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Simulation of sprinkler irrigation water uniformity impact on corn yield

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Abstract

In a previous work, the spatial and temporal wind effects on corn yield were analysed using Ador-Crop (based on the FAO crop model CropWat) and a solid set sprinkler irrigation model. The combined model could explain only 25% of the variability of measured yield. The objective of this work was to evaluate the predictive capacity of two more advanced crop models (EPICphase and DSSAT) when coupled to the solid set sprinkler irrigation model. EPICphase explained 44% of total dry mater (TDM) and grain yield (GY) variability when measured irrigation was used. The combination of EPICphase and the solid set sprinkler irrigation model explained better the variability of TDM than that of GY (42% and 35%, respectively), although the error in the estimation of GY with the coupled model was higher than when measured irrigation doses were considered (1.55 t ha^{-1} *vs.* 1.22 t ha^{-1}). The DSSAT model explained 39% and 38% of the variability in TDM and GY, respectively, when measured irrigation data was used. When DSSAT was considered in the coupled model, better results were obtained for TDM ($R^2 = 41\%$) than GY ($R^2 = 31\%$). The EPICphase model simulated grain yield more accurately than the DSSAT model because it produced a better prediction of the maximum LAI. The combination of the sprinkler irrigation model with the EPICphase or DSSAT models simulated crop growth and yield more accurately than when combined with the Ador-Crop model.

Additional key words: DSSAT; EPICphase; sprinkler irrigation model; water deficit; wind.

Resumen

Simulación del impacto de la uniformidad del riego por aspersión sobre el rendimiento del cultivo de maíz

En trabajos anteriores se ha estudiado el efecto espacial y temporal del viento sobre el rendimiento del cultivo de maíz utilizando el modelo Ador-Crop (basado en el modelo de FAO CropWat) y un modelo de simulación de la distribución del agua de riego por aspersión en cobertura total. El modelo combinado pudo explicar sólo el 25% de la variabilidad de la reducción de rendimiento medida. El objetivo de este trabajo fue estimar la capacidad predictiva de dos modelos de cultivo más avanzados (EPICphase y DSSAT) que el modelo Ador-Crop en el mismo caso de estudio. El modelo EPICphase explicó el 44% de la variabilidad de la biomasa y del rendimiento en grano. La combinación de EPICphase y el modelo de riego por aspersión explicó un poco mejor la variabilidad de la biomasa que la del rendimiento en grano (42% y 35%, respectivamente), aunque el error en la estimación del rendimiento en grano con el modelo acoplado fue mayor que con las dosis de riego medidas (1,55 t ha^{-1} *vs.* 1,22 t ha^{-1}). El modelo DSSAT explicó el 39% de la variabilidad de la biomasa y el 38% de la variabilidad del rendimiento en grano. Cuando se combinó el modelo de riego por aspersión con el modelo DSSAT, se obtuvo un mejor resultado en la simulación de la biomasa ($R^2 = 41\%$) que en la del rendimiento en grano ($R^2 = 31\%$). El modelo EPICphase simuló de forma más precisa el rendimiento en grano que el modelo DSSAT porque predijo mejor el índice de área foliar máximo. La combinación del modelo de riego por aspersión con EPICphase y DSSAT simuló mejor el crecimiento y rendimiento del cultivo que cuando se combinó con el modelo Ador-Crop.

Palabras clave adicionales: déficit de agua; DSSAT; EPICphase; modelo de simulación por aspersión; viento.

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Abbreviations used: CU (Christiansen uniformity coefficient), CV (coefficient of variation), DSSAT (decision support system for agrotechnology transfer), EPIC (erosion productivity impact calculator), ET (crop evapotranspiration), GY (grain yield), HI (harvest index), IDc (irrigation dose), LAI (leaf area index), PAR (photosynthetically active radiation), RMSE (root mean square error), SRGF (soil root growth factor), SWRC (soil water retention curve), TDM (total dry matter).

Introduction

Adequate water and nutrient management are critical for attaining acceptable crop yields and minimizing the environmental impact of irrigated agriculture. The sprinkler irrigation system has high potential application efficiency and can attain high crop yields (Clemmens and Dedrick, 1994). However, sprinkler irrigation performance is affected by design and management variables (particularly environmental conditions), which can severely reduce its potential. In fact, several authors have shown that sprinkler irrigation uniformity diminishes with the increase of wind speed (Faci and Bercero, 1991; Tarjuelo *et al*., 1994; Dechmi *et al.*, 2003; Sánchez, 2008). Numerical simulations based on a ballistic solid set sprinkler irrigation model quantified the decrease in irrigation uniformity as the sprinkler spacing increased (Playán *et al.,* 2006). Moreover, several studies have confirmed the negative impact of irrigation non-uniformity on crop yield and on water and nutrients deep percolation losses (Bruckler *et al*., 2000; Lafolie *et al*., 2000; Dechmi *et al*., 2004a; Li *et al*., 2005).

Crop models are considered valuable tools for simulating crop growth, soil water balance and solute movement in the soil. The use of crop models can minimize the field experimentation required to identify factors controlling crop yield and the environmental impact on surface and groundwater quality. In sprinkler irrigated areas, crop models can also be used to analyze the relationship between irrigation uniformity and the spatial variability of crop yield. A common approach is to consider a constant irrigation water application pattern during all crop growth stages (Orgaz *et al*., 1992; Mantovani *et al*., 1995; De Juan *et al*., 1996; Li, 1998). Dechmi *et al*. (2004a) considered the variation of sprinkler irrigation uniformity with meteorological conditions. These authors linked Ador-Crop, a simplified crop model based on the well-known FAO CropWat model (Smith, 1992) to the solid-set sprinkler irrigation model Ador-Sprinkler. The objective was to predict the effect on crop yield of the variability in time and space of sprinkler irrigation water.

Among the crop models available, a distinction can be made between crop growth models and simplified crop water-yield models. Crop growth models simulate the most relevant physiological and hydrologic processes. This is the case of CropSyst (Stockle *et al*., 2003), DSSAT (Jones *et al*., 2003), EPIC (Williams *et al.,* 1984), STICS (Brisson and Mary, 1999) and APSIM (McCrown *et al*., 1996). In the second category, simplified crop water-yield models have been developed for irrigation scheduling that does not explicitly simulate crop growth. This is the case of CropWat (Smith, 1992), ISAREG (Teixeira and Pereira, 1992) and AdorCrop (Dechmi *et al*., 2004a,b). These models consider the whole soil profile as a reservoir in which water is stored till reaching field capacity. Excess irrigation and precipitation is then treated as either surface runoff or drainage below the root zone. In crop growth models the soil profile is divided into layers. Variable rate water movement within the soil profile is considered: upwards and downwards redistribution of soil water between field capacity and wilting point is simulated using different approaches, such as the Richards flow equation (Richards, 1931). Calder *et al*. (1983) reported that layered models represent a considerable improvement over the single reservoir type models. On the other hand, models differentiating the effects of water stress on photosynthesis, leaf area index and harvest index, result in a better simulation of the effects of water stress on crop yield than simplified models (Cavero *et al*., 2000).

Dechmi *et al*. (2004a) concluded that Ador-Sprinkler adequately predicted irrigation water distribution during the growing season of a corn crop. In fact, Ador-Sprinkler could explain 87% of the variability in measured CU. When Ador-Crop was used in combination with measured irrigation depths, simulated yield reductions explained 38% of the observed yield reductions. However, the coupled model (Ador-Sprinkler and Ador-Crop) could only explain 25% of the observed yield variability, suggesting that the simplifications in Ador-Crop result in a relevant loss in predictive capability. An alternative option is to link the sprinkler irrigation model to a crop growth simulation model.

We have previously published some works where crop models have been linked to irrigation models (Cavero *et al.,* 2001; Dechmi *et al.,* 2004a,b). In the first work a surface irrigation model was linked to a crop growth model (EPICphase). In the second work a sprinkler irrigation model was linked to a very simple crop model (CropWat). The results that we found in the second work were not satisfactory so in the present work we have linked the sprinkler irrigation model to two more complete crop growth models in which water stress daily affects a number of processes. We wanted to evaluate if the use of these more complete crop models (EPICphase and DSSAT) could improve the simulation of yield variability due to irrigation non uniformity, as compared to CropWat. Moreover, the linking of the sprinkler irrigation model to more complete crop models —if the results are adequate— will allow evaluating the environmental consequences of irrigation non-uniformity, since these models also simulate the fate of nutrients in the soil. Thus, the purpose of this work was to (i) evaluate the predictive capability of two widely tested crop growth simulation models, and (ii) compare the results of the combination of both models with the sprinkler irrigation model Ador-Sprinkler with those presented by Dechmi *et al.* (2004a) for the coupling of Ador-Sprinkler and Ador-Crop.

Material and methods

Field experiment data

The experiment was conducted on a corn crop (*Zea mays* L. cv. Dracma) irrigated with a solid set sprinkler irrigation system, located at the experimental farm of the Agrifood Research and Technology Centre of Aragon, Spain. Experimental details are reported in Dechmi *et al.* (2003), and a succinct description of the experimental design follows. Two experimental plots A and B were selected in the field as Figure 1 shows. In each plot, 25 square parcels (1.5 × 1.5 m) were marked. These parcels represent the basic experimental units for all the measurements performed during the experiment. Two catch cans were installed in the middle of each parcel and maintained at the same height as the crop canopy. The sprinkler model was «VYR 70» (VYRSA, Spain), arranged in triangular spacing of 18 × 15 m. Sprinklers were equipped with two nozzles: 4.4 mm (main nozzle) and 2.4 mm (auxiliary nozzle). The operating pressure at the nozzles was 300 kPa, and was kept constant for the duration of the experiment.

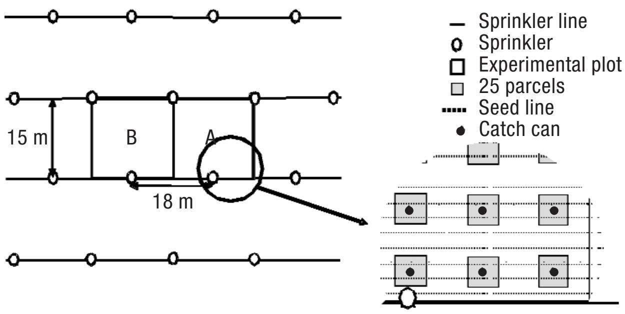

Figure 1. Detail of the experimental setup, indicating the location of the sprinkler spacings and parcels.

This configuration resulted in high irrigation uniformity under low wind speed conditions: the Christiansen uniformity coefficient (*CU*) (Christiansen, 1942) was as high as 94%. The sprinkler discharge was volumetrically measured before the experiment. Following each irrigation event, the irrigation depth was determined from this discharge and the irrigation time. The main climatic variables needed as model inputs were recorded using an automatic agrometeorological station (Campbell Sci, Logan, UT, USA) located about 200 m from the experimental plot.

Corn was planted in May 17, 2000, at a density of 8 plants m^{-2}. Irrigations were performed when the soil water balance indicated a deficit equivalent to 50% of the total available water. A total of 24 irrigation events were applied during the season. After each irrigation event, the water collected in both catch cans of each parcel was averaged and recorded as the catch can irrigation dose (*IDc*, mm). The *IDc*'s corresponding to each irrigation event were used to compute *CU*. Uniformity ranged between 51% and 94%, with an average of 80%. The percentage of photosynthetically active radiation (PAR) intercepted by the crop was measured five times during the crop season in each parcel using a ceptometer (Sunfleck, Decagon, Pullman, WA, USA). Leaf area index (LAI) was estimated from intercepted PAR measurements.

Sprinkler irrigation model

The solid set sprinkler irrigation model uses ballistic theory to simulate the flight of water drops from the sprinkler nozzle to the soil surface. In the model, the sprinkler is modelled as a device emitting drops of different diameters. The model performs the following operations: 1) the trajectory of single droplets of a given diameter is computed. Drops are launched at given vertical and horizontal angles, and under a given wind vector; 2) the landing point for drops of different diameters is combined with the drop size distribution curve characterizing the sprinkler. The spatial distribution of water application from a single sprinkler is thus obtained; 3) the water distribution of a single sprinkler is overlapped considering the desired sprinkler spacing; 4) the irrigation water dose applied in a 25-node square grid within a given sprinkler spacing is computed; and 5) the irrigation performance parameters are determined for each irrigation event. The 25-node network corresponds to the location of the 25 experimental parcels.

A detailed model description can be found in Dechmi *et al.* (2004a) and Playán *et al.* (2006). When applied to the experimental data reported in this experiment, the sprinkler irrigation model successfully reproduced the observed water distribution pattern ($R^2 = 0.871$***) (Dechmi *et al.*, 2004a). The average root mean square error (*RMSE*) between measured and simulated water application (0.95 mm h^{-1}) resulted comparable to the average *RMSE* between the measured water distributions in the two adjacent plots A and B (0.63 mm h^{-1}).

Crop models

The considered crop models were EPICphase (Cabelguenne *et al.*, 1999) and DSSAT (Jones *et al.*, 2003). EPICphase is an improved version of EPIC (Erosion Productivity Impact Calculator) model. DSSAT (Decision Support System for Agrotechnology Transfer) is a collection of independent programs that can operate in a coordinated fashion. For corn, DSSAT uses the CERES-Maize model (Jones and Kiniry, 1986). The CERES-Maize version used in this work is the one include in DSSAT-4.0. Both models describe daily phenological development and growth in response to environmental factors (soils, weather and management), and have shown reliability under different climate, soil and management conditions (Cavero *et al.*, 2000, 2001; Jones *et al.*, 2003). Both EPICphase and DSSAT use the Ritchie model to calculate crop evapotranspiration and to update the soil water balance on a daily basis as a function of the water transfer processes affecting the soil profile (precipitation, irrigation, transpiration, soil evaporation, runoff and drainage) (Ritchie, 1998).

The growth stages simulated by the DSSAT CERES-maize include germination, emergence, end of juvenile, floral induction, 75% silking, beginning grain fill, maturity and harvest. EPICphase only considers four growth stages (Cabelguenne *et al.,* 1999). Both models require the same input data, including daily weather data (maximum and minimum air temperature, solar radiation, precipitation, relative humidity and wind velocity), soil characteristics (field capacity, wilting point, depth, initial water content, bulk density) and crop management practices (sowing date, and dates and amounts of irrigation and N fertilization). DSSAT CERES-maize additionally considers plant density.

Models runs

The EPICphase and DSSAT models were run for each individual parcel considering its soil characteristics and the measured field experimental data. Each model was run using as irrigation input a) the measured irrigation dose (average of the two catch cans) or b) the simulated irrigation dose (obtained with the ballistic solid set sprinkler model). Following previous works using these crop growth models, the Penman equation was used to determine reference evapotranspiration, and the maximum rooting depth was set to 0.9 m (Cavero *et al.*, 2000). The corn crop parameters in EPICphase were derived from previous work in the same location using different experimental data sets (Cavero *et al.*, 2000). Nevertheless, for the DSSAT model the main physiological and phenological parameters of corn (6 cultivar coefficients) were iteratively adjusted until an adequate fit between measured and simulated phenological and productivity crop data was found. First, the model was run to fit PHINT value. After, P1 and P2 coefficients were adjusted to predict the day of flowering. Than P5, G2 and G3 were adjusted. For each case, the cultivar coefficient values presenting minimum RMSE between observed and simulated data were considered. Thus, the derived cultivar coefficients used for cv Dracma were: P1 = 274 (thermal time from seedling emergence to the end of the juvenile phase); P2 = 0.40 (extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate); P5 = 665 (thermal time from silking to physiological maturity); G2 = 620 (maximum possible number of kernels per plant); G3 = 11 (kernel filling rate during the linear grain filling stage and under optimum conditions) and PHINT = 70 (the interval in thermal time between successive leaf tip appearances). The ecotype coefficients values considered were: DSGFT = 180 (growing degree days from silking to effective grain filling period); RUE = 2.8 (radiation use efficiency) and; KCAN = 0.5 (canopy light extinction coefficient for daily PAR).

Statistical procedures for models evaluation

Comparison between measured and simulated values with both models of the total dry matter (TDM) at harvest, grain yield (GY), and harvest index (HI) was done. Comparisons were established in terms of plot average, but also considering the spatial variability in yield. The following parameters were used to assess the performance of the CERES-Maize (DSSAT) and EPICphase models in a spatially variable context: i) the coefficient of correlation (*r*) between simulated and observed values; ii) the coefficient of determination (R^2) of regressions between the simulated and observed values; iii) the Root Mean Square Error (RMSE); and iv) model Bias. They were computed as follows:

$$r = \frac{\sum\left(M_i - \overline{M}\right)\left(C_i - \overline{C}\right)}{\left(N-1\right)S_m S_S} \quad [1]$$

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

$$Bias = \frac{1}{N}\sum_{i=1}^{N}(C_i - M_i) \quad [3]$$

where N is the number of observed values, C and M are the calculated and measured values for the i^{th} observation, and, S_m and S_s are the standard deviation of measured and simulated values, respectively.

Finally, simulated daily LAI values were compared with estimated values from intercepted PAR measurements.

Results

EPICphase simulations

When the measured irrigation dose was used to simulate the experiment, the EPICphase model explained 45% of total dry matter (TDM) and 44% of grain yield (GY) variability (Fig. 2). The average simulated crop yield was similar to the measured, but the total dry matter was overestimated by the model by 13% (Table 1). The variability of the measured TDM (CV = 15.0%) was higher than that of the simulated (CV = 9.2%). However, the variability of measured GY (CV = 19.8%) was slightly lower than that of simulated GY (CV = 21.0%). In the case of the harvest index (HI), the average simulated value (Table 1) was 13% lower than the average measured value, while the variability of the simulated values was higher than the measured values. The correlation between measured seasonal irrigation dose and simulated GY was significant (r = 0.89*) and higher than the correlation using measured GY (r = 0.62**).

In general, the use of the simulated irrigation dose resulted in a higher variability of simulated TDM, GY and HI (Table 1). The combination of EPICphase and the sprinkler irrigation model resulted in a better simulation of TDM compared to that of GY (Fig. 3). The

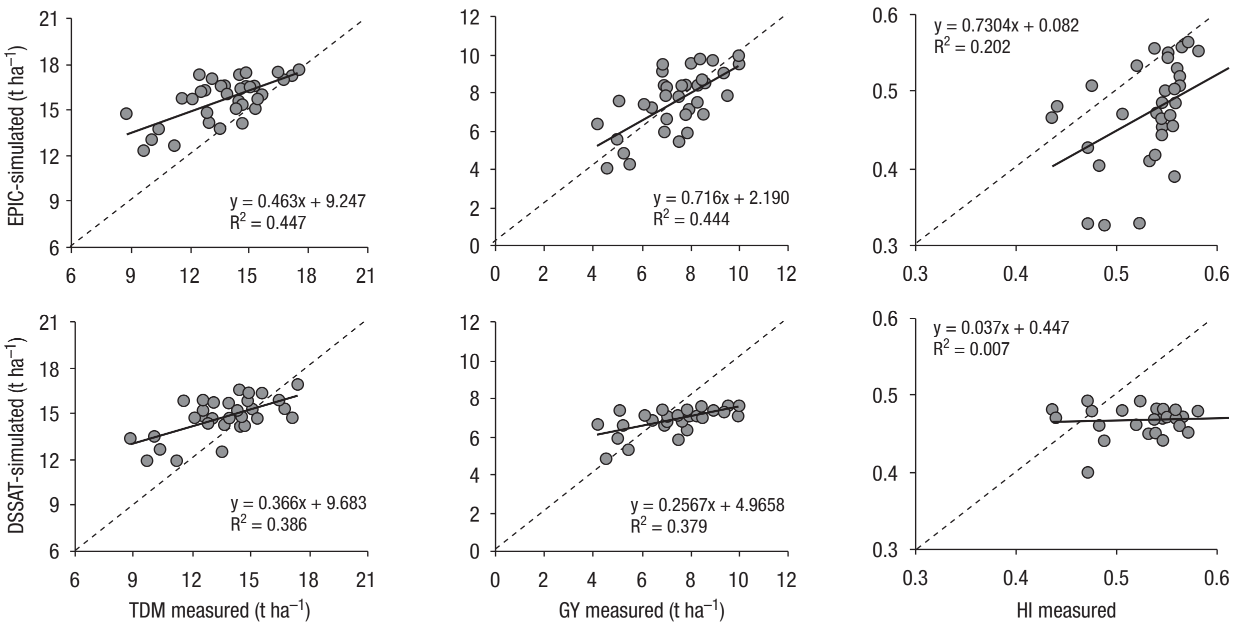

Figure 2. Relationship between measured and simulated total dry matter (TDM), grain yield (GY) and harvest index (HI) using EPICphase and DSSAT models, and considering the measured irrigation dose at each parcel. The dotted line represents the 1:1 relationship.

Table 1. Average, standard deviation (SD), BIAS and root mean square error (RMSE) of observed and simulated total dry matter (TDM), grain yield (GY) and harvest index (HI). Simulations were performed with the EPICphase and DSSAT models using measured and simulated irrigation doses at each parcel

	TMD (t ha^{-1})				GY (t ha^{-1})				HI			
	Average	SD	BIAS	RMSE	Average	SD	BIAS	RMSE	Average	SD	BIAS	RMSE
Measured	13.78	2.07	—	—	7.43	1.47	—	—	0.54	0.04	—	—
Simulated with measured irrigation												
EPICphase	15.63	1.43	1.75	2.33	7.51	1.58	0.08	1.22	0.47	0.06	–0.06	0.08
DSSAT	14.73	1.22	0.90	1.81	6.87	0.61	–0.53	1.27	0.47	0.02	–0.06	0.08
Simulated with simulated irrigation												
EPICphase	15.15	1.71	1.30	2.04	7.01	1.85	–0.40	1.55	0.45	0.08	–0.08	0.11
DSSAT	14.43	1.35	0.62	1.65	6.69	0.80	–0.70	1.38	0.46	0.02	–0.07	0.08

RMSE for GY was higher for the coupled model than for the measured irrigation dose (Table 1).

Figure 4 presents the comparison of LAI as measured and simulated with EPICphase, considering the average of all parcels (Fig. 4a), the case of a parcel where a seasonal irrigation dose of 609 mm was applied (Fig. 4b), and the case of a water stressed parcel (with an irrigation dose of 421 mm) (Fig.4 c). In all cases, the EPICphase model overpredicted LAI at the beginning of the season. However, the maximum LAI was adequately predicted in the three cases.

DSSAT simulations

When the measured irrigation dose was used, the DSSAT model explained 39% of TDM variability and 38% of GY variability (Fig. 2). The average simulated value of crop yield was underestimated by 8% (Table 1). However, the TDM was overestimated by 7%. Moreover, the model underpredicted the HI by 13%, mainly due to the underprediction of grain yield (Fig. 2). For all the considered crop parameters, less variability was observed in the simulated than in the observed values.

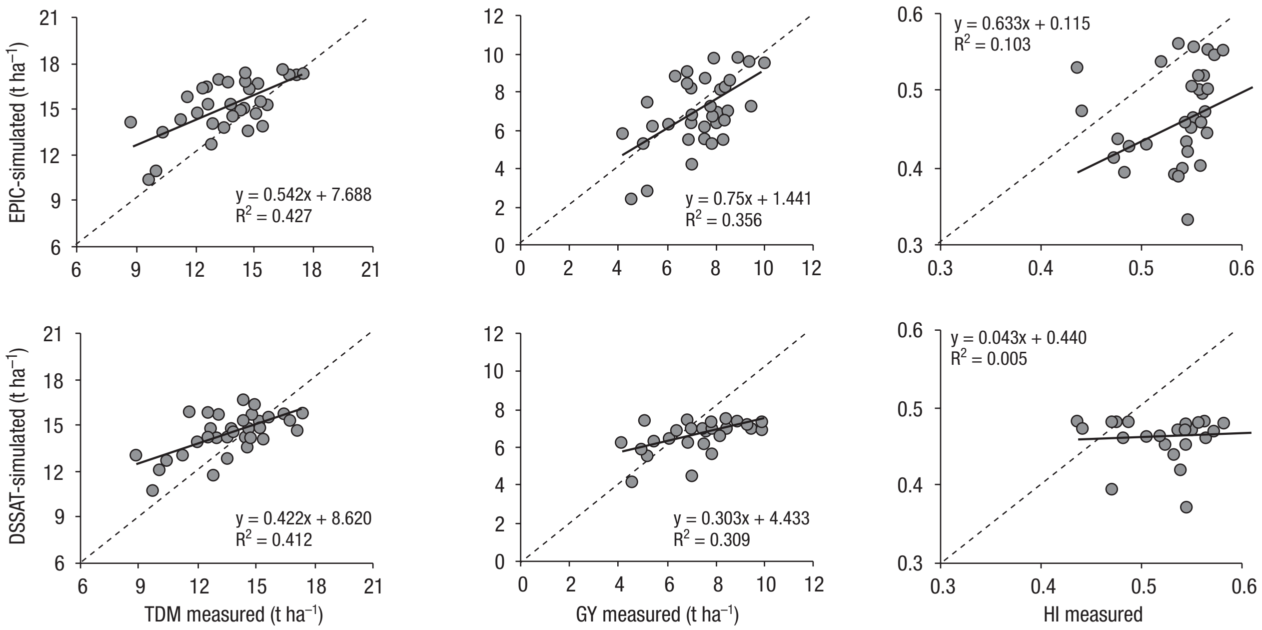

Figure 3. Relationship between measured and simulated total dry matter (TDM), grain yield (GY) and harvest index (HI) using EPICphase and DSSAT models, and considering the simulated irrigation dose by the sprinkler irrigation model at each parcel. The dotted line represents the 1:1 relationship.

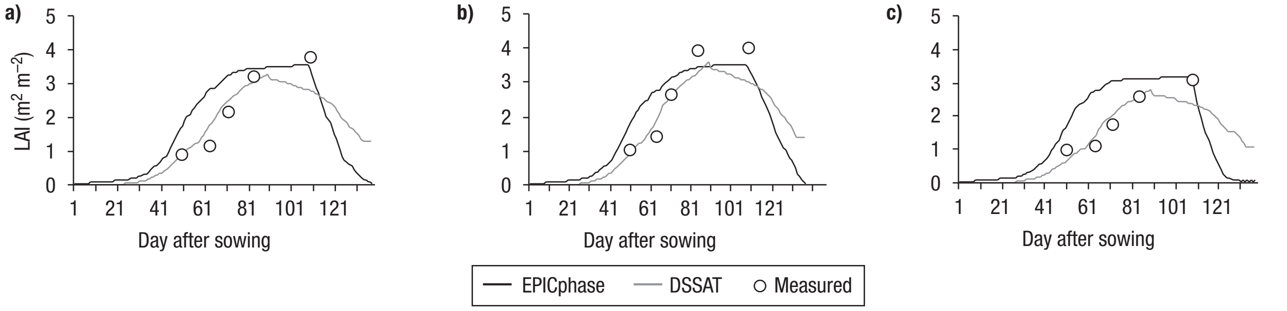

Figure 4. Comparison of measured and simulated leaf area index (LAI) with the EPICphase and DSSAT models: a) average values for all parcels, b) values obtained in a parcel where the seasonal irrigation dose was 609 mm, and c) values of water stressed parcel (irrigation dose of 421 mm).

Similarly to EPICphase, the use of simulated irrigation doses resulted in a higher variability in simulated TDM, GY and HI (Table 1) than for observed irrigation doses. When the sprinkler irrigation model was coupled with the DSSAT model (Fig. 3), a better fit between simulated and measured values was observed for TDM ($R^2 = 41\%$) than for GY ($R^2 = 31\%$). The relationship between the seasonal irrigation dose and the GY simulated by DSSAT was similar for simulated and measured doses ($r = 0.60$ and $r = 0.62$, respectively). DSSAT accurately simulated LAI early in the season (Fig. 4). However, the maximum LAI was underpredicted in all three cases.

Comparison of the two models

As shown in Figures 2 and 3, the EPICphase model simulated more accurately the TDM, GY and HI than the DSSAT model. However, the RMSE was generally lower for DSSAT than for EPICphase (Table 1). The main discrepancy between the two models was found in the simulated values of HI (Figs. 2 and 3). Although the seasonal crop evapotranspiración (ET) simulated by both models was similar (Fig. 5a), the DSSAT model simulated higher ET than EPICphase model when the seasonal irrigation dose was lower than 580 mm (Fig. 5b). On the other hand, it was observed that EPICphase simulated better the maximum LAI value (Fig. 4), but the DSSAT model simulated better the LAI early in the season. For both crop models, the coupled model explained better the variability in TDM than that of GY (Table 1).

Discussion

The advanced crop growth simulation models used in this work provided more accurate simulations of the variables studied than those found when the Ador-Crop model (based on CropWat) was used (Dechmi *et al.,* 2004a). When applied to the simulation of the experimental results, EPICphase outperformed DSSAT in terms of of GY and maximum LAI estimation. Dechmi

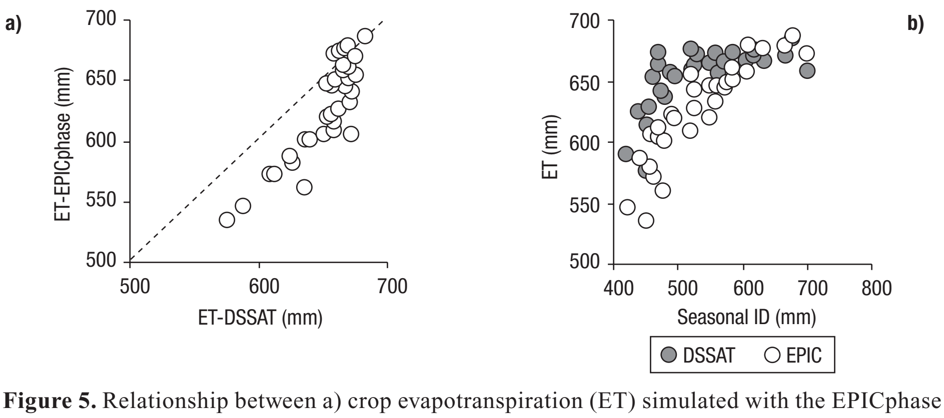

Figure 5. Relationship between a) crop evapotranspiration (ET) simulated with the EPICphase and DSSAT models, and between b) crop evapotranspiration simulated by both models and the seasonal irrigation dose measured in each parcel (ID).

et al. (2004a) indicated that a large part of the unexplained variability in measured yield parameters by the Ador-Crop model could be due to other factors affecting crop yield, such as mild soil and irrigation water salinity (Dechmi *et al.,* 2003). Neither EPICphase nor DSSAT simulate the yield reduction due to salinity stress. As a consequence, differences between measured and simulated values could be expected. Additionally, the performance of the nitrogen module of both models was not evaluated in this work.

Results indicate that EPICphase presented a tendency to overestimate TDM more than GY (Fig. 2). This was possibly due to the fact that the EPICphase overestimated LAI early in the season. Dechmi *et al.* (2003) indicated that in all experimental irrigation events there were at least 13 parcels under water stress. Additionally, eight of them presented continuous deficit during all irrigation events due to the spatial variability of sprinkler irrigation water distribution. In those parcels EPICphase overestimated LAI along the season except for the maximum value, which was adequately simulated. This result is in agreement with the fact that the simulation of the maximum LAI was improved in the EPICphase model version used in this work, particularly under water stress (Cavero *et al.*, 2000). In any case, the Bias and RMSE values were lower than those found in previous works with this model (Cavero *et al.*, 2000). Debaeke *et al.* (1996) indicated that EPICphase did not consider processes such as the direct effect of water stress on root growth, and that this simplification could be responsible for part of disagreement between measured and simulated values, particularly in the case of water stressed parcels. In a research report on a corn crop in the same location, the combination of a surface irrigation simulation model and EPICphase explained 56% of the variability of the measured yield (Cavero *et al.*, 2001). In that case, however, water stress was more relevant and more focused on a specific area of the field.

Simulations with DSSAT were less effective than those with EPICphase in predicting the spatial variability of the measured variables. This could be due to the required adjustments in the phenological parameters, which probably were not sufficiently sensitive to emphasize the effect of small changes in soil water availability. Only plant phenological parameters were considered to optimise the fit between simulated and measured corn yield and growth. However, the uncertainty in the measured soil parameters and root distribution can also have a relevant effect on simulated plant growth. In this sense, Ma *et al.* (2009) indicated that the soil water balance was more affected by saturated hydraulic conductivity (K-sat) than by the soil water retention curve (SWRC), whereas simulated crop growth was affected by both K-sat and SWRC. Anyhow, these authors indicated that small variations in the soil root growth factor (SRGF) did not affect soil and crop simulation.

The solid set sprinkler irrigation model coupled to the EPICphase and DSSAT models constitutes an interesting tool for the design and the economic evaluation of solid set sprinkler irrigation management. Even though the EPICphase or DSSAT models require more input data as compared to Ador-Crop, these models produced better simulation results, and resulted in a better prediction of the variability found in the real world. It will be important to test the models' ability to estimate the nitrogen cycle and soil water before using them extensively to identify alternative sprinkler irrigation water management practices in windy areas such as the middle Ebro valley in NE of Spain.

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