and soil water content were used. Precipitation and runoff values (Table III) affected only the IIIU plot. Although seeding took place in the middle of October, soil water content observations for treatments started at the end of November. For the first day of simulation the observed values of soil water content were used as initial conditions.

Since the LAI methodology allows soil evaporation and plant transpiration data to be obtained separately, both terms were considered when evapotranspiration was simulated for the IIIU treatment. In the rest of the plots, the soil was covered with polyethylene and soil evaporation modelling in the LAI methodology was inhibited. For these treatments only the plant transpiration was calculated, and water input to the system is only through irrigation (Table III). Therefore, it is expected that differences in evapotranspiration would only be obtained in IIIC, I01IC, I02IC and II01C treatments with the application of the K_c methodology, especially in the first stage of vegetative growth until the vegetation covers the soil surface ($LAI > 4$). After this stage, soil evaporation is negligible.

Figures 5–9 show the simulations of the soil water content corresponding to each irrigation management and MET parameterization methodology. Daily mean values of SWC for both active and passive root depth are presented. In all the cases, the depth of soil studied shows changes in its water content due to inputs by precipitation and/or irrigation. The irrigation management maintained potential water conditions taking into account the soil water content in the layer of 0–0.6 m depth. Therefore, in both well-watered treatments (Figures 5 and 6), the mean values of SWC in the depth studied were below potential conditions. For example, in IIIU at the end of the experiment, the amount of available water in the soil was below the limit of 50%. Modelled surface runoff (Table III) reduced the input of water into the soil (Figure 5). Good agreement between the observed and calculated soil water content shows that the parameterization of the maximum potential retention parameter (s), with the Curve Number methodology (Equation (6)), provides suitable estimations of surface runoff in this area of the Wet Pampas. In addition, in both well-watered cases, MET estimation by LAI methodology provided better predictions than the K_c methodology. During the vegetative phenological stages, the Kc model overestimates the soil water content, whereas for the reproductive period the model underestimates SWC values (Figures 5(b) and 6(b)). Figure 5 (IIIU plot) shows that the major differences between the observed and the estimated soil water content values are produced between initial simulation date and the date of the initial reproductive phenological stage of the maize, where the plants reach their maximum height (before 21 February 1999)

For stressed cases the model has satisfactory predictions. For treatment I01IC (Figure 7(a,b)), the fact that soil water content was maintained above 50% of available water in the 0–0.6 m depth, meant that the whole profile (0–1.2 m) remained in deficit based on the limits considered during the experiment. The simulation provided by the model was not very concordant during the first phenological stage, but it was good in the rest of the experiment. As can be seen in I02IC (Figure 8(a,b)), soil water content shows some differences in the plant's water consumption compared to the previous experiment, although the irrigation treatment applied during the vegetative period was the same. The model produced good estimations in these conditions except for the last days of the experiment. The main difference between the treatments with water stress induced during the initial reproductive stage was the soil initial conditions of the simulation. In I02IC the profile 0–1.2 m was already near the limit of water stress. I01IC began the simulation with an important soil water excess compared to I02IC, and it allowed an accumulation of the water content of the 0–1.2 m column, although the thickness studied for the determination of 'irrigation' or 'non-irrigation' was the 0–0.6 m layer.

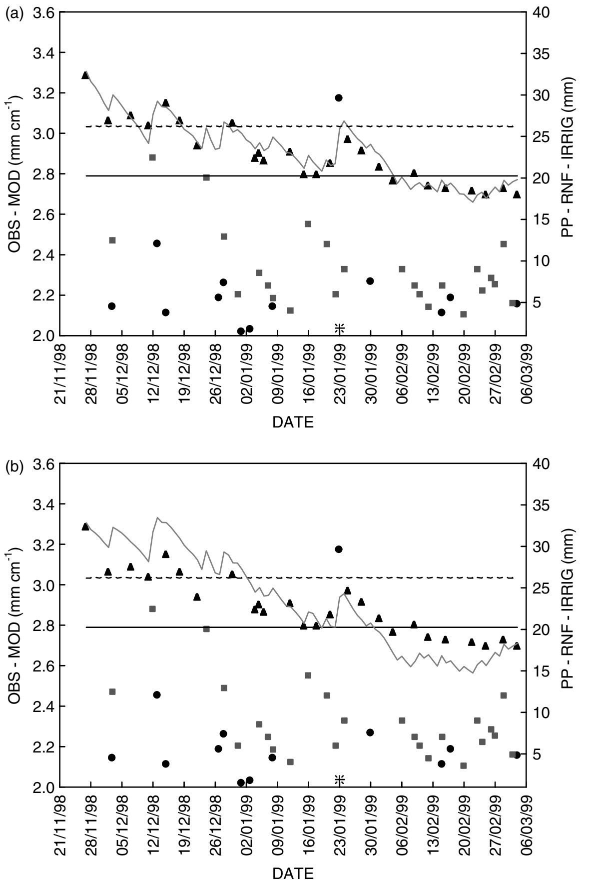

Figure 5. Simulation of daily soil water content in a 1.0 m deep column in IIIU plot, LAI (a) and K_c (b) methodologies for MET estimation. Marks: ● Precipitation, + Runoff, ■ Irrigation, ▲ Observed SWC, —— modelled SWC, ——— 50% of available water and - - - - 65% of available water.

For II01C (Figure 9(a,b)) the initial conditions were similar to I01IC, but the unsatisfied water demand applied

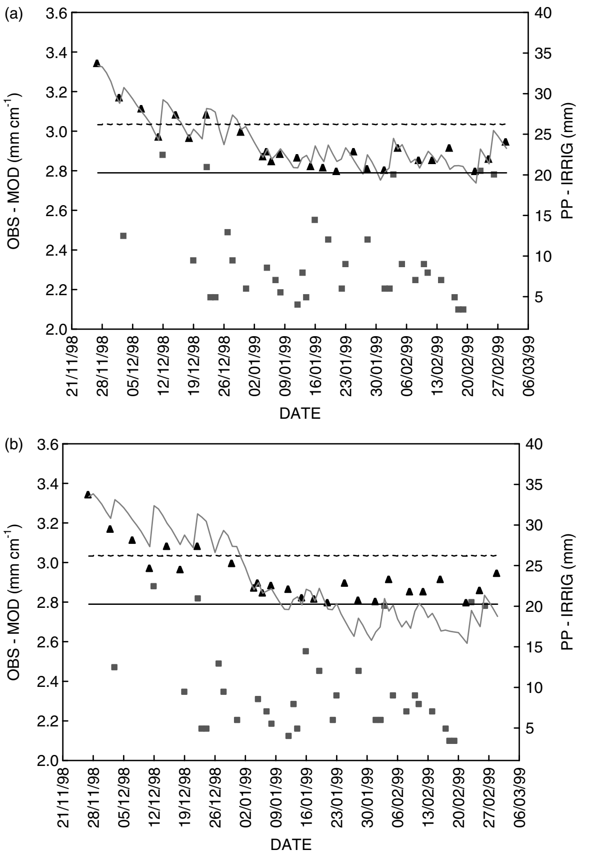

Figure 6. Simulation of daily soil water content in a 1.0 m deep column in IIIC plot, LAI (a) and K_c (b) methodologies for MET estimation. Marks: ■ Irrigation, ▲ Observed SWC, —— modelled SWC, ——— 50% of available water and - - - - 65% of available water.

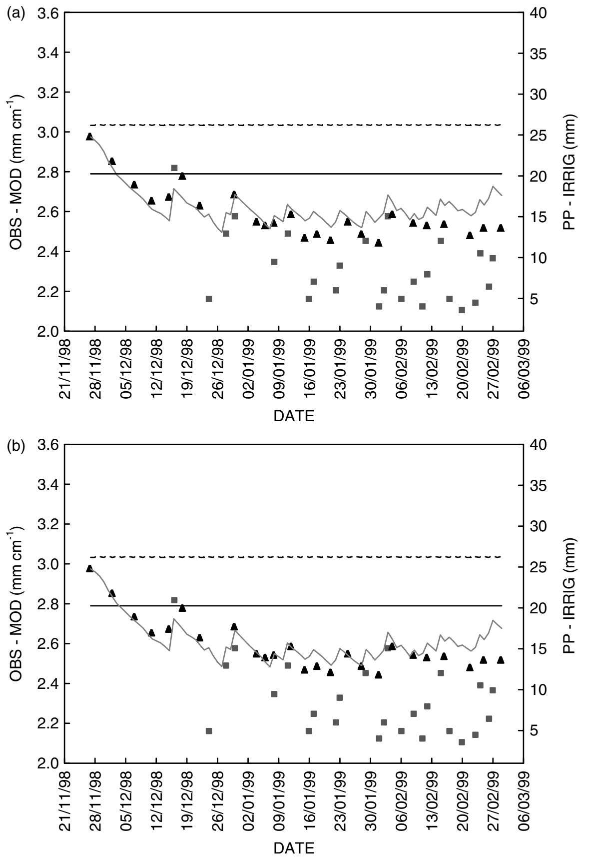

Figure 7. Simulation of daily soil water content in a 1.2 m deep column in I01IC plot, LAI (a) and K_c (b) methodologies for MET estimation. Marks: ■ Irrigation, ▲ Observed SWC, —— modelled SWC, ——— 50% of available water and - - - - 65% of available water.

during the grain filling period diminished drastically the soil water content in the 0–1.2 m layer. In this case the models also appropriately represent the soil water conditions. In the water stress treatments (I01IC, I02IC and II01C) the LAI methodology developed to estimate MET by Gardiol *et al.* (2003) appeared to work better than the standard K_c methodology.

Statistical values showed that there was variability in the predictive capacity of both evapotranspiration models for the different irrigation treatments. The results of the statistical analysis applied to the soil water balance content model considering both MET parameterizations are presented in Tables IV and V. The RMSE had relatively low errors of the analysed variables. The MBE and FB indicated a small overestimation of the SWC, but with a reasonably good approximation between observed and predicted values. SWC of treatments IIIU, IIIC and I01IC are better represented by the LAI methodology, while I02IC and II01C are better represented by the K_c methodology.

Figure 10 depicts the observed values of SWC of the five treatments *versus* the modelled ones, the line regression of the data and the ideal adjustment 1 : 1 line. It was considered that a good representation of the models should result in the linear regression slope relating to the estimated and observed values having a statistically equal slope to the unit. A Student's t-test was used to analyse whether the slopes calculated in the regression for each simulation, using LAI and K_c methodology, were significantly different to the unit value ($p < 0.05$) and the result was that the null hypothesis could not be rejected. This result indicates that the representation of both models provides a correct representation of the soil water content. The values of the determination coefficient for both methodologies indicate that the LAI methodology produces better SWC estimations than the K_c methodology for maize.

Table IV. Plots statistics values.

Statistic	IIIU	IIIC	I01IC	I02IC	II01C	Total
RMSE	0.0715	0.0370	0.0779	0.0557	0.0366	0.0595
MBE	0.0449	0.0038	−0.0362	0.0094	0.0229	−0.0046
FB	0.0129	0.0013	−0.0139	0.0034	0.0085	−0.0017
r^2	0.899	0.972	0.724	0.946	0.985	0.922

LAI methodology for ETM estimation (Gardiol *et al.*, 2003).

IIIU, uncovered well-watered treatment; IIIC, covered well-watered treatment; I01IC, covered treatment with water stress period during flowering; I02IC, covered treatment with water stress period during flowering; II01C, covered treatment with water stress period during grain filling.

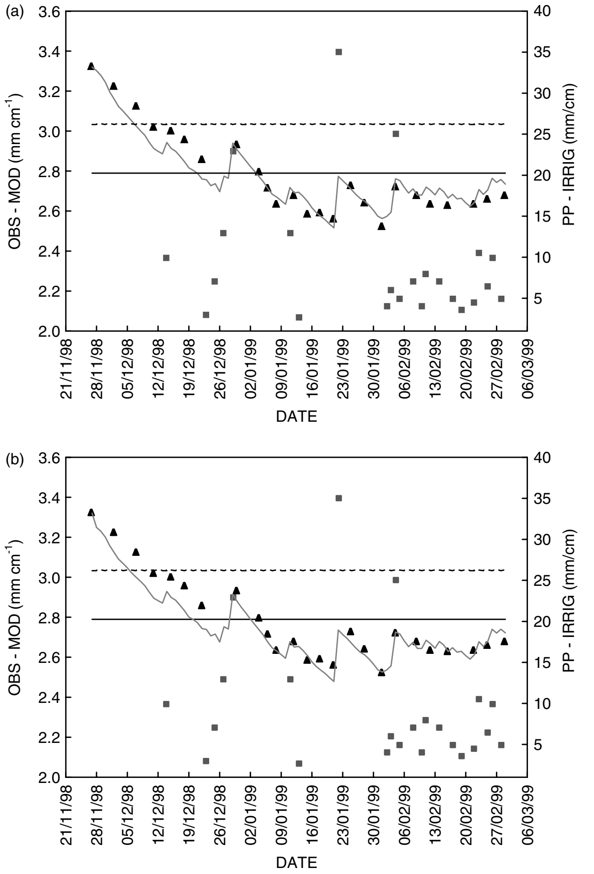

Figure 8. Simulation of daily soil water content in a 1.2 m deep column in I02IC plot, LAI (a) and K_c (b) methodologies for MET estimation. Marks: ■ Irrigation, ▲ Observed SWC, —— modelled SWC, ——— 50% of available water and - - - - 65% of available water.

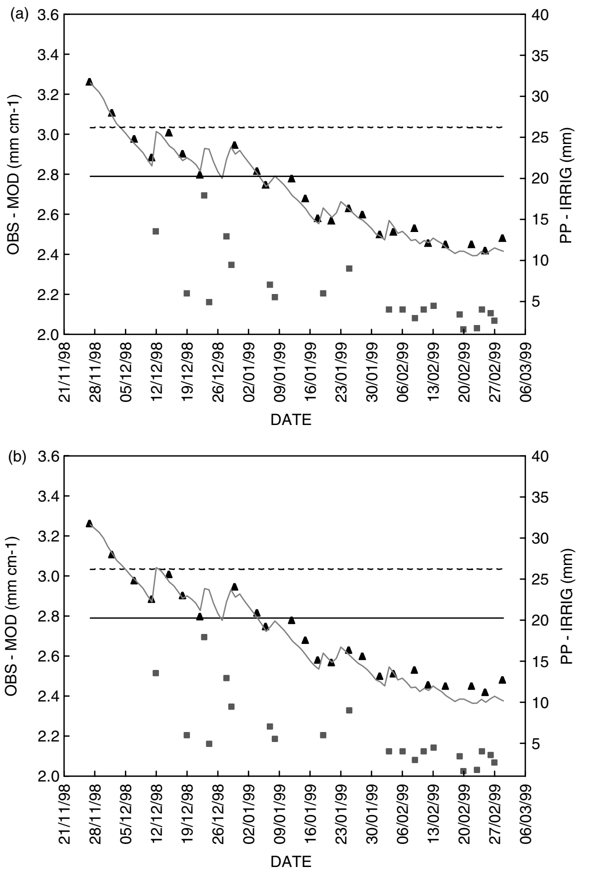

Figure 9. Simulation of daily soil water content in a 1.2 m deep column in II01C plot, LAI (a) and K_c (b) methodologies for MET estimation. Marks: ■ Irrigation, ▲ Observed SWC, —— modelled SWC, ——— 50% of available water and - - - - 65% of available water.

Table V. Plots statistics values.

Statistic	IIIU	IIIC	I01IC	I02IC	II01C	TOTAL
RMSE	0.1010	0.1278	0.0643	0.0652	0.0235	0.0630
MBE	−0.0023	0.0432	−0.0212	0.0391	0.0099	0.0066
FB	−0.0033	0.0149	−0.0082	0.0142	−0.0085	0.0001
r^2	0.887	0.768	0.782	0.948	0.998	0.871

K_c, methodology for ETM estimation (Allen *et al.*, 1998). IIIU, uncovered well-watered treatment; IIIC, covered well-watered treatment; I01IC, covered treatment with water stress period during flowering; I02IC, covered treatment with water stress period during flowering; II01C, covered treatment with water stress period during grain filling.

5. Summary and conclusions

Estimation of soil water content is of major concern because it is a parameter of extreme utility for agricultural and meteorological purposes. Its estimation, in general, is not easy but necessary at the time of evaluation of heat ground fluxes for studies of the partition of energy in the interface with different land use. It also has an important applicability for the improvement of water management through irrigation planning.

In this study, a simple balance model of soil water content was applied to a 1.2 m deep soil layer, with a maize crop cover under different water treatment conditions in the area of Balcarce, located in the south-eastern area of the Humid Pampas of the Buenos Aires province, Argentina.

The model adequately predicted the evolution of daily soil water content for all systems. The diverse statistical errors analysed showed that, generally, the model has a tendency of overestimation of daily mean values of soil water content. These results pointed out that the model is a useful tool to forecast soil water content during crop growing season.

Major errors were found when the crop was exposed to water limitations carrying the soil to non potential conditions. Major concern should be taken in the selection of pa-values, to distinguish conditions of soil water potential or with water stress during the different periods of growing season. It is not clear if this fraction should be constant throughout the different phenological stages.

Differences are found in estimations of AET (Figure 4). Results depicted in Figures 5–9 are obtained from the contribution of each term in Equation (1), and the differences between the AET due to the two methodologies show an impact on estimations of soil water content. It was found that the resistance model developed by Gardiol *et al.* (2003) performed a better estimation of MET than

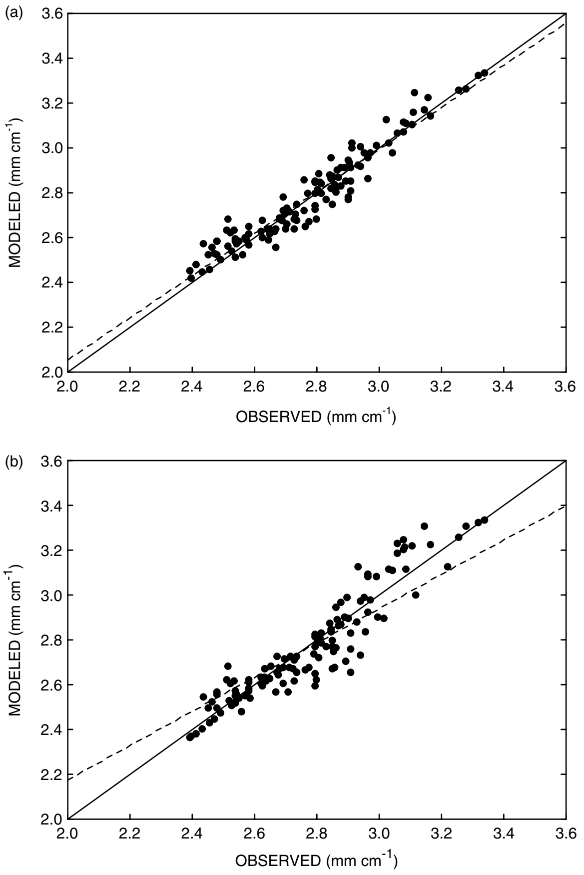

Figure 10. Comparison between modelled and observed values of soil water content, all LAI (a) and K_c (b) methodologies for MET estimation. Marks: ● Values, ——— Perfect regression and - - - - mean square regression.

the methodology suggested by FAO (K_c method). On the other hand, the parameterizations used for the other terms of Equation (1), especially those related to runoff, would seem to be appropriate for the system configuration considered in the experimental area.

The CN methodology applied to estimate the surface runoff values also produced successful results in SWC values. Major improvements should be made in the applicability of soil water content modelling and in the soil type classification of Argentinean land.

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