Title: Effect of non-uniform sprinkler irrigation and plant density on simulated maize yield

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ABSTRACT

Commercial field conditions under sprinkler irrigation include low irrigation uniformity and non uniform plant density, which can affect the crop yield and the environmental impact of irrigation. The effect of sprinkler irrigation and plant density uniformity on maize grain yield variability under semiarid conditions was evaluated and the relevance of spatial variability of these two variables on the simulation of maize grain yield with the DSSAT-Ceres-Maize model was tested. Experimental field data from three maize growing seasons (2006, 2009 and 2010) with nighttime or daytime sprinkler irrigation was used to test the model performance. Yield, irrigation depths and plant density distribution were measured in 18 x 18 m plots divided in 25 subplots. Regression analysis showed that variability of plant density and seasonal irrigation depth (due to irrigation non-uniformity) were able to explain from 28 to 77 % of maize grain yield variability in the conditions of the experiment of relatively high CU (73-84%) and high plant density (higher than 74,844 pl ha^{-1}). The inclusion of the irrigation depth distribution improved maize yield simulations compared with simulations with average irrigation water applied (RMSE decreased from 637 to 328 kg ha$^{-1)}$. Maize yield was overpredicted by 3% when irrigation depth distribution was not considered. Including plant density distribution in the simulations did not improve maize yield simulations. The simulated decrease in maize yield with decreasing CU of irrigation was variable depending on the year, ranging from 0.75 Mg ha^{-1} to 2.5 Mg ha^{-1} when decreasing from 100 to 70 % the CU. The ability of the model to simulate CU effects on maize yield is shown.

Keywords:

Coefficient of uniformity, sprinkler irrigation, DSSAT-Ceres maize, plant density

1. INTRODUCTION

Irrigation is the main source of water for summer crops under semiarid conditions, where reference evapotranspiration largely exceeds precipitation. Maize is one of the most widely grown field crops under irrigation in the Ebro River Valley and other irrigated areas of the world. It is important to adjust irrigation water depths to maize crop requirement and achieve optimum irrigation to avoid yield reduction due to water stress (Musick and Dusek, 1980) and the environmental problems linked to excess of water applied due to nutrient loss (Cavero et al., 2003).

The quality of irrigation application at field scale can be measured as the irrigation efficiency that is defined as the crop evapotranspiration divided by the total water applied as irrigation plus precipitation (Howell, 2003). Depending on the soil properties and irrigation management, irrigation efficiency at the field level can be low to moderate under surface irrigation (average 53 – 79 %) but can reach high values in well managed sprinkler irrigation systems (94%) (Causape et al., 2006). As a result, many agricultural areas devoted to field crops are changing to more efficient sprinkler irrigation systems and the area of irrigated land with sprinkler irrigating systems increased from 37 to 50% in USA from 1985 to 2000 according to the yearly survey of the *Irrigation Journal*.

An important parameter to evaluate the quality of irrigation under sprinkler irrigation systems is the uniformity of water distribution which is usually measured with the coefficient of uniformity (CU) (Christiansen, 1942). The CU indicates how uniform is the water distribution in an irrigated event at field scale. One of the most important factors that affect sprinkler irrigation uniformity is the wind speed (Dechmi et al., 2003a, 2003b; Faci and Bercero, 1991), decreasing irrigation uniformity as wind speed increases. It is well established that wind speed at daytime is usually higher compared to nighttime (Doorenbos and Pruitt, 1977), so higher irrigation uniformity is usually found when sprinkler irrigating at nighttime.

Under surface irrigation, some studies have been conducted to study the effect of irrigation uniformity on maize yield (Cavero et al., 2001; Warrick and Yates, 1987), concluding that maize yield decreases as irrigation uniformity decreases because some areas of the field do not receive enough water. Similarly, under sprinkler irrigation systems, the reduction in irrigation uniformity is also known to reduce yield due to a reduced water supply in some areas of the field (Bruckler et al., 2000; de Juan et al, 2008; Dechmi et al., 2003a; Stern and Bresler, 1983). Or and Hanks (1992) observed as well under non-uniform drip irrigation that maize yield was highly correlated with the dripper flow rate.

The effect of water supply on crop's yield has been mostly studied with experiments that analyze the production function of water under uniform irrigation conditions in space or time (Letey et al., 1984; Mantovani et al., 1995; Warrick and Gardner, 1983). However, it is difficult to extrapolate these results to non-uniform field conditions, where irrigation depth has a non uniform distribution in space but also in time. It is for instance known that the seasonal CU of irrigation is usually higher than the CU of a single irrigation event (Dechmi et al., 2003a). Stern and Bresler (1983) analyzed corn yield as a function of water applied and irrigation uniformity on two experimental plots and found that yield reductions when CU of irrigation was 75% ranged from 4 to 20 % depending on the total amount of irrigation, but yield reductions increased with lower CU. In this sense, a tool able to analyze the effect of irrigation uniformity variations over time on crop yield for different irrigation amounts is needed. The use of crop simulation models that adequately simulate the effect of water stress on plant growth over time can be a useful tool to study irrigation uniformity effect on yield. DSSAT-CERES-Maize has been shown to simulate accurately the effect of water stress on maize yield (Gabrielle et al., 1995; Kovacs et al., 1995; López-Cedrón et al, 2008). This model simulates crop growth dynamically, taking into account that water stress affects plant growth differently depending on the phenological stage of the plant.

Crop models have been previously used to simulate the effect of irrigation uniformity on crop yields (Bergez and Nolleau, 2003; de Juan et al., 1996; Li, 1998; López-Mata et al. 2010; Mantovani et al., 1995; Pang et al., 1997), but tests against measured field data are scarce. Cavero et al. (2001) studied the utility of the EPICphase model to simulate maize yield under surface irrigation and concluded that introducing irrigation uniformity improved maize yield predictions. Dechmi et al. (2010) studied the use of EPICphase and DSSAT models to simulate the impact of irrigation water uniformity on prediction of maize yield under sprinkler irrigation conditions and found that both models performed better than CROPWAT (Smith, 1992) related to the yield variability induced by the irrigation non-uniformity.

Spatial variability of other factors can interact with the spatial variability of irrigation water produced by the non uniform irrigation. For instance, maize plant density has been found to affect maize yield (Tetio-Kagho and Gardner, 1988), so spatial variability of plant density could influence yield at the field level. Most solid-set sprinkler irrigation systems for field crops use sprinkler spacings ranging from 15 to 18 m and variability in soil characteristics within this reduced area should be not very high but plant density can show some variability due to inadequate planting procedures and/or emergence problems.

Crop simulation models can be used to study the effect of irrigation uniformity on maize yields isolated from the effect of non-uniformity of plant density and of other factors that are present under field conditions. In addition, crop simulation models can be used in connection with irrigation models to provide calculations of water stress and crop yield spatial variation within a field. This could help to improve irrigation management because models can explore different management scenarios. The capability of the DSSAT-CERES-Maize model to simulate the effect of irrigation uniformity on maize yield has been explored with a limited data set (Dechmi et al., 2010). A more extensive study to asses the model performance under different sprinkler irrigation conditions is needed. Moreover the previous work did not take into account the relevance of the interaction between the spatial variability of water application and the spatial variability of plant density. The aim of this study was to study the relevance of sprinkler irrigation non-uniformity and plant density non-uniformity on maize grain yield variability considering experimental and simulation data.

The objectives of this work were: (1) evaluate the effect of sprinkler irrigation uniformity and plant density uniformity on maize grain yield variability under semiarid conditions, and (2) elucidate the relevance of spatial variability of these two variables on the simulation of maize grain yield with the DSSAT-Ceres-Maize model.

2. MATERIALS AND METHODS

2.1. Field experiments

The experiments were conducted in Zaragoza, Spain (41º43'N, 0º48'W, 225 m altitude) in a 2.34 ha field during 2006, 2009 and 2010. The soil is a deep clay loam (218 g kg^{-1} sand, 482 g kg^{-1} silt, and 300 g kg^{-1} clay) and is classified as Typic Xerofluvent, with a pH of 8.4 and a $CaCO_3$ equivalent of 309 g kg^{-1}. Organic carbon concentration is 8.6 g kg^{-1} and 5.1 g kg^{-1} in the 0-0.3 and the 0.3-1.2 m soil layers, respectively. Organic N concentration is 1.1 g kg^{-1} and 0.88 g kg^{-1} in the 0-0.3 and the 0.3-1.2 m soil layers, respectively. The climate is Mediterranean semiarid with mean annual maximum and minimum daily air temperatures of 20.9 ºC and 8.5ºC, respectively, yearly average precipitation of 322 mm, and yearly average reference evapotranspiration of 1100 mm.

A solid set sprinkler irrigation system was installed with an squared spacing of 18 x 18 m. The impact sprinkler and nozzles were manufactured in brass (RC-130, Riegos Costa, Lérida, Spain). Twelve irrigation sectors irrigated by four sprinklers each were installed. The borders of the field were irrigated independently of the main sectors. The irrigation volume was measured with an electromagnetic flow meter (Promag 50, Endress+Hauser, Reinach, Switzerland) which has a measurement error of ± 0.5%. Further details of the sprinkler irrigation system are given in Cavero et al. (2009) (Experiment 2).

Maize cultivar Pioneer PR34N43 was planted with a commercial seed drill on 28 April 2006, 21 April 2009, and 20 April 2010 in rows 0.75 m apart and at a plant density of 87,000 (2006 and 2009) and 92.000 (2010) seeds ha^{-1}. Maize was fertilized with N at pre-plant and with two side-dress applications to ensure a correct N supply to the maize plants (250 kg N ha^{-1} yr^{-1}). P and K were supplied each year at preplant at an average rate of 72 and 99 kg ha^{-1} yr^{-1} of P and K, respectively. Weed and pest control were conducted according to best management practices of the area.

Irrigation requirements were calculated following the FAO approach (Allen et al., 1998). Reference evapotranspiration (ETo) was computed with the FAO Penman-Monteith method from meteorological data obtained from an automated weather station located in the experimental farm. Wind speed was measured at 2 m above the ground. Crop coefficients (Kc) were calculated as a function of thermal time (Martínez-Cob, 2008). Daily maize evapotranspiration (ETc) was calculated from the corresponding daily values of ETo and Kc. The crop irrigation requirements (CIR) were calculated weekly as the difference between ETc and the effective precipitation, which was estimated as 75% of precipitation (Dastane, 1978), and assuming an irrigation efficiency of 100%. Irrigation was applied at nighttime until the crop was well established (V6 – V8 growth stage), and then two irrigation treatments were studied: daytime or nighttime application of the CIR. Daytime irrigation generally started at 1000 GMT while nighttime irrigation started at 2200 GMT of the same day, applying the same irrigation amount to both treatments. The weekly irrigation amount was generally applied in two irrigation events that lasted 4 to 6 h depending on CIR. The experimental design was randomized with six replicates per treatment in 2006 and three replicates in 2009 and 2010. The primary plot was the area limited by the four sprinklers of each irrigation sector. The area outside was not considered because it received water from two different irrigation sectors. To evaluate the irrigation water uniformity and the water losses of the irrigation events a grid of 25 catch cans separated 3.6 m was installed within the square area delimited by four sprinklers (18 m x 18 m) in two plots (GRID plots): one with daytime irrigation and the other with nighttime irrigation. The catch cans had a diameter of 0.18 m and were located just above the crop canopy. They were placed progressively higher as the crop height increased during the season. After each irrigation event, the water amount collected in each catch can was measured. Wind drift and evaporation losses (WDEL) were calculated as:

$$WDEL = 100\,\frac{I_{fm} - I_{cc}}{I_{fm}} \tag{1}$$

where: I_{fm}, applied irrigation amount measured with the flow meter; I_{cc}, mean irrigation amount measured at the 25 catch cans. The CU was computed from the amount of water collected in the 25 catch cans installed in the daytime and nighttime irrigated GRID plots. In each of these two plots, 25 square subplots (1.5 × 1.5 m) centered around each catch can and containing the two plant rows around the catch can were marked. At harvest (23 Oct. 2006, 6 Oct 2009, 4 Oct 2010), in each subplots of the GRID plots the number of plants was counted and the ears were collected. The grain was separated from the cob and its weight and moisture content measured. A subsample was dried at 60ºC for obtaining the weight of 1000 kernels.

At the other primary plots, the maize plants in a 3-m long section of two different rows in each sector were counted for estimating plant density. The primary plots (18 m x 18 m) were machine harvested with a combine, and the grain was weighed with a 1 kg precision scale. A subsample of grain was collected from each primary plot to measure the grain moisture. Another subsample was dried at 60ºC to calculate weight of 1000 kernels.

2.2. DSSAT model calibration and validation

The model was calibrated by adjusting the cultivar coefficients with data from the nighttime irrigated primary plots (18 m x 18 m) not used for catch can measurements, where plant density was measured in two 3-m long section of plant rows and the grain was obtained from the complete plot with a combine. The irrigation depth applied considered was the average of the measured in the GRID plots, because all the plots of the same type of irrigation (nighttime or daytime) were irrigated at the same time. The DSSAT- Ceres Maize model was calibrated with data from the nighttime irrigated plots because at nighttime irrigation uniformity is higher and water losses are lower, so water stress for the maize crop should be minimal (Cavero et al., 2008; Playán et al., 2005). In total, data from 4 plots in 2006, 2 plots in 2009, and 2 plots in 2010 were used for calibration of the model. Phenology data (flowering and maturity), maize grain yield, number of grains per unit area, and kernel mass were available for the model calibration. Calibration of the model consisted on the estimation of the 5 cultivar coefficients needed for CERES-Maize: P1 (Growing degree days to flowering), P2 (Delay in development with photoperiod above 12.5h, expressed as days), P5 (Growing degree days to maturity), G3 (Potential kernel growth rate), G2 (Potential kernel number per plant), and PHINT (Phyllochron interval). The obtained cultivar coefficients were: 203, 0.6, 999, 745, 6.75 and 51.2 for P1, P2, P5, G2, G3 and PHINT, respectively.

After the model had been calibrated in terms of the cultivar genetic coefficients, its ability to predict the average maize grain yield and its spatial variability within the plot was tested by comparing the simulated and observed maize grain yield in the GRID plots, where the irrigation water applied in each irrigation event and plant density were measured across 25 subplots. For this task, simulations were run for each of the 25 subplots in each irrigation treatment (daytime and nighttime), considering the observed plant density and irrigation applied at each subplot.

2.3. DSSAT model specifications affecting water balance

The values for the soil parameters affecting water retention properties used in the model (LL, lower limit; DUL, drained upper limit; and SAT, water content at field capacity) were obtained by the Richard pressure plates and readjusted based on soil measurements in another experiment in the same field (unpublished results). The values used were: 0.193, 0.306 and 0.494 m^3 m^{-3} for LL, DUL and SAT, respectively.

The method selected for computing crop evapotranspiration was the method of Penman-Monteith-FAO56 (Allen et al., 1998), as it has proven to give better water balance predictions under water limiting conditions in northwest Spain (López-Cedrón et al., 2008). This method requires daily data of solar radiation, minimum and maximum temperatures, relative humidity and wind speed, which were obtained from a nearby weather station. The soil evaporation method used was the one developed by Ritchie (1972, 1998).

2.4. Simulation of maize yield with variable CU

Different irrigation depths distributions were simulated with the ADOR-Sprinkler model (Dechmi et al., 2004) for each year of the experiment. Irrigation depths distributions were simulated in order to obtain the same average irrigation depths for each irrigation event, but variable CU (100, 90, 80 and 70 %). The ADOR-Sprinkler model gives an irrigation distribution within a sprinkler-delimited area divided in 25 subplots, similar to the one used in the experiments. For simplicity, the CU was set to a constant value (100, 90, 80 or 70%) in all the irrigation events over a whole irrigation season.

Maize yield was then simulated each year of the experiment (2006, 2009 and 2010), with the observed average plant density, and for each of the 25 irrigation depths distributions. Maize yield was expressed relative to the yield of a maize crop without water limitations (water simulation set to “off” in the model).

2.5. Data analysis

In order to assess the performance of the model, the following criteria were used:

(i) Comparison of the average and standard deviation of the simulated and observed data.

(ii) The root mean square error (RMSE) between observed and simulated values, computed as:

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

where *N* is the number of observed values, O_i and P_i are observed and predicted values for the *i*th data pair. The model fit is better as RMSE values are closer to 0.

(iii) Index of agreement (*d*; Willmott, 1982), computed as follows:

$$d = 1 - \frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} \left(|P'_i| + |O'_i| \right)^2} \qquad (3)$$

where $P'_i = P_i - O_{av}$ (average of the observed data) and $O'_i = O_i - O_{av}$. The model fit improves as d-index approaches unity.

(iv) Regression analysis between the observed and predicted values with the SAS software. When the intercept was not statistically different from 0 it was dropped from the model.

(v) Model efficiency (ME) (Nash and Sutcliffe, 1970), calculated by the equation:

$$ME = 1 - \frac{\sum_{n=1}^{n} (O_i - P_i)^2}{\sum_{n=1}^{n} (O_i - O_{av})^2} \qquad (4)$$

ME ranges between $-\infty$ and 1, with 1 being the optimal value. Values from 0 to 1 are generally viewed as acceptable levels of performance, whereas values < 0 indicate that the mean observed value is a better predictor than the simulated value.

3. RESULTS

3.1. Maize grain yield variability as affected by irrigation uniformity and plant density variability: experimental data.

Average wind speed during the irrigation events was 1.7 times higher at daytime than at nighttime in the three years of the experiment (Table 1). Consequently, the average WDEL were usually higher and CU lower at daytime irrigation events. However, in 2009 the wind speed was low (<1.3 m s^{-1}) at day and nighttime irrigation events, which resulted in a similar CU for both types of irrigation. The lower CU found at daytime irrigation compared with nighttime irrigation in 2006 and 2010 also resulted in a higher CV of irrigation depth. Average plant density was similar in the two irrigation time types in all years, the difference being lower than 2.6%. However, there was variability within each plot, so the CV ranged from 5 to 12.6 %. The variability of plant density was similar in each year for the two irrigation types. The lower CV of plant density found in 2010 was probably due to the use of a different and more precise seed drill because the CV was very similar in 2006 and 2009 when an older seed drill was used. In general, maize yield was slightly lower in the daytime irrigation plots (0.3 Mg ha^{-1} less). For each year, the variability in maize grain yield within each plot was similar for the two types of irrigation times. In 2010 the CV of maize grain yield was around 6% while in the previous years it was between 8.3 and 9.8%.

The variability of maize yield within each year and irrigation type (nighttime and daytime irrigation) was analyzed as a function of the irrigation water applied and plant density at each subplot (Table 2). A stepwise multivariate regression of plant density, irrigation, plant density * irrigation and the squares of these variables, revealed that maize yield variability was explained by plant density or the plant density*irrigation interaction in all combinations of year and irrigation time with the exception of nighttime irrigation in 2010 (Table 2). Maize yield variability in 2006 and in 2010 (daytime irrigation) was related to variability of irrigation depth through its interaction with plant density. The coefficient of determination (R^2) was not high (<0.49) except for 2009, where plant density explained 60 – 72 % of the variation in maize yield. However, the significance of plant density or plant density * irrigation was high in general ($P < 0.03$).

The analysis performed indicated that maize grain yield increased as plant density* irrigation depth interaction increased in 3 out of the 6 cases studied. In the other 3 cases where irrigation depth variability did not explain the maize yield variability, the CU of irrigation was higher than 82% (Table 1).

Figure 1 shows observed and simulated maize yield as a function of irrigation water applied in each of the 25 subplots for each year-irrigation time. A general tendency can be seen for an increase in maize yield with increasing depths of irrigation water applied in the three years, but observed values showed a high variability.

3.2. Calibration and testing of the model to simulate maize grain yield spatial variability

Results from the calibration are shown in Table 3. The RMSE of the simulated yield was relatively low (229 kg ha^{-1}), d-Stat was 0.97, and simulated and observed maize yield correlated with a high R^2 (0.90) (Figure 2).

In Table 4 the results of the comparison of observed and simulated values of maize grain yield for the 25 subplots are shown. The RMSE of maize grain yield ranged from 935 to 1337 kg ha^{-1} across all irrigation treatments and years which represents 7 to 10% of the observed values. Thus, the average maize grain yield was simulated with an error lower than 5%. According to the *d* values, performance of the model was relatively good. Model efficiency was greater than 0 in 2006 and for night irrigation in 2009, indicating a good performance of the model in these cases. In 2010 and in day irrigation 2009, ME had negative values but not too far from 0. In four out of six cases simulated values of maize grain yield showed lower variability than observed.

3.3. Relevance of irrigation and plant density uniformity on maize yield simulation

Once tested the accuracy of the model to simulate the mean maize yield of the plot and the within–plot variability of maize yield, the relevance of irrigation and plant density uniformity in maize simulation was studied. Thus, data within each GRID plot was then averaged to study if the inclusion of plant density and irrigation depth variability could improve the model prediction of average maize grain yield in a field as compared with model simulations with average plant density and irrigation water applied (Figure 3). The model accurately predicted maize grain yield when taking into account plant density and irrigation depth variability in the 25 subplots (Figure 3a). When variability of plant density and irrigation uniformity was not taken into account the average maize yield was overpredicted by 3% and the RMSE increased from 328 to 655 kg ha^{-1} by 200% (Figure 3b). When the variability of irrigation depth was considered but the variability of plant density was not considered the average maize yield was only overpredicted by 0.3% (Figure 3c) and the RMSE was similar than when both sources of variability were considered. Taking into account only the variability of plant density resulted in overprediction of average maize yield by 3% and the RMSE increased to 637 kg ha^{-1}. Furthermore, the observed yield reduction under daytime irrigation as compared with nighttime irrigation was not adequately simulated in 2006 and 2010 when irrigation depth variability was not considered (Figure 3b and 3d).

Simulated maize grain yield relative to the potential yield without water limitations was found to decrease as irrigation uniformity coefficient decreased (Figure 4). The extent of the reduction in relative maize yields with CU from 100 to 70% was variable depending on the year. In absolute values, maize grain yield decreased from 0.75 Mg ha^{-1} in 2006 to 2.5 Mg ha^{-1} in 2010. Figure 4 suggests that the decrease of maize yield as a function of CU is dependent on the seasonal irrigation water applied (Table 1), with a higher effect of CU in 2010 when the seasonal irrigation water applied was lower.

4. DISCUSSION

4.1. DSSAT-CERES-Maize model applicability to simulate irrigation uniformity effects on maize grain yield

Regression analysis showed that within plot variability of maize grain yield was related to plant density variability in all except one of the year-irrigation time cases study. However, regression analysis indicated that irrigation depth variability was only related with maize yield trough the interaction with plant density in three out of six year-irrigation time cases. Thus, only when irrigation uniformity was lower than 83% the variability in the seasonal irrigation depth within the plot partially explained the yield variability in the regression analysis. The R^2 of these relationships was often low (< 0.49), or only moderate in 2009 (0.60 – 0.72). This should be taken into account when analyzing the DSSAT-Ceres Maize model simulations because the model can only be well related to observed data to a certain extent, as sources of variation for model runs are only water applied and plant density, and other field variability exists that were not taken into account in the model simulations (e.g., nutrients).

After calibration, the DSSAT-Ceres Maize model capability to simulate the mean yield and the within plot (GRID plot) variability in a sprinkler irrigated plot was evaluated. The model predicted the mean yield within the GRID plot with an error lower than 5%. However, lower within plot variability of maize yield was simulated than observed. Thus the standard deviation of simulated values ranged from 25% to 97% of the observed values and only was higher in one case of study (day irrigation 2010). This result shows that part of the variability in grain yield was related to some other factors not considered in our study. Thus, the model performed reasonably well, taking into account that only spatial variability of irrigation and plant density were considered.

Previous studies with maize under flood irrigation showed that between 50 and 70 % of yield variability can be explained by differences in water availability when using crop growth simulation models in soybean (Paz et al., 1998) and maize (Cavero et al., 2001). Under the sprinkler irrigation conditions of this experiment, less variability in maize yield should be expected to be explained by water availability, as sprinkler irrigation has a higher uniformity coefficient than flood irrigation. Our results are similar to those obtained by Stern and Bresler (1983) that found that 40 % of the grain yield variability in sweet corn can be explained by the irrigation water applied (when the CU was approximately 75%), whereas the remaining 60 % by other soil and/or crop factors. Dechmi et al. (2010) found under the same climatic and sprinkler irrigated conditions that the EPICphase and DSSAT models explained between 30 and 40% of the variability in maize grain yield.

4.2. Taking into account irrigation uniformity improves predictions of maize grain yield

Predictions of the model improved when considering the non uniformity of irrigation water applied, as compared with simulations with the average water applied across the 25 subplots, that overpredicted maize grain yield by 3% (on average 375 kg ha^{-1}). This improvement was due to a decrease in predicted maize grain yield when lower amounts of water were available in some parts of the field. The reduction of average maize yield with decreasing CU of irrigation has been previously observed experimentally under surface irrigation conditions (Warrick and Yates, 1987), sprinkler irrigation (Bruckler et al., 2000; Dechmi et al., 2003a) and drip irrigation (Or and Hanks, 1992). Simulations works have studied as well the effect of water irrigation uniformity on maize yield based on water distributions that were constant over time (Letey et al., 1984; López-Mata et al., 2010; Mantovani et al., 1995; Warrick and Gardner, 1983). Lopez-Mata et al. (2010) and Mantovani et al. (1995) reported maize yield reductions due to a decrease in CU, with values ranging from 25 to 3% depending on the seasonal amount of irrigation. The yield reduction by 3% simulated in this experiment agrees with these previous works, given the already high CU of the sprinkler irrigated system (75 – 84%) and that the crop was supplied with the total amount of CIR. However, higher yield reductions should be expected in conditions of similar CU but with lower seasonal water applied (e.g. in years when water shortage limits irrigation of crops).

Similar yield reductions were simulated or observed by other authors, but the present work is the first to test the model performance against measured yield and irrigation distributions. The results indicate that the model can simulate most of the variation in maize yield that can be attributed to variations in irrigation water depths. In this way, considering irrigation distribution was able to improve model predictions of average maize yield within an irrigated field. The results of Montazar et al. (2010) in alfalfa support our finding, as they concluded that alfalfa forage production was better predicted using a normal distribution of irrigation water, as compared with simulations with a uniform amount of water applied, that tended to overpredict alfalfa yield. The accurate predictions in the present experiment indicate that daily simulation of the water balance and its consequences on maize yield was crucial to show the relevance of spatial variability of irrigation water in maize yield when this variability is not very high (high values of CU).

The different daytime and nighttime irrigation conditions in this experiment allowed to test the accuracy of the model to simulate maize yield under these two different conditions. There are two main differences between daytime and nighttime sprinkler irrigation: wind drift and evaporation losses are higher during daytime irrigation (Cavero et al., 2008) and irrigation uniformity is lower during daytime irrigation because wind speed at daytime is usually higher compared to nighttime (Doorenbos and Pruitt, 1977). Thus, maize yields are lower with daytime sprinkler irrigation compared to nighttime irrigation (Cavero et al., 2008). In this experiment, when considering the non-uniformity of water applied, the model was able to simulate the reduction in maize yields observed in daytime irrigation as compared with nighttime irrigation. However, when simulating with average irrigation depths applied at nighttime and daytime irrigation the model only predicted a decrease in maize yield with daytime irrigation in one of the years. These results indicate that maize yield reduction were mainly linked to the effect of irrigation uniformity in space and time, and not to the different total amount of water applied. As indicated, there are other factors (e.g. nutrients) that can affect yield but were not taken into consideration. Moreover, the lower yields obtained with daytime irrigation could be linked to microclimatic changes from daytime or nighttime irrigation that can affect crop growth (Cavero et al, 2009), but that the model does not take into account.

On the other hand, consideration of the spatial variability of plant density did not improve model simulations as compared with average plant density. This could be due to the fact that we used high plant densities (>74,844 plants ha^{-1}) with relatively low CV (<12.6 %). In any case, our experiment represent the common sowing density in the region and CV obtained by commercial seed drills, but different results could be expected at lower plant densities and higher spatial variability.

4.3. Exploring the effect of irrigation uniformity on maize grain yield

There was some year variability in the effect of irrigation CU on maize yield, but in general terms maize grain yield decreased as the irrigation CU decreased. This was also predicted in a modeling study conducted with CERES-Maize by Pang et al. (1997) and also experimentally observed as stated before. The sharper decrease in maize yield with decreasing CU in 2010 could be related with the fact that the seasonal irrigation depth was lowest this year (Table 1).

New curves could be calculated for lower seasonal irrigation depths, that would have a sharper decrease as the irrigation depth decreases. This implies that the amount of irrigation required for reaching maximum maize yields will increase with decreasing CU of irrigation. As stated by Li (1998) and Letey et al. (1984), the optimum irrigation amount for maximizing net return will decrease with irrigation uniformity but increase with the ratio of yield price to water cost. The present calibrated and validated model can allow to study the optimum irrigation amounts and management for maximizing net return for a given water availability and price-cost scenario.

Irrigation uniformity was considered constant for these simulations, but the model can be used to study variations of CU over time, or even could be connected to a simulator of irrigation depth distribution with real weather data. These could allow studying different effects of CU during different phenological stages of maize (e.g. flowering time). The model could also be used to select the better deficit irrigation strategy, as investigated by Lopez-Mata et al (2010). This can be useful as a decision tool to help farmers to guide them under water scarcity and/or high water price situations.

5. CONCLUSIONS

Regression analysis showed that variability of plant density and seasonal irrigation depth (due to irrigation non-uniformity) were able to explain from 28 to 77 % of maize grain yield variability in the conditions of the experiment of relatively high CU (73-84%) and high plant density (>74,844).

The inclusion of the irrigation depth distribution within 18 x 18 m plots improved the prediction of maize yield as compared with simulations with the average irrigation water applied. RMSE was reduced from 637 to 328 kg ha^{-1} when taking into account irrigation distribution. Not considering this source of variation lead to an overprediction of maize yield by 3%. On the other hand, including plant density spatial distribution in the simulations did not improve predictions of maize yield.

The model was able to simulate the reduction in maize yields observed with daytime irrigation compared to nighttime irrigation (on average 300 kg ha^{-1} less) if non uniformity of irrigation was considered.

The simulated decrease in maize yield with decreasing CU of irrigation was variable ranging from 0.75 Mg ha^{-1} to 2.5 Mg ha^{-1} when decreasing from 100 to 70 % the CU.

Given the ability of the model to simulate CU effects on maize yield it could be used to select the better irrigation strategy and aid farmers under water scarcity and/or high water price situations.

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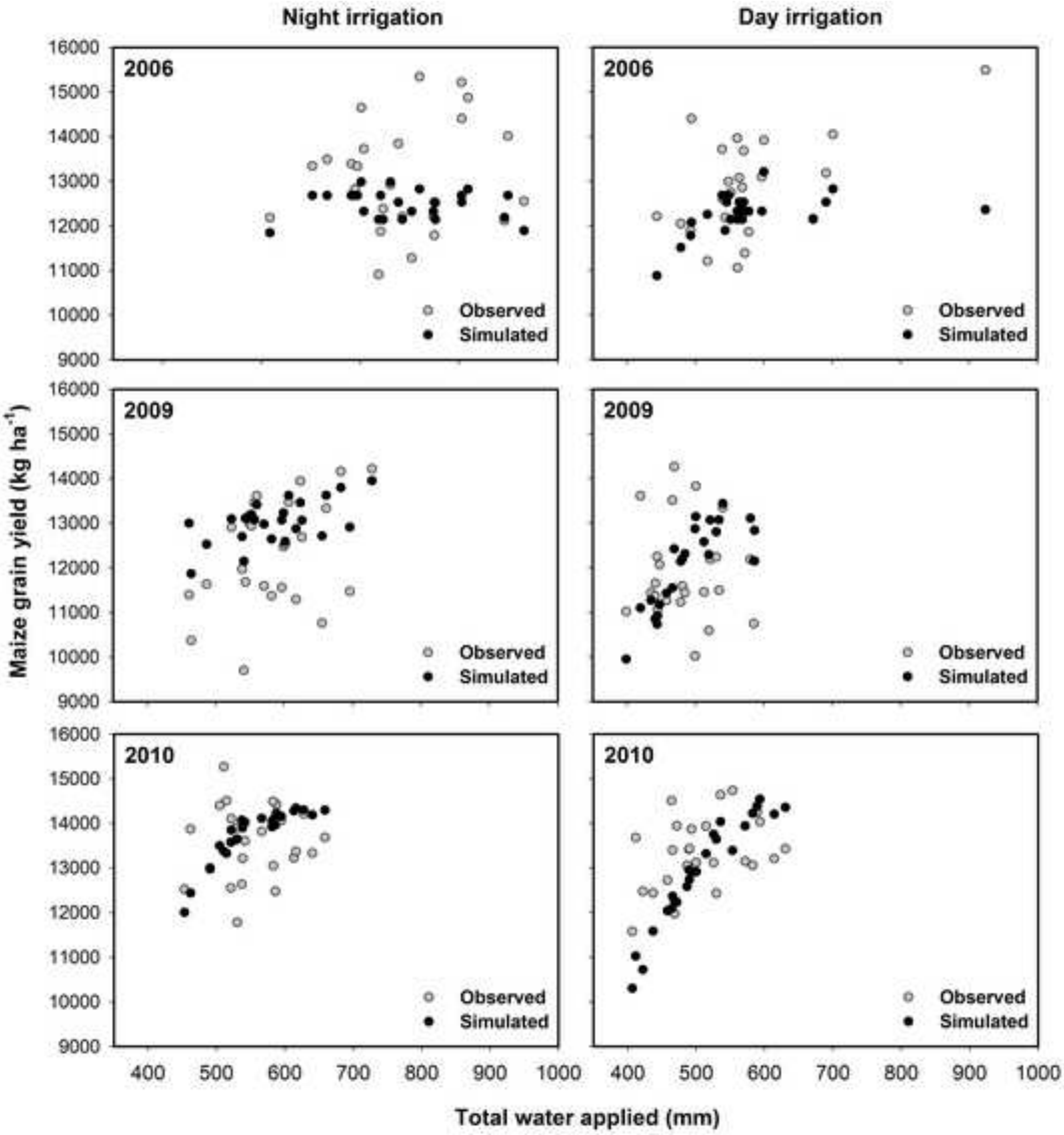
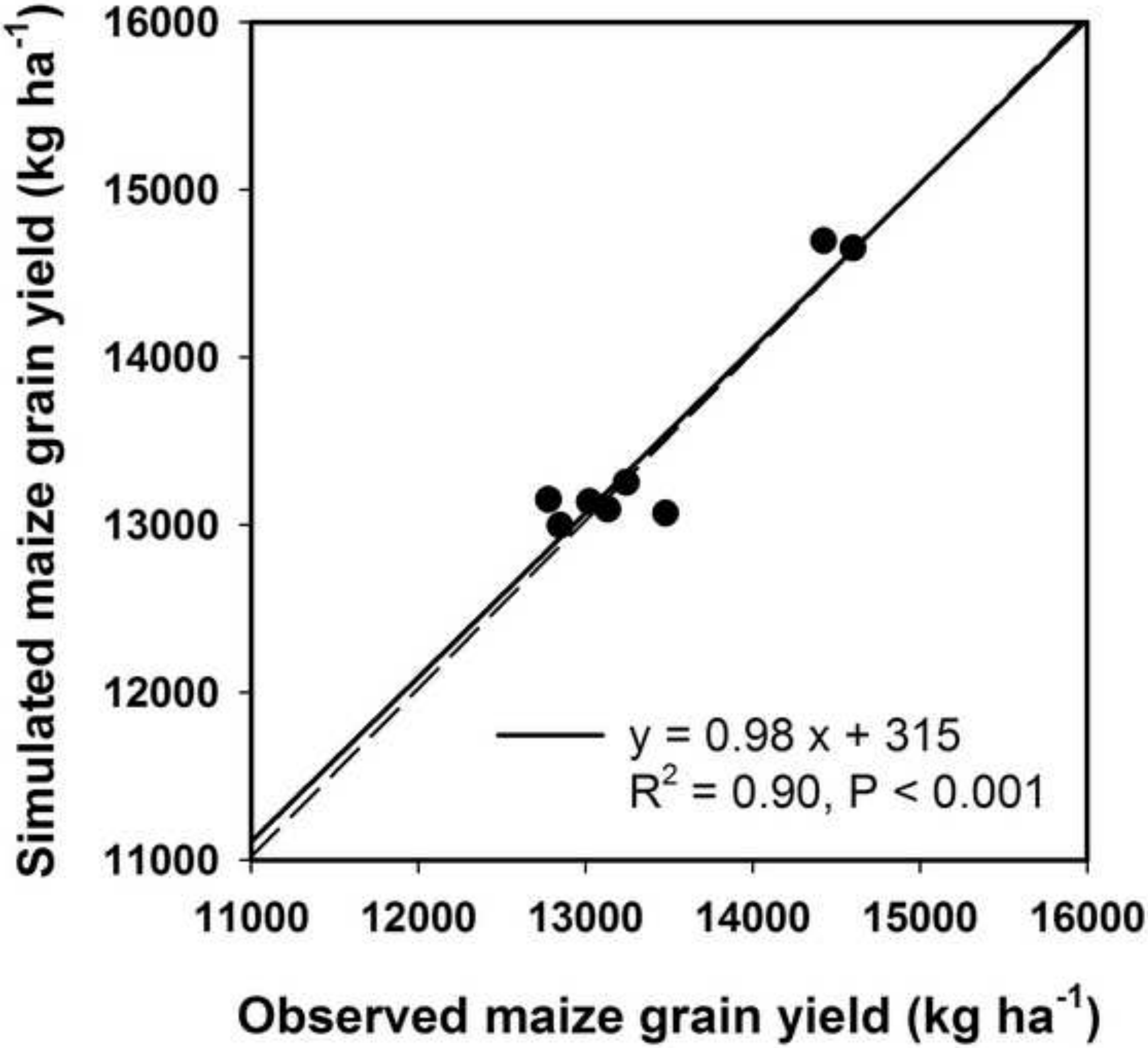
Figure1


Night irrigation
Day irrigation
2006
2009
2010
Observed
Simulated
Maize grain yield (kg ha^{-1})
Total water applied (mm)
9000
10000
11000
12000
13000
14000
15000
16000
400
500
600
700
800
900
1000



Simulated maize grain yield (kg ha^{-1})
16000
15000
14000
13000
12000
11000
11000
12000
13000
14000
15000
16000
Observed maize grain yield (kg ha^{-1})
y = 0.98 x + 315
R^2 = 0.90, P < 0.001

Figure3

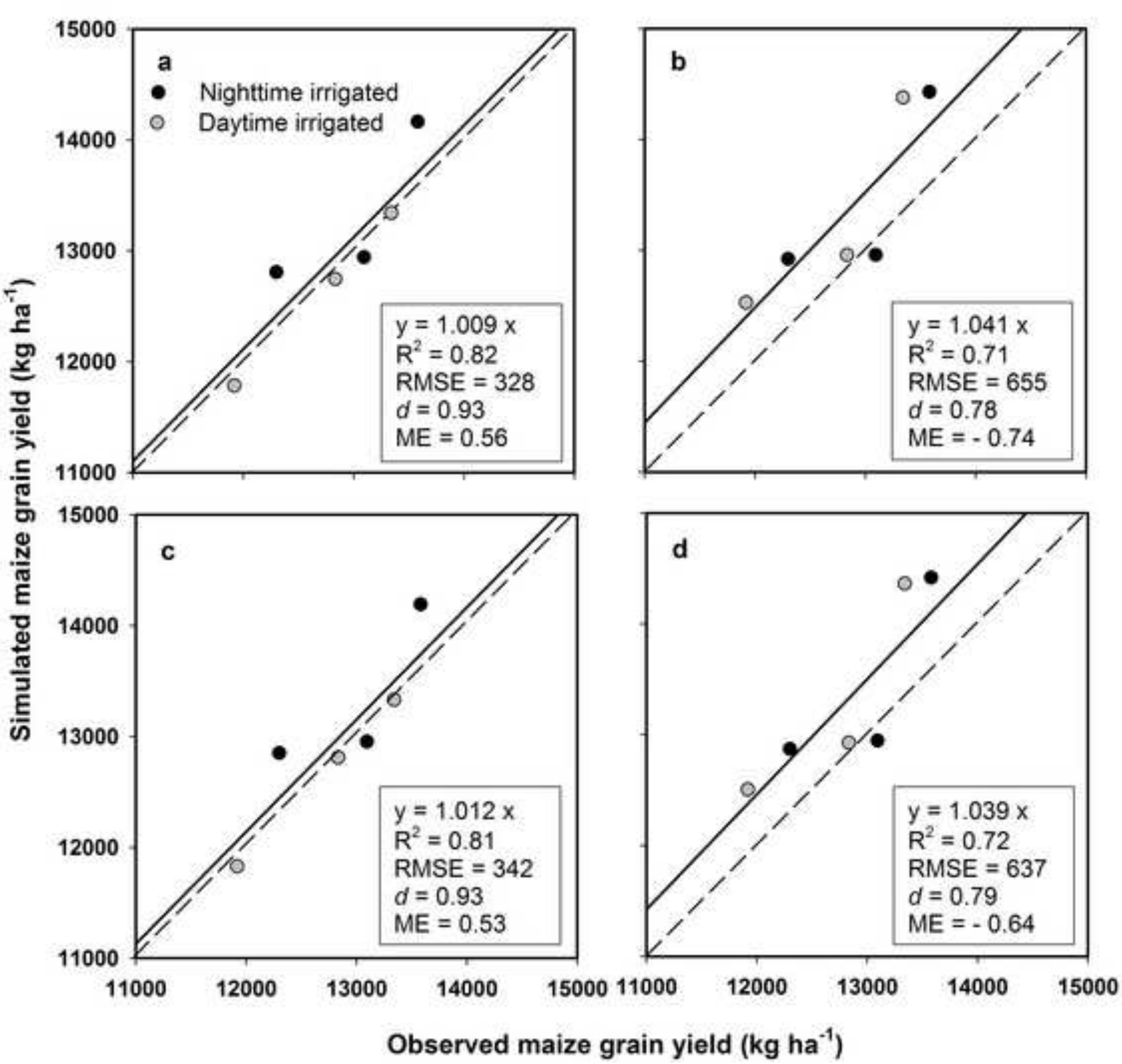

a
Nighttime irrigated
Daytime irrigated
y = 1.009 x
R² = 0.82
RMSE = 328
d = 0.93
ME = 0.56
b
y = 1.041 x
R² = 0.71
RMSE = 655
d = 0.78
ME = - 0.74
c
y = 1.012 x
R² = 0.81
RMSE = 342
d = 0.93
ME = 0.53
d
y = 1.039 x
R² = 0.72
RMSE = 637
d = 0.79
ME = - 0.64
15000
14000
13000
12000
11000
Simulated maize grain yield (kg ha⁻¹)
Observed maize grain yield (kg ha⁻¹)

Figure4

Click here to download high resolution image

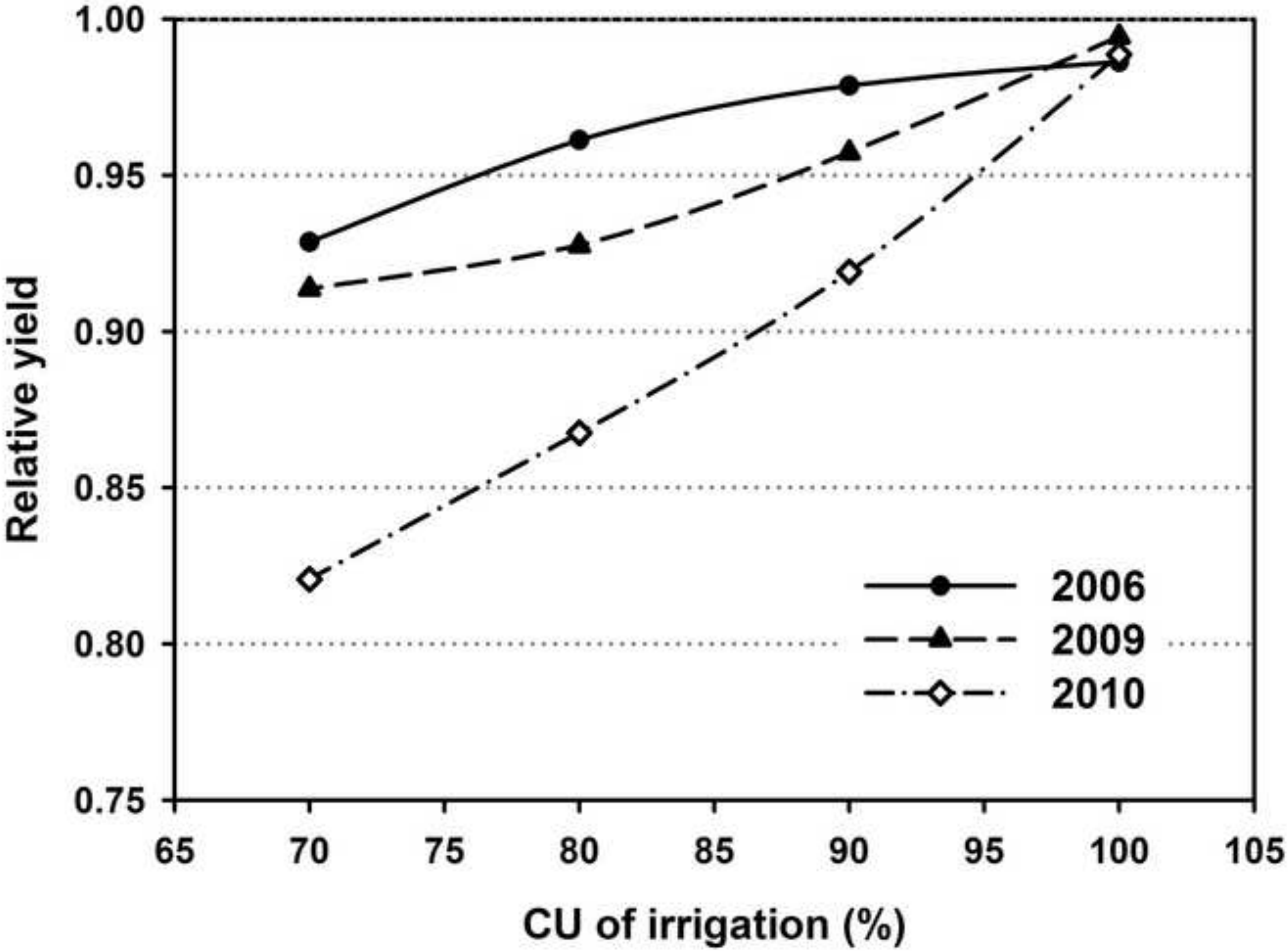


Table 1. Average values of wind speed, total irrigation, number of irrigation events, wind drift and evaporation losses (WDEL), Christiansen coefficient of uniformity (CU), coefficient of variation (CV) of irrigation events and average and CV of plant density and maize grain yield for the different years and irrigation time.

Year	Irrigation time	Wind speed	Irrigation					Plant density		Maize yield	
			Volume	Number	WDEL	CU	CV	Average	CV	Average	CV
		m/s	mm	(nº)	(%)	(%)	(%)	nº/ha	(%)	(Mg/ha)	(%)
2006	**Night**	2.00	645	21	11.4	82	12.9	75378	10.4	13.10	9.20
	Day	2.67	577	21	21.7	75	22.1	74844	10.1	12.84	8.26
2009	**Night**	0.58	585	21	3.3	84	14.7	77689	11.9	12.30	9.82
	Day	1.24	490	21	21.8	83	14.1	75733	12.6	11.92	8.99
2010	**Night**	1.58	495	21	9.5	83	12.1	83733	7.5	13.58	5.97
	Day	2.80	470	21	16.4	78	16.4	83022	5.0	13.34	6.02

Table 2. Results from the stepwise regression analysis of maize grain yield as a function of plant density (density), irrigation, plant density*irrigation, and the squares of these variables (n=25).

Irrigation time	**Model**		
	Equation	**P > F**	**R^2**
	2006		
Night	$y = 9200 + 3.83 \times 10^{-7} * \text{Density}^2 + 7.08 \times 10^{-13} * (\text{Density} * \text{Irrigation})^2$	0.011	0.46
Day	$y = 9269 + 8.2 \times 10^{-5} * \text{Density} * \text{Irrigation}$	< 0.001	0.49
	2009		
Night	$y = 3665 + 0.110 * \text{Density}$	< 0.001	0.72
Day	$y = 8659 + 5.60 \times 10^{-7} * \text{Density}^2$	< 0.001	0.60
	2010		
Night	No variable met the 0.15 significance level for entry into the model.		
Day	$y = 10713 + 6.2 \times 10^{-4} * \text{Density} * \text{Irrigation}$	0.03	0.18

Table 3. Model calibration (n=8). Average and standard deviation of observed and simulated data, root mean square error (RMSE), coefficient of determination (R^2), index of agreement (d-Stat) and model efficiency (ME). Data from nighttime irrigated plots from 2006, 2009 and 2010.

	Average		**Standard dev.**					
Variable Name	**Obs.**	**Sim.**	**Obs.**	**Sim.**	**RMSE**	**R^2**	**d-Stat.**	**ME**
Anthesis day	76	76	3.8	3.4	3.1	0.40	0.78	0.25
Maturity day	145	141	7.7	5.0	4.7	1.00	0.83	0.56
Maize grain yield (kg ha^{-1})	13442	13506	699	724	229	0.90	0.97	0.88
Number of grains (grains m^{-2})	4070	4088	310	237	96	0.94	0.97	0.89
Grain weight (g $grain^{-1}$)	0.3311	0.3307	0.0197	0.0156	0.009	0.75	0.92	0.75

Table 4. Model validation. Average and standard deviation of observed and simulated maize grain yield, root mean square error (RMSE), index of agreement (*d*) and model efficiency (ME) for the different years and irrigation time treatments.

	Maize grain yield						
	Average		Standard deviation				
	Obs.	Sim.	Obs.	Sim.	RMSE	*d*	ME
	---------- kg ha^{-1} ----------						
			2006				
Night irrigation (n=25)	13095	12941	1205	301	1039	0.49	0.23
Day irrigation (n=25)	12836	12743	1060	461	935	0.53	0.20
			2009				
Night irrigation (n=25)	12301	12806	1208	398	1026	0.66	0.27
Day irrigation (n=25)	11919	11782	1071	1041	1337	0.57	-0.57
			2010				
Night irrigation (n=25)	13581	14164	811	574	993	0.46	-0.53
Day irrigation (n=25)	13342	13339	804	1385	1238	0.68	-1.41