Evapotranspiration of tomato simulated with the CRITERIA model

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Abstract

The CRITERIA model simulates crop development and water dynamics in agricultural soils at different spatial scales. The objective of this paper was to test CRITERIA in order to evaluate the suitability of the model as a tool for scheduling irrigation at field scale. The first step of the work was to validate this hypothesis, by means of calibration and validation of CRITERIA on processing tomato in two experimental sites in Southern Italy (Rutigliano and Foggia) for the years 2007 and 2008 under different irrigation regimes. The irrigation treatments were: i) absence of plant water stress (the control treatments set up for both years and sites), ii) moderately stressed (applied in Rutigliano for 2007), and iii) severely stressed (applied in Foggia for 2008). The second step consisted in the evaluation of the expected impact of different irrigation regimes on daily actual evapotranspiration. For model calibration, the 2007 data of the control treatment was used, whereas in the validation process of actual evapotranspiration, the other part of the dataset was used. The observed data were crop evapotranspiration, agrometeorological data, leaf area index, physical-chemical and hydrological characteristics of soil, phenological stages and irrigation management. In order to evaluate model performance we used three statistical indicators to compare simulated and measured values of actual evapotranspiration: the normalised differences of seasonal values are less than 10% for all treatments; the model efficiency index on the typical period between two irrigations (4 days) was positive for all treatments, with the best values in the Foggia site, for both the irrigated and the severely stressed experiments; the relative root mean square error (RRMSE) was smaller than 20% in both the control treatments, but higher than 30% for the stressed treatments. The increase in RRMSE for the stressed experiments is due to CRITERIA simulating a crop in good soil water conditions and, as a consequence, with a larger evapotranspiration demand with respect to water stressed crop.

Therefore, we can consider CRITERIA as a suitable tool to manage irrigations of processed tomato, especially for the full irrigation regime; an improvement can be reached by simulating the impact of water stress conditions on the eco-physiological parameters of the crop, in order to use the model also under deficit irrigation regimes.

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Introduction

Italy is one of the world's major producers of processing tomatoes (*Lycopersicum esculentum* Mill.), with a production of 600,000 t (in 2009), amounting to 23% of world production. In Puglia, the tomato crop is particularly common, with an incidence of 29% of Italian production (ISTAT, 2012).

In southern Italy, the water consumption for this crop was estimated between 400 and 600 mm depending on climatic conditions (Rana *et al.*, 2012). The production, in terms of fresh fruit yield, ranges from 80 to 160 t ha^{-1} (Rinaldi *et al.*, 2011).

Water management is a crucial point for the tomato crops, given the limited availability of water resources in southern Italy, with a climate characterised by mild winters and hot and dry summers. Hence, evapotranspiration is not balanced by the moderate amount of rainfall.

In this environment, the sustainable use of water resources is a priority, requiring an irrigation management based on the exact assessment of the water needs in terms of evapotranspiration.

The competition for different water uses often implies that the required irrigation volumes are not always available. Therefore, irrigation should be managed in conditions of regulated water deficit (Rinaldi *et al.*, 2011).

A proper water management should take into account the agro-techniques (water regime, mineral supply and water quality), the crop factors (species, varieties and sensitivity of the growth stage to stress) and the environment (climate and soil proprieties). The potential interactions between these factors must be considered in order to provide wise strategies for water management (Katerji *et al.*, 2008; Garcia-Vila and Fereres, 2012). This aim can be reached through the correct use of crop models (Brisson *et al.*, 1998). Nowadays many models have been developed to satisfy the above cited needs; moreover these models are available in the scientific literature over the past thirty years.

CRITERIA (Marletto and Zinoni, 1998; Marletto *et al.*, 2007) is a modeling system for the simulation of soil water balance developed at the Italian Regional Agency for Prevention and Environment (ARPA-SIMC, *Agenzia regionale per la prevenzione e l'ambiente - Servizio Idro-Meteo-Clima*) that can be used also at the regional scale. The system, provided with daily data of precipitation and temperature, estimates the evapotranspiration and calculates the daily flow of superficial runoff, hypodermic runoff and drainage.

The water balance of CRITERIA takes into account precipitation, irrigation, capillary rise, runoff, evapotranspiration, transpiration, percolation, redistribution and deep drainage. Some of these variables, such rainfall, are easy to measure; others are estimated through algorithms based on meteorological data and characteristics of soil and crops. The water balance is calculated on a daily basis.

In this paper, the CRITERIA model is calibrated and validated with a data set obtained from experimental field observations of tomato, grown in different seasons and sites under different water regimes. It is intended to test the hypothesis that the CRITERIA model can be used as a tool for irrigation scheduling.

Materials and methods

Two experimental setups were used to calibrate and validate the CRITERIA model at two sites in Southern Italy. The first site was located in Rutigliano (lat: 40° 59' N, long: 17° 01' E, alt: 147 m asl), on an experimental farm belonging to the Agricultural Research Council-Research Unit for Cropping Systems in Dry Environments (CRA-SCA). The second was located in Foggia (lat: 41° 25' N, long: 15° 31' E, alt: 55 m asl), on a private farm.

Southern Italy is characterized by a Mediterranean climate with warm and dry summers (maximum air temperature ranges from 32°C to 43°C and minimum relative humidity ranges from 15% to 40%) (Campi *et al.*, 2009). The cumulated annual precipitation is almost the same in both the sites, 535 mm in Rutigliano and 554 mm in Foggia. The rainfall is mainly concentrated in the autumn and late winter period and it is greatly reduced or absent in the spring-summer period. The main soil features measured at the Rutigliano and Foggia sites are reported in Table 1.

The soil at the Rutigliano site is mainly clayey and it is homogeneous in the vertical profile. The calcareous parent rock is located in the first horizons of the soil, and the average depth of the soil is 0.60 m, so the crop root system has a reduced capacity to expand beyond this layer.

The soil of Foggia has a 3 m-depth and a loam-clay texture. Nonetheless, a 1.2 m-deep calcareous layer prevents the roots from expanding beyond this layer.

Tomato plants were cultivated for one season in Rutigliano (transplant dates: 14th May 2007) and for one season in Foggia (transplant date: 13th May 2008) at a density of 3.3 plants m^{-2}. The tomato crops were grown using conventional agro-techniques (200 kg ha^{-1} K_2O whit 80 kg ha^{-1} P_2O_5 before transplanting and 200 kg ha^{-1} N). The experimental design was a randomised block replicated three times, where each plot had an area of 150 m^2. The dates of the main phenological stages, expressed in days after transplanting (DAT) and collected during the 2007 crop season at the Rutigliano site, are: recovery after transplanting (11 DAT); flowering (44 DAT); length of the flowering stage (40 days); start of senescence (93 DAT); and maturity (109 DAT).

Two different protocols were adopted for the irrigation of the tomato plots. At the Rutigliano site, the two irrigation schedules were: a control treatment (IRR), restoring 100% of the readily available soil water, and a moderately stressed treatment (STR1), reducing the irrigation volume by 50% compared with the control treatment from 30 days after transplanting (DAT) until harvest. At the Foggia site, the two irrigation schedules were: a control treatment (IRR) and a severe stress (STR2) treatment, where the irrigation was stopped from 50 DAT until harvest.

Table 1. The main soil characteristics at the Rutigliano and Foggia sites.

Soil characteristics	Rutigliano	Foggia
Depth (m)	0.6	1.2
Clay (%)	40	49
Silt (%)	45	36
Sand (%)	15	15
Water content at field saturation (% in volume)	48	50
Water content at field capacity (% in volume)	33.5	39
Water content at wilting point (% in volume)	22.5	23
Total available soil water (mm)	66	192

The irrigation volume was calculated according the FAO-56 methodology (Allen *et al.*, 1998) and the irrigation water was supplied by a drip irrigation system.

Daily actual evapotranspiration (ET) was measured indirectly (Lhomme and Katerji, 1991) using a simplified soil water balance approach. At the Rutigliano site, runoff and capillary rise are negligible because of the flat ground and the presence of a cracked rocky layer that limits the soil depth and ascending water. At the Foggia site, runoff can be neglected because the area is flat, while the capillary rise can be assumed to be zero because of the presence of a calcareous layer at 1.2 m-deep that prevents the roots from expanding and the water stored in the deeper soil layers from moving up to the soil surface.

The simplified equation for the soil water balance can be expressed, at a daily scale, as:

$$ET = \pm \Delta W + P - Dr \tag{1}$$

where:
ET, daily actual evapotranspiration (mm d^{-1});
P, precipitation and/or irrigation (mm d^{-1});
$\pm\Delta W$, the difference in volume of soil water content in the whole soil profile (mm d^{-1}) measured with time domain reflectometry (TDR) probes;
Dr, drainage (mm d^{-1}).

The same technique for monitoring the soil water content was used for both sites. Coaxial probes (0.3 m long) were installed horizontally into the soil at two levels (15 and 45 cm from the soil surface at Rutigliano, 20 and 60 cm at Foggia) in only one block.

The probes were linked to a TDR100-CR1000 data logger (Campbell Scientific Inc., Logan, UT, USA). The drainage (Dr) was estimated as the amount of water exceeding the maximum water capacity in the entire soil profile.

For model calibration, the dataset referring to 2007 for the IRR treatment in Rutigliano was used. The calibration of the CRITERIA model was done taking into account the following inputs measured during the tests:
- Agrometeorological data: daily measurements of global radiation, wind speed, air humidity and temperature, collected from standard agro-meteorological stations close to the experimental plots in Rutigliano and Foggia.
- Leaf area index (LAI) trend, by an area meter (LAI-2000 Plant Canopy Analyzer, Li-Cor, Lincoln, NE, USA); the values simulated by CRITERIA were then compared with measured values for the calibration dataset (Figure 1).
- Crop coefficient (Kc): a 1.1 value was taken into account and it was obtained by the ratio of ET, calculated with Eq. 1 in optimal irrigation condition (IRR), to ET0, calculated with the Penman-Monteith equation.

- Root depth: a value of 0.6 m was used.
- Physical-chemical and hydrological characteristics of soil (Table 1).
- Irrigation management: the actual irrigation amount and timing of each treatment were provided as input.

Since tomato growers in the Capitanata area usually perform on average 2 irrigations per week, the ET was validated at a 4-day time scale. Thus, simulated and measured values of daily actual evapotranspiration were cumulated for the following four days.

To assess the quality of the model to predict seasonal actual evapotranspiration in each water regime treatment of the crop, we considered the normalized difference between simulated and measured values (D, expressed in %). If D does not exceed 15%, as suggested by Brisson *et al.* (2002), the simulation is considered as acceptable.

Moreover, to test model performance, we applied to simulations the modeling efficiency index (Nash and Sutcliffe, 1970), as calculated by the following equation,

$$EF = 1 - \frac{\sum_{i=1}^{n}(Predicted_i - Observed_i)^2}{\sum_{i=1}^{n}(Observed_i - AvgObserved)^2} \quad (2)$$

where:
n represents the number of data pairs;
i is the pair index and AvgObserved is the average of the observed data. EF provides a simple index of model performance on a relative scale, where EF=1 indicates a perfect fit, EF=0 suggests that the model predictions are no better than the average, and a negative value indicates poor model performance.

The evaluation model indicator used is the relative root mean square error (RRMSE), calculated from the following equation:

$$RRMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \cdot \frac{100}{\overline{O}} \quad (3)$$

where:
n is the number of observations, P_i is the value predicted by CRITERIA; O_i is the measured value, and is the mean of the measured values. The validation is considered to be excellent when the RRMSE is <10%, good if the RRMSE is between 10 and 20%, acceptable if the RRMSE is between 20 and 30%, and poor if >30% (Jamieson *et al.*, 1991).

Results

Figure 2 shows the variation in soil water availability for each tomato treatment condition during the two seasons. The differences between stressed (STR1 and STR2) and irrigated treatments began 30 and 51 DAT in 2007 and 2008, respectively. In particular, for each year, in the IRR treatment, the soil water content was always close to field capacity while under the STR1 treatment (2007) soil water content was below field capacity though always above the wilting point (Figure 2A), and under the STR2 treatment soil water content reached the wilting point at 65 DAT (Figure 2B).

In Figure 3, the measured values of cumulative ET during the growing season of tomatoes (ET) compared with the CRITERIA simulated values are shown. With the exception of the calibration dataset, there is a good relation between measurement and simulation in all the irrigated conditions.

Table 2 reports the values measured and those simulated by CRITERIA for seasonal ET (mm) for both years in all treatments. From the analysis of the difference between simulated and measured data (D) and the modeling efficiency index (EF), CRITERIA shows a good skill in

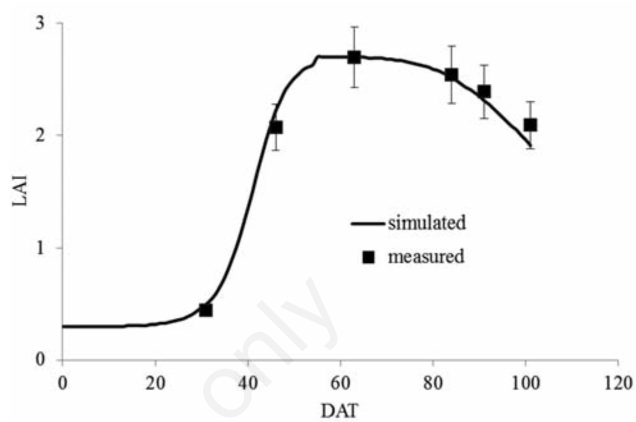

Figure 1. Leaf area index (LAI) measured and simulated during season 2007 used in model calibration. DAT, days after transplanting.

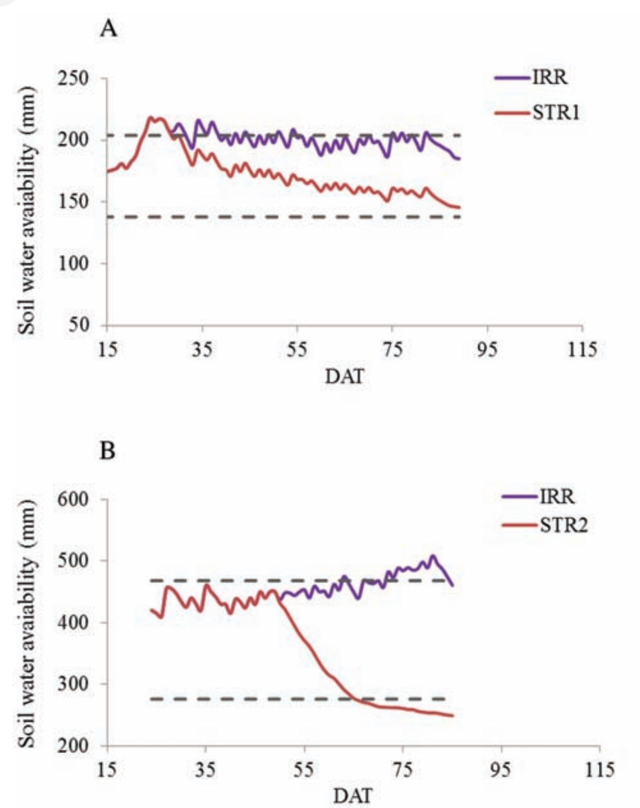

Figure 2. A) and B) Cumulated actual evapotranspiration measured and simulated during two seasons (2007 and 2008) for three water regimes (IRR, STR1, STR2). DAT, days after transplanting.

predicting seasonal ET, if the tomato is well irrigated. Also in the case of sub-optimal water regime (STR1 and STR2) CRITERIA simulates ET adequately: no D value exceeds the 15% threshold (D values are less than 10%) and the EF indexes are always positive.

Figure 4 shows the measured and simulated values of the 4-day cumulated ET for all treatments during the seasons 2007 and 2008.

RRMSE values have been calculated when daily measurements of ET were available. These values show a good skill of CRITERIA to simulate ET, from seasonal to a shorter scale (4-day ET). In the case of IRR treatment, the values of RRMSE ranges between 15% and 18%; it means that CRITERIA provides a good estimations of the cumulated evapotranspiration between two successive irrigations. Whereas, in the case of the water stress treatments (STR1 and STR2), the skill of the model decreases (RRMSE >32%).

The increase of the RRMSE value for the stressed crops is due to the fact that CRITERIA simulates a crop under optimal development conditions and the water stress factors are not modeled. As a consequence, CRITERIA is conceived for non limiting evapotranspiration conditions.

These validation tests of CRITERIA can be considered as an original result because it takes into account different conditions of water regime (optimum and deficit irrigation) of tomato, in environments characterised by water scarcity. A first attempt (Campi *et al.*, 2012) to simulate horticultural crops (but not tomato) growing with limited water supply (50% of ET) demonstrated good predictions of cumulated ET (at seasonal scale). Validation tests of ET simulated at daily scale are quite rare in literature (Katerji *et al.*, 2013) and they lacks for CRITERIA. This paper approaches the CRITERIA calibration at a short time scale (4-day intervals), which are consistent with the tomato irrigation scheduling in Mediterranean conditions. At the moment this results cannot be compared to other observations taken from the literature,

Table 2. Seasonal evapotranspiration, measured and simulated by the CRITERIA model for tomato crops grown under three water treatments: IRR, STR1 and STR2. The normalised differences between simulated and measured values (%) and the modeling efficiency index (-) are reported.

Years	Treatment	ΣET (mm) Meas	Sim	D (%)	EF (-)
2007	IRR	485	448	−7.6	0.51
	STR1	345	337	−2.3	0.36
2008	IRR	486	487	−0.2	0.86
	STR2	290	265	−8.6	0.75

ΣET, seasonal evapotranspiration; Meas, measured ΣET; Sim, simulated ΣET; D, differences between simulated and measured values; EF, efficiency index.

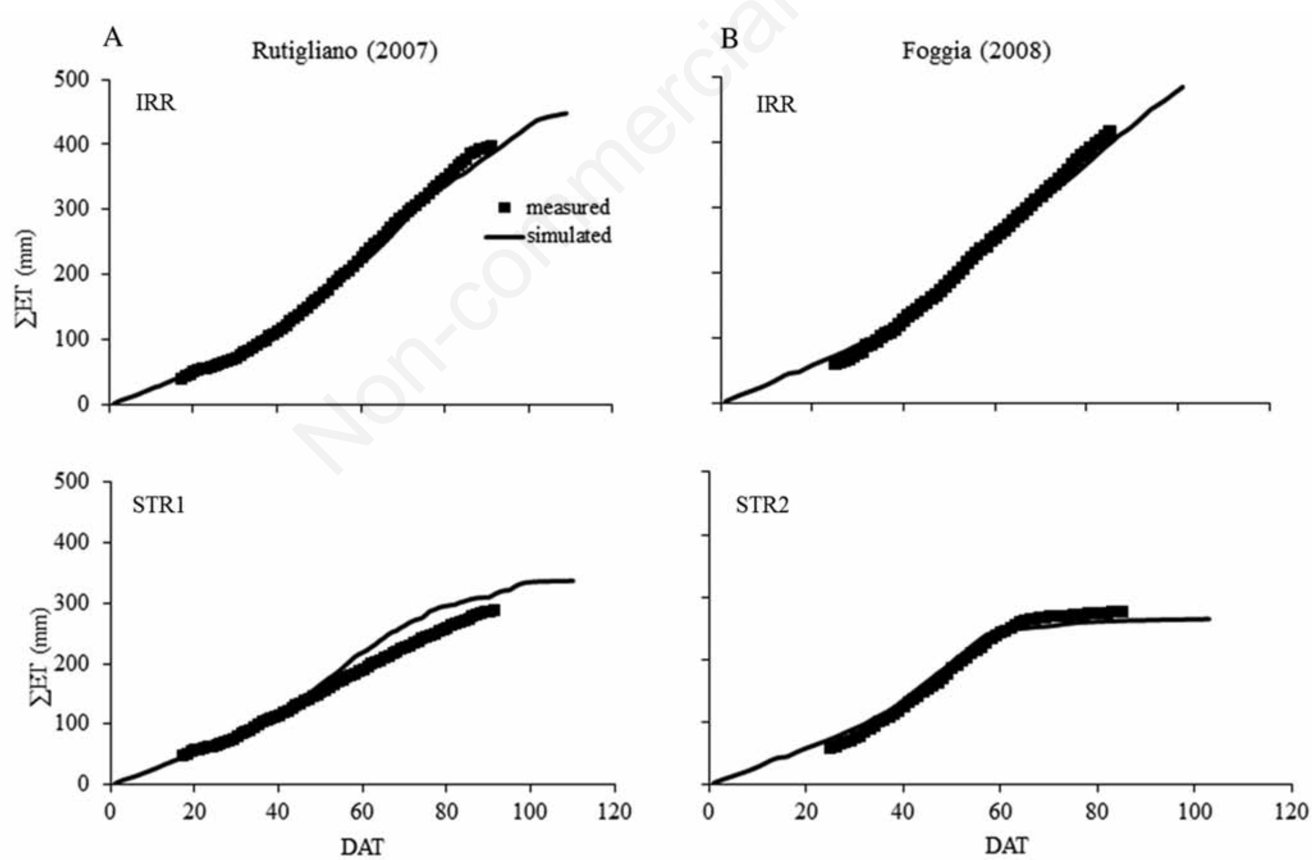

Figure 3. Soil water availability measured during the experiment; the A) plot refers to the season 2007 in Rutigliano characterized by the treatments: IRR (black solid line) and STR1 (black dashed line), while the plot B) refers to 2008 in the experimental site of Foggia characterized by the treatments: IRR (black solid line) and STR2 (black dashed line). Gray lines show wilting point (gray dashed line) and field capacity (gray solid line) for the specific soil. DAT, days after transplanting.

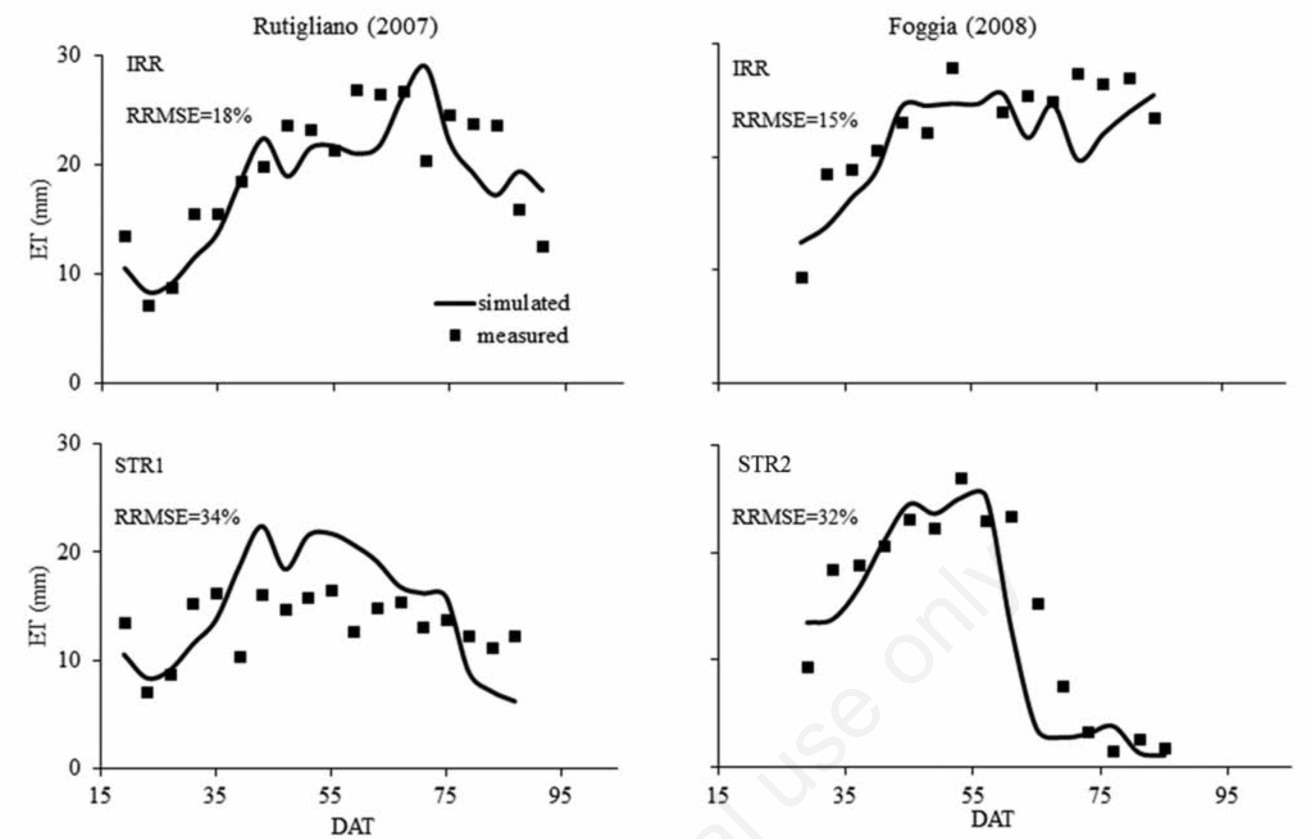

Figure 4. Evapotranspiration values (cumulated every 4 days) measured and simulated by CRITERIA model during two cropping seasons of tomato (2007 and 2008) for three treatments (IRR, STR1, STR2). The relative root mean square errors (RRMSE in %) between simulated and measured values are reported. DAT, days after transplanting.

because the performance of CRITERIA were tested under not limiting water conditions (northern Italy) and for different crops (Tomei *et al.*, 2007; Marletto *et al.*, 1998, 2007). However, these results should be confirmed by further studies carried out under water stress conditions, which consider specific observations on crop eco-physiology, which allow parameterising the effect of water stress on evapotranspiration. After that an exhaustive analysis can be drawn on the aptitude of CRITERIA to simulate tomato crop productivity and water requirement under soil water stress condition.

The tomato ET was analysed in previous studies by other crop models. For example, AquaCrop (Steduto *et al.*, 2009) simulates correctly the seasonal evapotranspiration of tomato (Rinaldi *et al.*, 2011; Palumbo *et al.*, 2012; Katerij *et al.*, 2013) under good conditions of water supply. While in the case of tomato grown with deficit irrigation, AquaCrop shows a poor skill to predict ET (Katerij *et al.*, 2013).

Conclusions

CRITERIA is already used for irrigation scheduling of crops grown in several areas where the water does not represent a constraint for irrigated crops (northern Italy). In this paper CRITERIA is tested as tool for irrigation scheduling in southern Italy, where the irrigation skill should be more accurate because of water scarcity.

CRITERIA model is based on the two-step approach: reference ETo and Kc. This double approach has generated much criticism when it was applied, mainly in areas with arid and semi-arid climate (Testi *et al.*, 2004; Katerji and Rana, 2006; Lovelli *et al.*, 2007; Irmak and Mutiibwa, 2009). Despite this, validation tests of the model CRITERIA on tomato crop in southern Italy highlight a good skill of the model to simulate seasonal evapotranspiration under different irrigation regimes. If used for the irrigation scheduling, the skill of the model is good in case of fully irrigated treatments.

In order to use CRITERIA model also for the deficit irrigation regime, additional experimental tests under water deficit conditions are required in semiarid conditions. These tests will allow introducing in CRITERIA model the reaction of crop behavior in relation to the crop water stress.

This is an important issue for irrigated cropping systems in the Mediterranean areas where shortage of water resources entails the implementation of deficit irrigation.

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