WIND EFFECTS ON SOLID SET SPRINKLER IRRIGATION DEPTH AND CORN YIELD

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ABSTRACT

A field experiment was performed to study the effect of the space and time variability of water application on solid set sprinkler irrigated corn yield. A solid set sprinkler irrigation setup – typical of the new irrigation developments in the Ebro basin of Spain – was considered. Analyses were performed to (1) study the variability of the water application depth in each irrigation event and in the seasonal irrigation, and (2) relate the spatial variability in crop yield with the variability of the applied irrigation and with the soil physical properties. The results of this research showed that a significant portion of the Christiansen coefficient of uniformity (*CU*) variability, wind drift and evaporation losses were explained by the wind speed alone. The seasonal irrigation uniformity (*CU* of 88 %) was higher than the average uniformity of the individual irrigation events (*CU* of 80 %). No evidence has been found proving that the

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soil diminishes the heterogeneity induced by the irrigation water distribution. The uniformity of soil water recharge was lower than the irrigation uniformity and the relationship between both variables was statistically significant. Results indicated that grain yield (*GY*) variability was partly dictated by the water deficit resulting from the non-uniformity of water distribution during the crop season. The uniformity of the irrigation events applied beyond the flowering stage was correlated with grain yield, indicating that in this period a proper selection of the wind conditions is required in order to attain high yield in sprinkler irrigated corn.

INTRODUCTION

Two irrigation technologies are currently used for the irrigation of field crops, such as corn: surface and sprinkler irrigation. Several authors have reported on the advantages of sprinkler irrigation over surface irrigation (Cuenca, 1989; Fuentes-Yagüe, 1996). These advantages have led to a steady increase in sprinkler irrigation acreage during the last decades. For instance, according to the yearly survey of the Irrigation Journal, from 1985 to 2000 the percent acreage of sprinkler irrigation in the United Sates increased from 37 % to 50 %.

One of the most relevant parameters in the operation of sprinkler irrigation systems is the uniformity of water distribution (Merriam and Keller, 1978). Irrigation evaluations are used in the field to establish irrigation performance, which in sprinkler irrigation is primarily represented by irrigation uniformity. During the evaluation process, quantitative levels of uniformity are established. Sprinkler irrigation systems require a minimum value of uniformity in order to be considered acceptable. For solid set sprinkler systems, Keller and Bliesner (1991) classified irrigation uniformity as “low” when the Christiansen Coefficient of Uniformity (*CU*) is below 84 %.

Several authors have reported that wind is the main environmental factor affecting sprinkler performance (Seginer et al., 1991; Faci and Bercero, 1991; Tarjuelo et al., 1994; Kincaid et al., 1996; Dechmi et al., 2000). These references have led to two firm conclusions. First, part of applied water is lost by evaporation and – particularly – wind drift out of the irrigated area. Second, under windy conditions, the water distribution pattern of an isolated sprinkler is distorted and reduced. Therefore, the Coefficient of Uniformity shows a clear trend to decrease as wind speed increases. However, particular combinations of nozzle size, operating pressure and sprinkler spacing may show a slight increase in *CU* at low wind speeds (Dechmi et al, 2002).

The response of crop yield to irrigation water supply has been extensively analysed (Doorenbos and Kassam, 1979; Hanks, 1983). Several works have confirmed the negative impact of irrigation non-uniformity on crop yield and on deep percolation losses. Bruckler et al. (2000), summarizing previous research efforts, reported that the pattern of spatial variability in soil water, crop height and crop yield is often similar to that of the irrigation water application. A number of experiments were designed to characterise the impact of the spatial variability of the available soil water on crop yield (Stern and Bresler, 1983; Dagan and Bresler, 1988; Or and Hanks, 1992). A common conclusion of these studies is that besides water application variability, water dynamics in the vertical (deep percolation and capillary rise) and horizontal directions condition its availability at the crop root zone. Authors differ in the interpretation of the effects of the heterogeneity tied to soil properties on the water distribution in the profile: some consider that soil effects increase the irrigation water distribution heterogeneity (Sinai and Zaslavsky, 1977), while others consider that the soil diminishes the heterogeneity induced by the irrigation system (Hart, 1972; Stern and Bresler, 1983; Li, 1998).

No reference was found in the literature about the effect of the environmental factors (such as wind speed) on the time evolution of irrigation uniformity (during the irrigation season), and on the variability of crop yield within a solid set sprinkler spacing. This is a key issue for irrigation water conservation and for the proper design and management of solid set irrigation systems.

In the conditions of the Ebro valley of Spain, corn is one of the main irrigated crops. Current developments in new irrigation projects and in irrigation modernization are leading to a rapid increase in solid set sprinkler acreage. In the Ebro valley conditions, wind is a serious limiting factor to sprinkler irrigation, due to its high frequency and intensity (Hernández Navarro, 2002). In fact, more than 50 % of the daily average wind speeds registered in the irrigated areas of Aragón between April and September are higher than 2 m s^{-1} (Oficina del Regante, 2002). Crop water requirements for corn are among the largest in the area. This crop is very sensitive to water stress, particularly during the flowering stage. Relevant decreases in crop yield have been locally reported when the irrigation supply is limited (Cavero et al., 2000; Farré et al, 2000).

The purpose of this paper is to evaluate experimentally the effect of irrigation water distribution under variable environmental conditions on corn yield in a solid set sprinkler irrigation setup typical of the new irrigation developments in the Ebro basin.

Particular objectives include: a) to analyse the variability of the water application in each irrigation event and in the seasonal irrigation; and b) to relate the spatial variability in crop yield with the variability of applied irrigation and with the soil physical properties. The results of this research will serve two additional purposes: 1) to compare the magnitude of the variability and the derived relationships with those reported for a previous, similar experiment in the same area using surface irrigation; and 2) to establish a base for the calibration of sprinkler irrigation and crop simulation models. These models will be applied in future research to the exploration of alternative irrigation strategies.

MATERIAL AND METHODS

Experimental site

The experiment was conducted at the experimental farm of the Agricultural Research Service of the Government of Aragón in Zaragoza, Spain (41º 43´N, 0º48´W, 225 m of altitude). The climate is Mediterranean semiarid, with mean annual maximum and minimum daily air temperatures of 20.6ºC and 8.5ºC, respectively. The yearly average precipitation is 330 mm, and the yearly average reference evapotranspiration (*ETo*) is about 1,110 mm (Faci et al., 1994). The experimental soil was a Typic Xerofluvent coarse loam, mixed (calcareous), mesic, following the U.S Soil Survey Staff (1992) guidelines for soil classification and taxonomy. The P and K content in the upper 0.30 m soil layer was determined in a composite sample. The resulting values were 25.8 ppm of P and 194.0 ppm of K. The organic matter ranged from 1.4 % at the surface to 0.6 % at 1.5 m depth. The average pH was 8.2. Soil salinity levels (EC_e = 3.88 dS m^{-1} on the average) were found to be well above the threshold values for corn.

Irrigation water is pumped from the Urdán canal, diverting water from the Gállego river (a tributary of the Ebro river). The Urdán water carries a relevant salt load (about 2 dS m^{-1}) during the summer. For this reason, the electrical conductivity of the irrigation water (EC_w) was monitored in each irrigation event.

Experimental design

The experimental design of the solid set sprinkler irrigation system was defined to obtain high irrigation uniformity under low wind speed conditions. The nozzle diameters were 4.4 mm (main) and 2.4 mm (auxiliary), and were located at a height of 2.30 m over the soil surface. The sprinkler spacing was triangular, 18 by 15 m. The sprinklers and nozzles were manufactured by VYRSA (Briviesca, Burgos, Spain). The sprinkler model was “VYR 70”. The nozzle operating pressure was kept constant during the season at 300 kPa. In this sprinkler configuration, the resulting *CU* under calm conditions was high (above 94 %). The sprinkler discharge was volumetrically measured to be 0.48 L s^{-1}. The irrigation depth for each irrigation event was determined from this discharge, the irrigation time and the sprinkler spacing.

A corn crop (Zea mays L. cv. Dracma) was planted on May 17, 2000, at a density of 8 plants m^{-2}, with the rows being 0.75 m apart. Fertilisation consisted of 667 kg ha^{-1} of a 9-18-27 complex applied before sowing, and 234 kg N ha^{-1} as Ammonium Nitrate applied on June 1. Pests and weeds were controlled according to best management practices in the area.

Two experimental plots (hereafter designated as plot A and plot B) were selected in the field as shown in Figure 1a. In each plot, twenty-five square parcels (1.5 m in side) were marked. Berms were built around them to prevent surface runoff. These parcels were the basic units for all the measurements performed during the experiment. Two catch cans were installed in the middle of each parcel and maintained at approximately the same height than the crop canopy (the height of the catch cans was increased from 0.36 m to 2.16 m throughout the season). Twenty-five access tubes for soil water content measurements by neutron probe (Model 3320, Troxler Electronic Laboratories, North Carolina) were installed to a depth of 1.5 m in each parcel of plot A. Details of the design of plot A are presented in Figure 1b.

Crop water requirements and irrigation scheduling

Meteorological data were daily recorded using an automatic station (Campbell Scientific, Logan, Utah) located about 200 m of the experimental parcel. These data were used to compute the daily crop water requirements during the corn cycle. The daily corn evapotranspiration (*ETc*, *mm*) was estimated from daily values of reference evapotranspiration (*ETo, mm*) calculated using the FAO Penman-Monteith equation, and from tabulated crop coefficients (K_c) following the FAO approach (Allen et al., 1998). During all the experiment, two-minute averages of wind speed and direction were recorded in the abovementioned meteorological station. For each irrigation event the average wind speed ($W, m\ s^{-1}$) was determined, and a statistical analysis was performed on the evolution of the wind speed and direction.

An initial irrigation event (irrigation # 0) was applied in June 1 with a dose of 25 mm. This irrigation event was not evaluated in detail, and therefore its results were only used for irrigation scheduling purposes. This irrigation was performed when water stress was observed in approximately 25 % of the plants. For the rest of the season, the irrigation schedule criterion was changed, and irrigations were performed when the soil water balance indicated that the level of allowable water depletion (50 % of the total available water) had been reached. Each irrigation event lasted for the time required to regain field capacity. The daily evolution of the average soil water content (SWC_i, *mm*) was determined at the time when the initial soil water content was gravimetrically measured. Daily soil water content was updated as:

$$SWC_i = SWC_{i-1} + P_i + IDc_i - ETc_i \ , \qquad [1]$$

where SWC_{i-1} is the average soil water content on day *i-1* (mm); P_i is the precipitation for day i (mm); IDc_i is the catch can irrigation dose for day *i* (mm); and ETc_i is the crop evapotranspiration for day *i* (mm). Runoff was assumed to be negligible because the field was laser levelled to zero slope and each parcel was surrounded by earthen berms. Drainage below the rooting depth was equally neglected for scheduling purposes. According to this approach, a total of 23 additional irrigation events were applied during the whole corn cycle. Figure 2 presents the cumulative *ETc* and water applied (catch can irrigation dose plus precipitation) during the growing season. At the beginning of the season a light overirrigation can be appreciated. Towards the end of the corn cycle, irrigation was slightly deficitary, in order to avoid an excess in soil water at harvest, following the local farmers’ practice.

Measured soil Properties

Selected soil properties were analysed in each parcel of both plots, by 0.3 m layers and to a depth of 1.5 m when possible. The analysed properties included texture and gravimetric water content at field capacity (w_{FC}) and wilting point (w_{WP}). These gravimetric measurements were computed at the laboratory using pressure plates. Considering the soil texture, pressures of 0.02 and 1.5 MPa were considered representative of field capacity and wilting point, respectively. The average bulk density was determined as 1.45 Mg m^{-3} from the 18 samples collected for the calibration of the neutron probe and discussed in the next paragraph. Bulk density was used to determine the corresponding volumetric water contents (θ). Soil depth was measured during the soil sampling performed to determine soil properties. All these properties were combined to determine the total soil available water (*TAW*, *mm*) as defined by Walker and Skogerboe (1987).

The field calibration of the neutron probe was performed at 0.15 m intervals to a depth of 1 m. A total of 18 points were read and undisturbed soil samples were extracted to determine the volumetric water content. The regression analysis (neutron probe measurements *vs.* measured volumetric water content) yielded a determination coefficient (R^2) of 0.96. The neutron probe readings were performed only in plot A at an interval of 0.30 m and to a depth of 1.5 m. The readings were taken one day before and one day after four irrigation events distributed along the season.

In each experimental parcel of both plots, the gravimetric water content and the 1:5 soil extract electrical conductivity ($EC_{1:5}$) were measured at the same 0.30 m layers at sowing and harvest times. The electrical conductivity of the soil saturation extract (EC_e) was estimated from $EC_{1:5}$ using the relationship obtained by Isla (1996) at the same experimental field.

Irrigation evaluation

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 the Christiansen uniformity coefficient *CU*, (Christiansen, 1942) and the Distribution Uniformity, *DU*, (Merriam and Keller, 1978). These parameters were computed separately for plots A and B for each irrigation event. Seasonal coefficients were also computed for each plot from the cumulative *IDc* applied to each parcel. The classification of *CU* values proposed by Keller and Bliesner (1991) was used in this work. The wind drift and evaporation losses (*WDEL, %*) produced during each irrigation event were computed from the irrigation dose discharged by the sprinkler system (*IDd*, obtained from the sprinkler discharge, the spacing and the duration of the irrigation event, and expressed in mm) and the average *IDc*:

$$WDEL = \frac{IDd - \overline{IDc}}{IDd} 100 \qquad [2]$$

A similar principle can be applied to each parcel in a given irrigation event. In this case, a deficit coefficient (C_D) can be computed to express the water deficit after each irrigation event in points receiving less water than *IDd*. The deficit coefficient (C_D) and the seasonal deficit coefficient (C_{DS}) were computed following the expressions:

$$C_D = \frac{IDd - IDc}{IDd} 100 \quad ; for \quad IDd > IDc \qquad [3]$$

$$C_{DS} = \frac{IDd_S - IDc_S}{IDd_S} 100 \quad ; for \quad IDd_S > IDc_S \qquad [4]$$

where the subscript "S" indicates seasonal, cumulative values.

In order to compare the irrigation depth collected in the twenty-five catch cans of both plots during each irrigation event, the Root Mean Square Error (*RMSE*) of the application rate was determined as:

$$RMSE = \frac{1}{25\,t}\sqrt{\sum_{i=1}^{25}\left(IDc_{iA} - IDc_{iB}\right)^{2}} \qquad [5]$$

Where t represents the duration of the irrigation event. The *RMSE* was used to quantify the differences in the water application pattern between two adjacent identical sprinkler spacings irrigated at the same time and under similar environmental conditions.

Corn Yield and seasonal irrigation water applied

At crop maturity, the aerial parts of corn plants from all parcels in plots A and B were hand harvested. The ears were separated from the rest of the plants and were oven dried at 60ºC to constant weight. The grain was separated from the corncob, its moisture was measured and the resulting weight was adjusted to represent a moisture content of 14 %. The analysed crop yield parameters included corn grain yield at moisture content of 14 % (GY, $kg\ ha^{-1}$) and total dry matter (TDM, $kg\ ha^{-1}$).

Data analysis

The statistical analysis of data and derived variables from the experiment was performed using the SAS statistical package (SAS, 1996). The procedures used were PROC REG and PROC CORR for regression and correlation analysis, respectively. The statistical significance levels considered in all the analyses were: "*ns*" to indicate non significant ($P > 0.05$); "*" to indicate $0.05 \geq P > 0.01$; "**" to indicate $0.01 \geq P > 0.001$; and "***" to indicate $0.001 \geq P$.

RESULTS AND DISCUSSION

Irrigation water distribution pattern analysis

Table 1 presents the characteristics of the 23 evaluated irrigation events. In 56 % of them, the average wind speed was lower than the value of 2.1 m s^{-1} reported by Faci and Bercero (1991) as the threshold for an accused descent of the *CU* in the middle Ebro valley conditions. In 22 % of the irrigation events wind blew from all directions, and the average wind speed in these cases was lower than 2 m s^{-1}. Nearly 50 % of the frequent wind directions correspond to either Northwest winds (*cierzo*, in the local terminology) or Southeast winds (*bochorno*, in the local terminology). The highest average wind speeds correspond to the *cierzo* spells. This wind pattern is very common of the middle Ebro valley area (Faci and Bercero, 1991).

According to Ayers and Westcot (1989), the salinity of the water used for irrigation in this experiment (average EC_w of 1.78 dS m^{-1}) is above the threshold values for corn (1.1 dS m^{-1}). These authors report that the expected yield should be about 90 % of maximum. The *IDd* ranged from 12.8 mm to 44.8 mm between irrigation events, while the average *IDc* varied from 9.7 mm to 32.4 mm. The seasonal amount of irrigation water applied was 664 mm, with a crop evapotranspiration of 623 mm. The values of *WDEL* ranged from 6 % to 40 %, with an average of 20 %. Therefore, the seasonal wind drift and evaporation losses amounted to 133 mm.

The spatial distribution of the water applied in plots A and B was different in each irrigation event. The extreme values of *CU* correspond neither to the highest average wind speed (irrigation 14, W= 6.5 m s^{-1}) nor to the lowest (irrigation 19, W= 0.6 m s^{-1}). This may be explained by the frequent changes of wind speed and direction during each particular irrigation event. The variability could also be observed in the difference between the volume of water collected in both A and B catch can sets during each of the 23 irrigations. The *RMSE* of the water collected in the catch cans attained maximum values when the wind speed was high and the wind direction range was narrow. Values of *RMSE* ranged from 0.39 mm h^{-1} to 1.27 mm h^{-1}, with an average of 0.63 mm h^{-1}. A regression analysis performed between the *CU* values computed in both plots indicated that the regression slope and intercept were not significantly different from 1 and 0, respectively ($R^2 = 0.970^{***}$).

In Figure 3, two cases of water distribution during two consecutive irrigation events of the same duration are presented. The first case represents an irrigation event with low uniformity (irrigation 9, *CU*'s of 51.6 % and 57.8 % in plots A and B, respectively). The second case represents an irrigation event with high uniformity (irrigation 10, *CU*'s of 91.4 % and 91.8 % in plots A and B, respectively). It can be observed (particularly in irrigation 9) that the wind distortion of the water distribution pattern concentrates precipitation in particular areas of the experimental field. In irrigation 9 the *IDd* was 26.1 mm, but the values of *IDc* collected in the 25 parcels of both plots showed slightly different dispersions. The *IDc* in Plot A ranged from 4.5 to 38.5 mm, with an average of 17.6 mm and a *CV* of 58.1 %. In plot B the *IDc* ranged from 5.5 to 37.0 mm, with an average of 16.2 mm and a *CV* of 53.5 %. In this irrigation event, 76 % and 84 % of the catch cans in plots A and B, respectively, received an irrigation dose lower than *IDd*.

The *CU* of the irrigation events performed under wind speeds lower than the threshold value proposed by Faci and Bercero (1991) (52 % of the irrigation events) was larger than 84 %, except for irrigation 23, in which the *CU* was 81.2 % in plot A and 80.4 % in plot B. This could be due to the fact that during 37 % of the irrigation time the wind speed was slightly beyond the threshold value (with an average of 2.6 m s^{-1}), whereas the average wind speed was 1.8 m s^{-1}. The best fit between the wind speed and the *CU* of both plots was obtained with a third degree polynomial function (Figure 4). This relationship explains 90 % of the variation of the *CU*. For wind speeds beyond 2 m s^{-1} the value of *CU* is clearly affected by the wind speed. This perception confirms the validity of the threshold value reported by Faci and Bercero (1991). Urrutia (2000), under similar experimental conditions, found an accused descent of the *CU* when the wind speed exceeded 3.5 m s^{-1}. This value almost doubles the threshold proposed by Faci and Bercero (1991).

The relationship between the wind speed and the *WDEL* of both plots showed that the data dispersion increases with the wind speed, particularly beyond 2 m s^{-1} (Figure 5). This seems to be due to the variability of wind speed and direction during the irrigation time. In fact, heavy wind spells can induce drift losses that can not be explained by the average wind conditions. Both the lineal (R^2 = 0.810) and potential (R^2 = 0.792) regression models showed adequate fitting to the experimental data. Relevant differences between both models are observed for wind speeds below 0.5 m s^{-1}. In fact, for calm conditions the lineal and potential regression models estimate

WDEL values of 7.5 % and 0.0 %, respectively. It will be difficult to assess which model is more adequate in the Ebro valley conditions, since it is not easy to find a calm period lasting for a few hours. The potential model does not seem adequate for low wind conditions, since there are reasons to believe that *WDEL* will always be greater than zero. The lineal model, however, may overestimate the *WDEL* under calm conditions.

The average *CU* of all irrigation events can be classified as low (Table 1), while seasonal irrigation had a high uniformity (*CU* of 88.0 % on the average of both plots). Indeed, the differences in wind speed and direction between irrigation events lead to a compensation process that results in the seasonal uniformity being higher than the average uniformity of the individual irrigation events. In this case the difference amounts to 7.5 %. This is frequent in sprinkler irrigation, due to the marked random character of the water distribution pattern (Dagan and Bresler, 1988). In an experiment performed with the same crop and in the same farm, but using surface irrigation, Zapata et al. (2000) found that the distribution uniformity (*DU*) was 5.2 % higher for the seasonal data than for the average of the irrigation events. In our work, if *DU* values were used (data not presented), the difference would be of 11 %. These results suggest that the wind induced randomness in sprinkler irrigation water application doubles the intensity of the compensation process found in surface irrigation.

Spatial variability of the measured soil properties

Soil depth in plot A reached 1.50 m in all parcels, while in plot B, soil depth varied from 1.03 m to 1.50 m. Plots A and B showed similar average values of the three textural classes in all soil layers (Table 2). In addition, the upper layers (0 – 0.60 m) were characterized by a low spatial variability in the textural classes. The gravimetric water contents at field capacity (w_{FC}) and wilting point (w_{WP}) showed low variability among soil layers and the highest average values were observed at the upper 0.30 m layer. As soil depth increases both w_{WP} and w_{FC} decrease. This could be attributed to the moderate increase in the sand fraction. The value of *TAW* is not clearly reduced at deeper layers, exception made of the two deepest layers in plot B, where the decrease in *TAW* is due to the reduced soil depth. In the top layers (0.0 – 0.60 m) the coefficient of variation of w_{Wp} and w_{FC} is small, and therefore the resulting spatial variability of the topsoil *TAW* is small. In deeper soil layers (0.60 – 1.50 m) the coefficients of variability approximately double those found at the upper layers. The variability of these soil properties in the deep layers should not have a relevant effect on the soil water regime, since the experimental *IDc* (22 mm per irrigation event on the average) is small in comparison with the top layers *TAW* (which averaged 101.9 mm, with a *CV* of 8.6 %). This circumstance could reduce the dependence of sprinkler irrigated corn water status and yield on soil physics. Zapata et al. (2000) reported this dependence as being very relevant in surface irrigated corn.

The average EC_e was slightly higher in plot B at harvest than in plot A (Table 2). In the top layer (0 – 0.30 m) soil salinity decreased along the growing season, while in the 0.30 – 1.50 m layers there was a moderate increase in salinity. This increase was particularly relevant at the 0.60 – 0.90 m and 0.90 – 1.20 m layers of plot B. Considering all the soil profile, the increase in soil salinity from sowing to harvest time was 0.09 dSm^{-1} in plot A and 0.78 dSm^{-1} in plot B. The soil salinity found in our experimental site is above the published soil salinity tolerance threshold values for corn (1.7 dSm^{-1}, Ayers and Westcot, 1989). Under these soil salinity conditions the expected yield should be reduced to 50 – 75 % of the potential yield. However, several authors have reported that yield is unaffected by salt stress at moderate water stress levels, while in full irrigation schedules salt stress can cause significant yield reductions (Russo and Bakker, 1987; Shani and Dudley, 2001).

Relationship between irrigation water distribution and soil water content

The spatial distribution of soil water after each irrigation event was characterized by the Christiansen uniformity coefficient of soil water content (CUs_a) as proposed by Li (1998). Figure 6a illustrates the relationship between the uniformity of irrigation water (CU) and the uniformity of soil water content within the soil perfil ($CUs_{a1.50}$) for irrigations 2, 9, 13 and 21. $CUs_{a1.50}$ values were very high (above 94 %) for all the considered irrigation events and there was no significant statistical relationship between both variables. The results obtained by Stern and Bresler (1983) and Li (1998) under similar experimental conditions showed that CUs_a exceeded 90 % even when the CU was below 70 %. In this research, however, $CUs_{a1.50}$ reached values between 94 and 95 % even for very low irrigation uniformities (CU = 51 %).

Only the upper soil layer (0 – 30 m) showed a significant increment in its water content following each irrigation event. Considering only the upper soil layer, soil water uniformity values ($CUs_{a0.3}$) were also higher than CU (Figure 6b), increasing as the CU increased (R^2 = 0.924*). Hart (1972), Li and Kawano (1996) and Li (1998) reported that sprinkler irrigation water was more uniformly distributed in the soil (CUs) than at the soil surface (CU) because of the redistribution of irrigation water in the soil. Under this hypothesis, the available soil water for the crop would be quite similar in the field and consequently the crop yield would show a lower variability due to the non-uniformity of the irrigation water.

Prior to each irrigation event, the upper soil water content tends to reach a uniform value controlled by crop water extraction and soil physical properties. In order to prove this hypothesis, Figure 6c was prepared. A scatter plot presents the *CU* of the previous irrigation event (CU_{i-1}) *vs.* the soil coefficient of uniformity before the irrigation event at the upper layer ($CUs_{b0.30}$). The values of this last variable were systematically high (beyond 92 %), and showed no statistical relationship with CU_{i-1}.

The soil coefficient of uniformity for soil water recharge (θ_R), labelled $CUs_{R1.50}$, was always lower than the corresponding *CU* (Figure 6d). This difference was particularly relevant for the lowest value of *CU*. The low values of *IDc* in some parcels may have resulted in a very shallow, centimetric water recharge, very prone to evaporation and difficult to measure accurately with the neutron probe. However, a significant linear regression was found between the uniformity of soil water recharge and *CU*, proving the link between catch can uniformity and soil water recharge uniformity. Therefore, it can be concluded that short-term soil water redistribution was not relevant in this experiment. These findings also announce the possibility of explaining the spatial variability of crop yield using catch can data.

A correlation analysis was performed between the catch can irrigation dose (*IDc*), the volumetric water content measured with neutron probe before and after the irrigation events (θ_b and θ_a, respectively) and the water recharge ($\theta_R = \theta_a - \theta_b$). This analysis was applied to irrigation events 2, 9, 13 and 21 (Table 3). Correlation between

θ_b and θ_a in each irrigation event was always high and strongly significant (ranging from 0.831^{***} to 0.990^{***}). The *IDc* applied in irrigations 2, 9 and 13 presented significant correlation coefficients with soil water recharge, varying from 0.527^{**} to 0.781^{***}. The best correlation was found for irrigation 9, characterized by the lowest value of *CU*. No significant correlation was found in irrigation 21. This seems to be due to the uniform water distribution (*CU* = 88.7 %, the highest among the four irrigation events with available soil water measurements). These findings suggest that the relationship between *IDc* and θ_R heavily depends on irrigation uniformity. The relationship between *IDc* and θ_a follows the same trend identified for *IDc* and θ_R. Finally, as expected, no statistical relationship could be established between *IDc* and θ_b in any of the four irrigation events.

An additional correlation analysis was performed to characterize the relationships between the considered irrigation events. The selected variables were θ_b, θ_a, θ_R and *IDc*. The soil water content before each irrigation ($\theta_{b\,\mathrm{i}}$ *vs.* $\theta_{b\,j}$) and after each irrigation ($\theta_{a\,i}$ *vs.* $\theta_{a\,j}$) showed significant correlations in all cases. This can be explained by an additional fact: all the data sets for θ_b and θ_a showed significant correlations with w_{fc} and w_{wp}, indicating that the water retention properties governed the local water content throughout the experiment. Concerning *IDc* and θ_R, significant correlations were only found for IDc_{13} *vs.* IDc_{21} (0.692***) and for $\theta_{R\,13}$ *vs.* $\theta_{R\,21}$ (0.475*). The remaining correlations for *IDc* and θ_R were non significant. It can be concluded that, in sprinkler irrigation, the spatial variability of the irrigation dose as determined with catch cans (*IDc*) or neutron probes (θ_R) strongly varies between irrigations. In a similar experiment in surface irrigation, Zapata et al. (2000) found strong correlations between the recharges corresponding to all pairs of irrigation events. The spatial variability of water application in sprinkler irrigation is therefore dictated by random variables such as wind speed and direction. From the presented correlation analyses, it can also be concluded that the catch can analysis is very representative of soil water recharge.

Relationship between irrigation water distribution and deficit coefficient

The deficit Coefficient (C_D) was determined at the parcels receiving less water than *IDd* during each irrigation event (data not presented). In the following analyses, water deficit was only considered when C_D was higher than 10 %. This value represents a difference of 0.63 mm h^{-1} between the local values of *IDc* and *IDd*, and corresponds to the average value of Root Mean Square Error between the volumes of water collected in both plots (Table 1). The magnitude of C_D is related to the water distribution pattern and to the wind drift and evaporation losses. Since these losses were relevant in our experimental conditions, deficit appeared in a large number of parcels.

In all 23 irrigation events, there were at least seven parcels in plot A and six in plot B where C_D exceeded 10 %. The irrigation water distribution pattern, conditioned by the wind speed and direction, induced continuous deficit (in all irrigation events) in a number of parcels (five in plot A and three in plot B). The location of these parcels within each plot is the same for three of them (located in the region between both sprinkler lines), representing 12 % of the plot area. This means that although water distribution was very uniform (with *CU*'s above 94 %), there was a continuous, localized water deficit. An additional amount of irrigation water should be applied in this case to maximize yield if economic and environmental factors allow.

This finding suggests that in sprinkler irrigation, characterizing the variability of irrigation water application using exclusively *CU* may not be an adequate choice. In fact, the value of *CU* does not provide an indication of the water deficit induced in the field. However, a relationship between *CU* and the average C_D can be derived. Figure 7 presents the relationship between the *CU* and the average C_D of the plots with a C_D higher than 10 % corresponding to each irrigation event. Results showed a highly significant increase of the average C_D as *CU* decreased ($R^2 = 0.93^{***}$). Mantovani et al. (1995) and Li (1998), using an empirical model, reported the same trend (increased deficit with reduced *CU*), and applied it to irrigation decision making in a context of rising water prices. These authors considered a seasonal *CU* and a constant C_D for all the irrigation events applied during the crop cycle, while in this experiment, the average C_D obtained in each plot during each irrigation event and the corresponding *CU* were considered. The regression equation derived from our experiment can be used to estimate the average water deficit rate induced by any level of irrigation uniformity. This is important for sprinkler irrigation management in the middle Ebro river basin, since water is becoming increasingly scarce or expensive and the meteorological conditions (wind speed and direction) are frequently inadequate for sprinkler irrigation.

Seasonal irrigation and yield response

In some parcels the seasonal irrigation dose exceeded the average *IDcs* and, however, the resulting yield (around 5,000 kg ha^{-1}) was well below the field average (7,129 kg ha^{-1}) (Figure 8). In some of these parcels the low yield could be attributed to a low plant density (20 % lower than the average density of emerged plants). In the remaining parcels, the low yield was due to a very low infiltration rate, causing water stagnation leading to asphyxia in the root system. The following analysis was restricted to the rest of the parcels, i. e., the parcels marked in Figure 8a were excluded.

The values of the seasonal deficit coefficient (C_{DS}), seasonal catch can irrigation dose (*IDcs*), total dry matter (*TDM*) and corn grain yield (*GY*) were similar in plots A and B (Table 4). Among these variables the seasonal C_{DS} showed the highest variability. The *GY* and *TDM* values obtained in each plot showed more variability than the IDcs, being slightly higher in plot A. The *CV* of *GY* was slightly higher than the *CV* of *TDM* in both plots. In a drip irrigation experiment, where wind does not affect water distribution, Or and Hanks (1992) found that the magnitude of yield variability was smaller than the magnitude of water application variability.

The minimum grain yield corresponds to the parcel receiving the minimum seasonal irrigation dose, while the highest yield was obtained in a parcel receiving slightly less than the average seasonal water application. The seasonal irrigation depths beyond 475–500 mm had no effect on yield (Figure 9a). This threshold corresponds to 85–90 % of the calculated net irrigation requirement ($ETC - P$). If this analysis was performed using *IDd* instead of *IDc,* the conclusion would be that water applications of 107-112 % of the net irrigation requirement would lead to zero yield losses. Considering the total available water (Figure 9b) (initial soil water content + irrigation + rainfall) a threshold around 600 mm can be observed. Below these threshold values for *IDcs* and total available water a decrease in grain yield was generally observed. These results are readily comparable to those reported by Cavero et al. (2001), based on the experiments performed by Zapata et al. (2000) in the same soil and crop, but using surface irrigation.

A correlation analysis was performed to characterize the effect on crop yield parameters (*TDM* and *GY*) of seasonal irrigation dose (*IDcs*), seasonal available water (initial soil water content + irrigation + rainfall), C_{DS}, EC_e at sowing and EC_e at harvest. No significant correlation was found between *GY* and CE_e neither at sowing nor at harvest. *GY* showed correlations with *IDcs* (r = 0.502****)** and seasonal available water (r = 0.584***). C_{DS} was correlated with *GY* (r = -0.513***), indicating that *GY* variability was partly dictated by the water deficit resulting from the non-uniformity of water distribution during the crop season.

Concerning the correlation between *GY* and *IDcs*, the value obtained in this work is similar (though somewhat lower) than those reported in previous works performed in sprinkler irrigation systems (Stern and Bresler, 1983 ; Dagan and Bresler, 1988). In surface irrigation, and following the standard techniques of water application estimation (Merriam and Keller, 1978), Zapata et al. (2000) found a correlation of 0.45, slightly lower than the available references for sprinkler irrigation.

Yield response to the variability of water distribution in time and space

A correlation analysis was performed between crop yield parameters and the *IDc* corresponding to the 23 irrigation events. Only seven of them were significantly correlated with *TDM* and corn grain yield (Table 5). These seven irrigation events were applied during the flowering and grain filling stages and had low *CU*'s (66.5 % on the average) (Table 1). During that period, the remaining irrigation events, for wich *IDcs* were not correlated with *GY* and *TDM*, showed *CU* values above 86%. Non-uniform irrigation events applied before the flowering stage did not show a significant correlation with crop yield. The most significant correlations were found for irrigation events 8, 9 14 and 22, which had the highest C_D, ranging from 36 % to 52 %. These results illustrate the relevance of irrigation non-uniformity beyond the flowering stage in corn grain yield variability under sprinkler irrigation when the irrigation water depth applied is equal to the crop water requirements.

SUMMARY AND CONCLUSIONS

A field experiment was performed to study the effect of the space and time variability of water application on solid set sprinkler irrigated corn yield. The experimental design guaranteed high irrigation uniformity under low wind speed conditions. Irrigation was scheduled to fulfill corn water requirements during all growth stages assuming no wind effects, and applying light irrigations. Irrigation events were applied during variable meteorological conditions (wind speed and direction) inducing different spatial patterns of water distribution in each irrigation event. The following remarks and conclusions are supported by this study:

The *CU* values of 48 % of the irrigation events were lower than 84 % in both plots. The extreme values of *CU* corresponded neither to the highest average wind speed nor to the lowest. A large percentage (90 %) of the variability in *CU* was explained by the wind speed alone. This environmental factor also explained the 80 % of the wind drift and evaporation losses. The differences in wind speed and direction among irrigation events lead to a compensation process that results in the seasonal *CU* being higher than the average *CU* of the individual irrigation events (88.0 % *vs.* 80.5 %). The marked wind-induced random character of individual irrigation *CU* values induces doubts as to the representativity of the seasonal *CU*. In this case, the seasonal *CU* would fall in the category of uniform irrigation, while about half of the irrigation events were of questionable uniformity.

In this experiment, the dependence of sprinkler irrigated corn water status and yield on the analyzed soil properties was low. No evidence was found proving that the soil diminishes the heterogeneity induced by the irrigation water distribution. In fact, the uniformity of soil water recharge was lower than the irrigation water distribution uniformity, and the relationship between both variables was statistically significant ($R^2 = 0.916^*$). It was also found that the relationship between *IDc* and water recharge heavily depends on irrigation uniformity.

The magnitude of C_D is related to the water distribution pattern and to the wind drift and evaporation losses. Since these losses were very relevant in our experimental conditions (20 % on the average), water deficit appeared in a large number of parcels. Even in very uniform irrigation events, a number of parcels showed values of C_D over 10 % (in fact, 16 % of the parcels suffered continuous localized water deficit). As a conclusion, in sprinkler irrigation systems, characterizing the variability of irrigation water application using exclusively *CU* may not be an adequate choice. The average C_D was significantly related with *CU*. This relationship can be used to determine the minimum *CU* required to ensure that all parts of the field receive an adequate amount of water.

GY presented more variability than *TDM* in both plots, and both *GY* and *TDM* showed more variability than *IDcs*. The variability of *GY* was due to the spatial and temporal variability of *IDc*, which limited the amount of crop available water and induced a variable crop water stress in time and space. Indeed, C_{DS} variability was higher than *GY* variability, and showed better correlation with *GY* than ID_{CS}. Non-uniform irrigations performed at or after the flowering stage resulted in significant correlations between *IDc* and *GY*. Therefore, farmers should be particularly careful at these crop growth stages in selecting the adequate wind conditions for irrigation. Events performed with wind speeds beyond the 2.1 m s^{-1} threshold will result in uneven water applications leading to either additional irrigation water application or water stress associated to relevant yield losses.

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NOTATION

The following symbols are used in this paper:

θ = volumetric soil water content (%);
θ_a = volumetric soil water recharge after irrigation (%);
θ_b = volumetric soil water recharge before irrigation (%);
θ_R = volumetric soil water recharge (%);
C_D = deficit coefficient (%);
C_{DS} = seasonal deficit coefficient (%);
CU = Christiansen Coefficient of Uniformity (%);
CUs = Christiansen uniformity coefficient of soil water content (%);
CUs_a = Christiansen uniformity coefficient of soil water content after irrigation (%);
$CUs_{a1.50}$ = Christiansen uniformity coefficient of soil water content after irrigation within the soil perfil (%);
$CUs_{a0.3}$ = Christiansen uniformity coefficient of soil water content after irrigation considering only the upper soil layer (%);
$CUs_{b0.30}$ = soil coefficient of uniformity before the irrigation event at the upper layer (%);
$CUs_{R1.50}$ = soil coefficient of uniformity for soil water recharge (%);
CU_{i-1} = Christiansen uniformity coefficient of the previous irrigation event (%);
CV = coefficient of variation (%);
DU = distribution uniformity (%);
$EC_{1:5}$ = electrical conductivity of the 1:5 soil extract (dS m^{-1});
EC_e = electrical conductivity of the soil saturation extract (dS m^{-1});
EC_w = electrical conductivity of the irrigation water (dS m^{-1});
ETc = crop evapotranspiration (mm);
ETc_i = crop evapotranspiration for day i (mm);
ET_0 = reference evapotranspiration (mm);
IDc = catch can irrigation dose (mm);
IDc_i = catch can irrigation dose for day i (mm);
$IDcs$ = seasonal catch can irrigation dose (mm);
IDd = sprinkler discharge dose (mm);
GY = grain yield (kg ha^{-1});
K_c = crop coefficient;
P_i = precipitation for day I (mm);
R^2 = determination coefficient;
$RMSE$ = Root Mean Square Error;
SWC_i = average soil water content on day i (mm);
SWC_{i-1} = average soil water content on day i-1 (mm);
T = duration of the irrigation event (s);
TAW = total soil available water (mm);
TDM = total dry matter (kg ha^{-1});
W = average wind speed (m s^{-1});
$WDEL$ = wind drift and evaporation losses (%);
w_{FC} = gravimetric water content at field capacity (mm);
w_{WP} = gravimetric water content at wilting point (mm).

List of tables

Table 1. Characteristics of the 23 evaluated irrigation events, as well as average value of Wind Drift and Evaporation Losses (*WDEL*), values of the Christiansen Coefficient of Uniformity calculated for Plot A (CU_A) and plot B (CU_B) and Root Mean Square Error (*RMSE*) between the volume of water collected in both A and B catch can sets.

Table 2. Textural classes, gravimetric water content at field capacity (W_{FC}) and wilting point (W_{WP}), total available water (*TAW*) and electrical conductivity at sowing (EC_e-s) and harvesting (EC_e-h) measured in each parcel of both plots, by 0.3 m layers and to a depth of 1.5 m where possible. Coefficients of variation are presented in parenthesis.

Table 3. Correlation matrix between catch can irrigation dose (*IDc*), volumetric water content measurement before (θ_b) and after (θ_a) the selected irrigation events and soil water recharge (θ_R).

Table 4. General statistics for the seasonal deficit coefficient (C_{DS}), the seasonal irrigation catch can dose (*IDcs*), total dry matter (*TDM*) and grain yield (*GY*) measured or determined in plots A and B.

Table 5. Results of the correlation analysis between yield parameters (*GY* and *TDM*) and catch can irrigation dose (*IDc*) for each irrigation event. Only significant correlations are presented.

Table 1. *Characteristics of the 23 evaluated irrigation events (Average wind speed (W), dominant wind direction (WD), water electrical conductivity (EC$_w$), Irrigation dose discharged (IDd), Cath can irrigation dose (IDc), average value of Wind Drift and Evaporation Losses (WDEL), values of the Christiansen Coefficient of Uniformity calculated for Plot A (CU$_A$) and plot B (CU$_B$) and Root Mean Square Error (RMSE) between the volume of water collected in both A and B catch can sets).*

# irrigation	**W** (m s^{-1})	**WD** (º)	**EC$_w$** (dS m^{-1})	**IDd** (mm)	**IDc** (mm)	**WDEL** (%)	**CU$_A$** (%)	**CU$_B$** (%)	**RMSE** (mm h^{-1})
1	4.8	90-135	1.60	19.2	11.6	39.6	66.2	63.5	1.27
2*	3.2	225-270	1.13	44.8	32.4	27.7	75.4	74.3	0.64
3	1.4	225-270[‡]	1.73	38.4	31.3	18.5	93.7	94.2	0.40
4	2.7	180-225	-	12.8	10.8	15.6	82.8	80.2	0.92
5	1.1	135-180[‡]	1.75	32.0	26.7	16.6	94.5	94.1	0.55
6	2.0	90-135[‡]	1.71	19.2	14.8	22.7	89.3	85.9	0.62
7	2.6	135-180	1.89	12.8	9.7	23.8	82.9	79.8	0.52
8	4.2	315-360	1.81	32.0	23.0	28.1	73.1	77.0	0.75
9*	5.3	315-360	2.02	26.1	16.6	36.4	51.6	57.8	1.13
10	1.2	135-180	2.07	25.6	21.3	16.8	91.4	91.8	0.39
11	2.4	180-225	1.31	38.4	29.6	22.9	73.8	73.6	0.44
12	0.6	0-45[†]	1.71	25.1	20.0	-	92.9	92.7	0.39
13*	3.1	135-180	1.92	38.4	32.4	15.5	70.2	70.4	0.51
14	6.5	315-360	1.86	38.2	27.4	28.3	53.2	59.6	1.15
15	1.1	135-180	1.90	20.3	17.3	14.7	93.7	94.2	0.39
16	1.3	0-45	1.77	35.2	30.2	14.1	86.8	87.5	0.50
17	0.8	0-45[†]	1.82	26.7	22.9	14.0	89.2	87.1	0.63
18	1.2	45-90[†]	1.75	25.6	22.7	11.3	86.1	86.1	0.40
19	0.6	45-90[†]	1.71	19.2	18.0	6.0	89.8	88.2	0.51
20	0.7	0-45[†]	1.83	19.2	17.6	8.1	90.8	89.5	0.45
21*	1.0	0-45[‡]	1.76	32.0	28.3	11.4	88.7	87.4	0.63
22	6.2	270-315	-	32.0	21.9	31.4	51.3	57.3	0.79
23	1.8	225-270[‡]	2.29	25.6	21.7	15.2	81.2	80.4	0.41
Average	2.4	-	1.78	27.8	22.1	19.9	80.4	80.6	0.63

* Neutron probe measurements were performed before and after the irrigation event.

‡ A dominant wind direction was established, but wind blew from all directions during the irrigation event.

† Calm periods were recorded during the irrigation event.

– Unavailable data.

Table 2. *Textural classes, volumetric water content at field capacity (*W_{FC}*) and wilting point (*W_{WP}*), total available water (TAW) and electrical conductivity at sowing (*EC_e*-s) and harvesting (*EC_e*-h) measured in each parcel of both plots, by 0.3 m layers and to a depth of 1.5 m when possible. Coefficients of variation are presented in parenthesis.*

Soil layers (m)	**Sand (%)**	**Silt (%)**	**Clay (%)**	**w_{FC} (%)**	**w_{WP} (%)**	**TAW (mm)**	**EC_e-s (dS m^{-1})**	**EC_e-h (dS m^{-1})**
Plot A								
0-0.3	52.9 (2.9)	34.2 (6.4)	12.8 (12.6)	26.4 (6.4)	9.6 (3.7)	50.3 (9.9)	5.1 (15.8)	4.6 (15.5)
0.3-0.6	56.4 (7.6)	31.5 (12.7)	12.0 (12.4)	24.8 (7.3)	8.6 (7.7)	48.4 (8.7)	4.7 (13.1)	4.9 (12.0)
0.6-0.9	56.0 (13.1)	32.7 (21.1)	11.2 (10.0)	24.9 (13.6)	8.0 (14.5)	50.8 (15.2)	4.3 (15.1)	4.8 (14.3)
0.9-1.2	56.2 (12.8)	34.0 (18.7)	9.6 (16.4)	24.6 (15.6)	7.0 (14.8)	52.7 (17.4)	3.9 (17.3)	4.2 (15.6)
1.2-1.5	59.9 (21.2)	30.2 (37.2)	9.4 (19.8)	24.0 (22.3)	6.6 (23.7)	52.2 (23.2)	4.0 (18.9)	4.1 (29.8)
Plot B								
0-0.3	49.0 (5.7)	36.8 (7.9)	14.0 (10.2)	27.4 (4.4)	9.5 (5.8)	53.5 (7.4)	5.6 (16.0)	5.1 (16.1)
0.3-0.6	52.3 (6.6)	36.1 (10.3)	11.6 (18.4)	25.2 (5.8)	8.0 (6.8)	51.4 (8.5)	5.0 (10.4)	5.7 (17.3)
0.6-0.9	56.8 (14.0)	32.9 (20.8)	10.3 (19.3)	23.6 (13.9)	6.2 (17.1)	52.0 (15.5)	4.3 (21.2)	5.8 (21.4)
0.9-1.2	55.4 (18.4)	34.8 (26.4)	9.8 (23.6)	23.9 (18.2)	5.9 (23.1)	47.7 (29.6)	3.9 (18.8)	5.5 (14.6)
1.2-1.5	44.4 (15.6)	36.9 (19.3)	9.8 (16.4)	24.8 (14.6)	6.6 (16.5)	32.5 (43.2)	4.4 (24.3)	5.0 (22.9)

Table 3. *Correlation matrix between catch can irrigation dose (IDc), volumetric water content measurement before (θ_b) and after (θ_a) the selected irrigation events and soil water recharge (θ_R).*

	Irrigation 2			**Irrigation 9**		
	θ_b **(%)**	θ_a **(%)**	θ_R **(mm)**	θ_b **(%)**	θ_a **(%)**	θ_R **(mm)**
IDc (mm)	0.306 **ns**	0.532 **	0.527 **	0.330 **ns**	0.568 **	0.781 ***
θ_b **(%)**		0.831 ***	0.146 **ns**		0.945 ***	-0.031 **ns**
θ_a **(%)**			0.670 ***			0.296 **ns**

	Irrigation 13			**Irrigation 21**		
	θ_b **(%)**	θ_a **(%)**	θ_R **(mm)**	θ_b **(%)**	θ_a **(%)**	θ_R **(mm)**
IDc (mm)	0.426 **ns**	0.632 ***	0.662 ***	0.368 **ns**	0.386 **ns**	0.158 **ns**
θ_b **(%)**		0.928 ***	0.068 **ns**		0.991 ***	0.008 **ns**
θ_a **(%)**			0.435 *			0.142 **ns**

Table 4. *General statistics for the seasonal deficit coefficient (C_{DS}), the seasonal irrigation catch can dose (IDcs), total dry matter (TDM) and grain yield (GY) measured or determined in plots A and B.*

Plot		**C_{DS} (%)**	**ID_{CS} (mm)**	**TDM (kg ha^{-1})**	**GY (kg ha^{-1})**
A	Minimum	11	391	7,660	3,769
	Maximum	39	680	17,560	10,102
	average	24	509	13,053	7,064
	CV	33	15	21	26
B	Minimum	12	399	10,024	4,831
	Maximum	37	654	17,490	10,013
	average	24	508	13,459	7,195
	CV	31	14	15	19
A and B	average	24	509	13,256	7,129
	CV	32	14	18	23

Table 5. *Results of the correlation analysis between yield parameters (GY and TDM) and catch can irrigation dose (IDc) for each irrigation event. Only significant correlations are presented.*

	IDc_8 (mm)	IDc_9 (mm)	IDc_{11} (mm)	IDc_{13} (mm)	IDc_{14} (mm)	IDc_{22} (mm)	IDc_{23} (mm)
TDM (kg ha^{-1})	0.476 **	0.493 **	0.353 *	0.339 *	0.466 **	0.425 **	0.335 *
GY (kg ha^{-1})	0.441 **	0.468 **	0.373 *	0.362 *	0.454 **	0.416 **	0.338 *

List of figures

Figure 1. Design of the field experiment: (a) general experimental setup; and (b) detail of plot A.

Figure 2. Time evolution of cumulative average catch can irrigation dose plus precipitation ($IDc+P$) and ETc, used for irrigation scheduling purposes.

Figure 3. Water distribution pattern (IDc, mm) of two consecutive irrigation events having the same duration. The recorded average wind speed was 5.3 m s^{-1} for irrigation 9 and 1.2 m s^{-1} for irrigation 10.

Figure 4. Christiansen Coefficient of Uniformity (CU) measured in plots A and B *vs.* wind speed (W).

Figure 5. Average wind drift and evaporation losses ($WDEL$) for both plots *vs.* wind speed (W).

Figure 6. Soil water content uniformity (CUs) as a function of sprinkler water application uniformity (CU) for irrigation events 2, 9, 13 and 21; and considering CUs: (a) after the irrigation event in all soil profile ($\mathrm{CUs}_{\mathrm{a}1.5}$); (b) after the irrigation event in the upper soil layer (0-0.30 m) ($CUs_{a0.3}$); (c) before the irrigation event ($CUs_{b0.3}$) and vs. the previous irrigation event uniformity (CU_{i-1}); and (d) calculated considering the soil water recharge ($CUs_{R1.5}$).

Figure 7. Average C_D vs. CU for each irrigation event and for each plot.

Figure 8. Contour maps of (a) grain yield (kg ha^{-1}); and (b) seasonal irrigation water ($IDcs$, mm).

Figure 9. Relationship between grain yield (GY) and (a) ID_{CS}; and (b) crop available water (initial available water + irrigation + rainfall).

Figure 1. *Design of the field experiment: (a) general experimental setup; and (b) detail of plot A.*

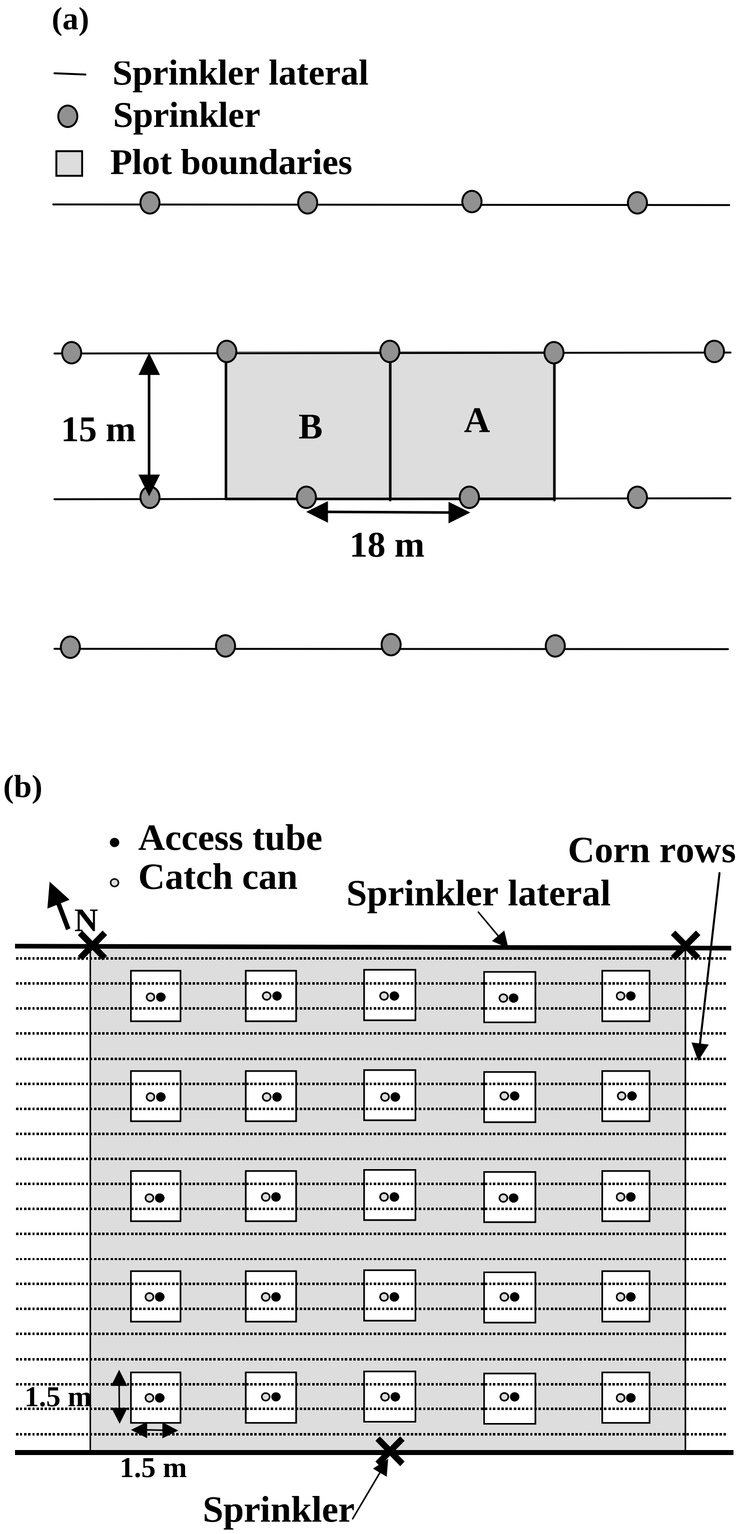
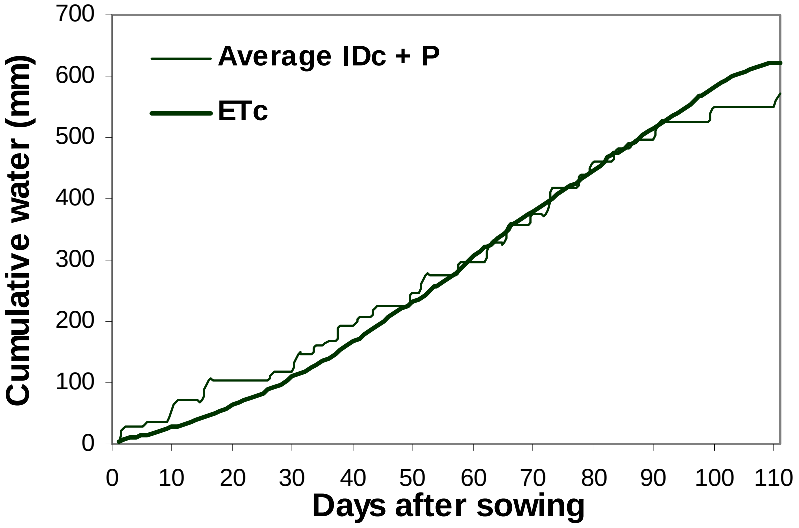


Figure 2. *Time evolution of cumulative average catch can irrigation dose plus precipitation (IDc+P) and ETc, used for irrigation scheduling purposes.*



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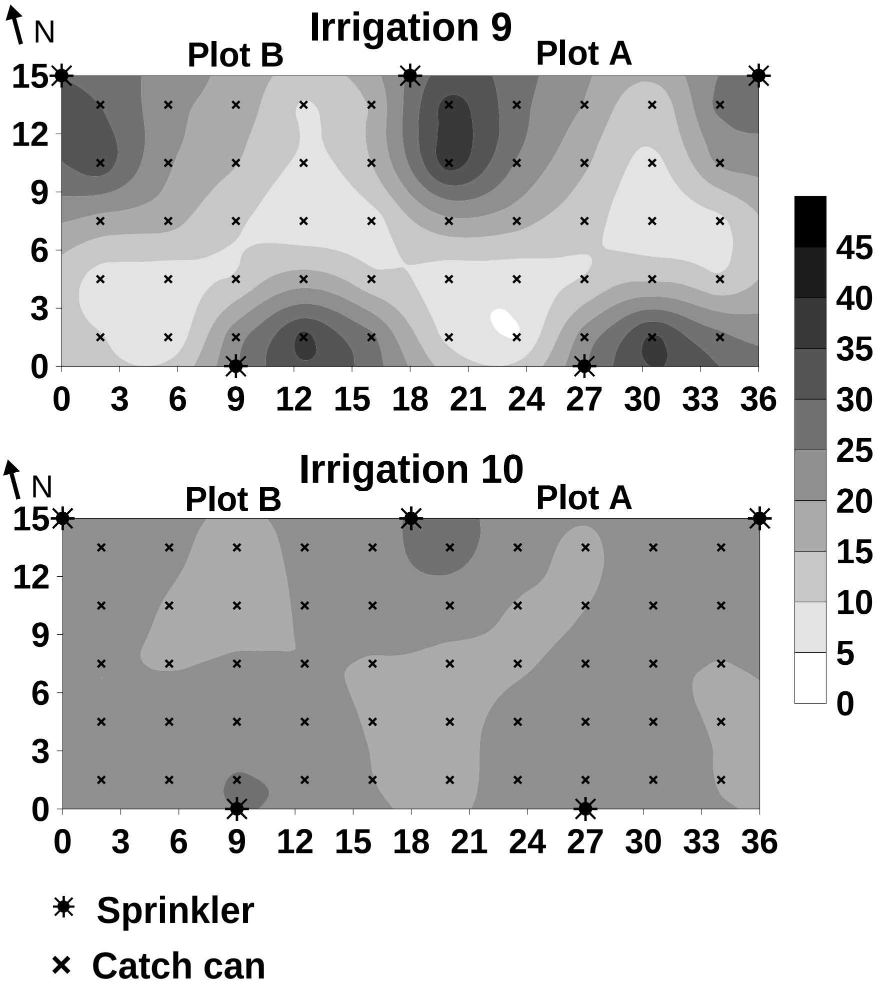


Figure 4. *Christiansen Coefficient of Uniformity (CU) measured in plots A and B vs. wind speed (W).*

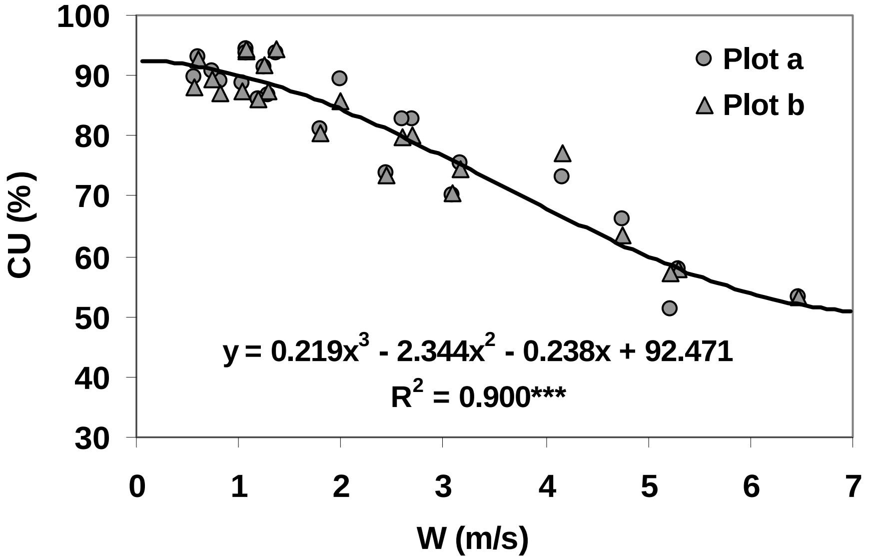
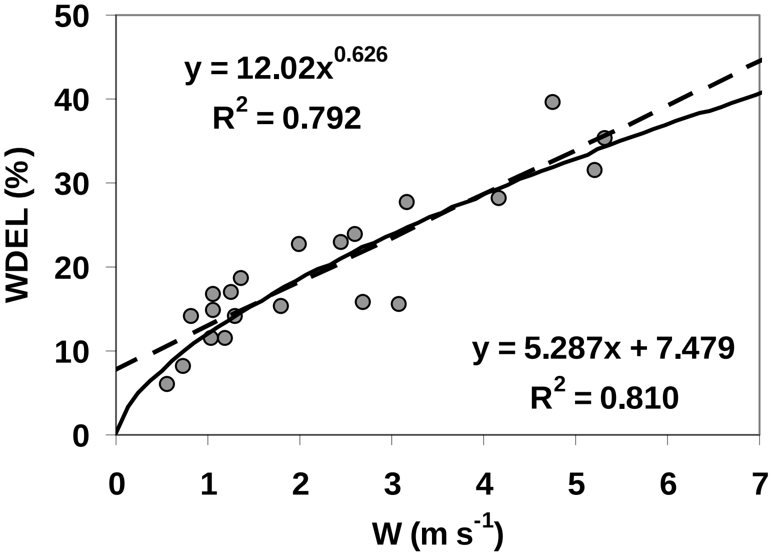


Figure 5. *Average wind drift and evaporation losses (WDEL) for both plots vs. wind speed (W).*



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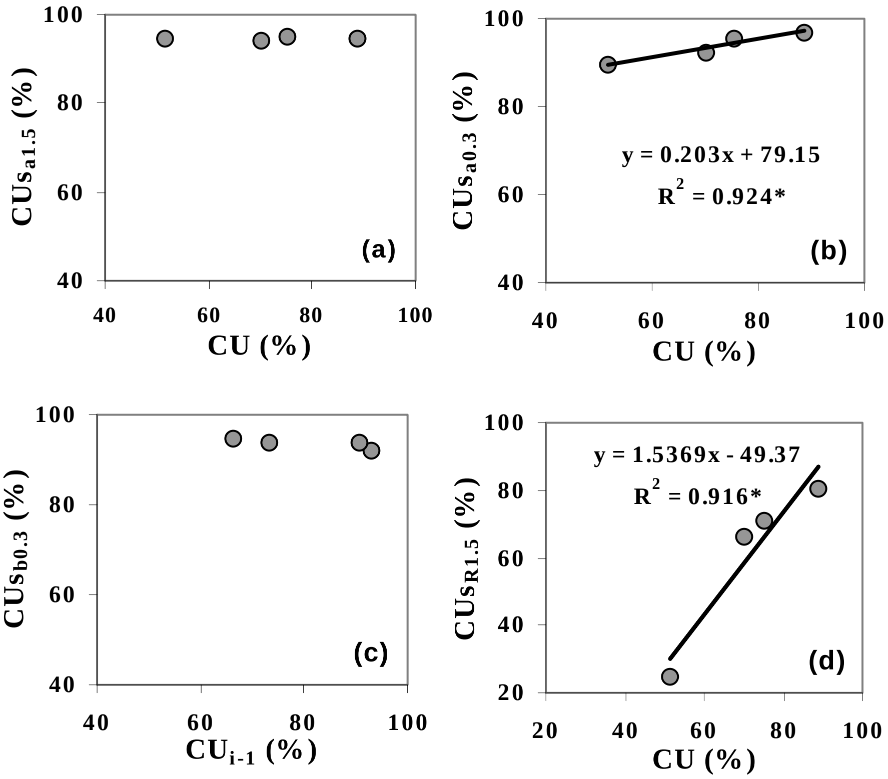

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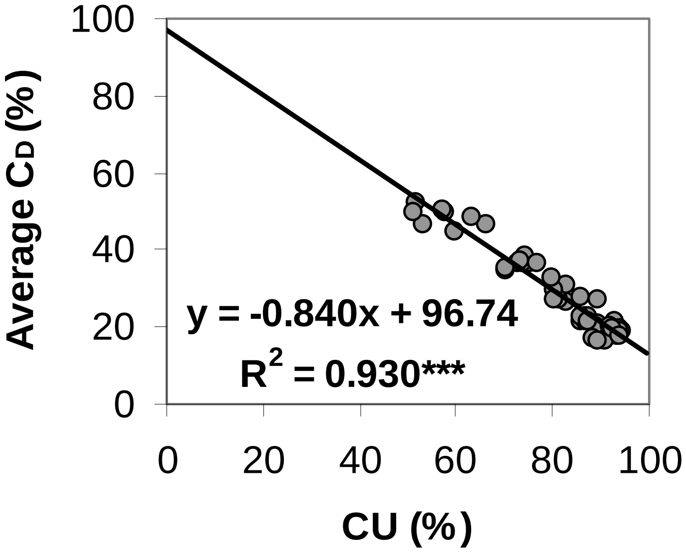

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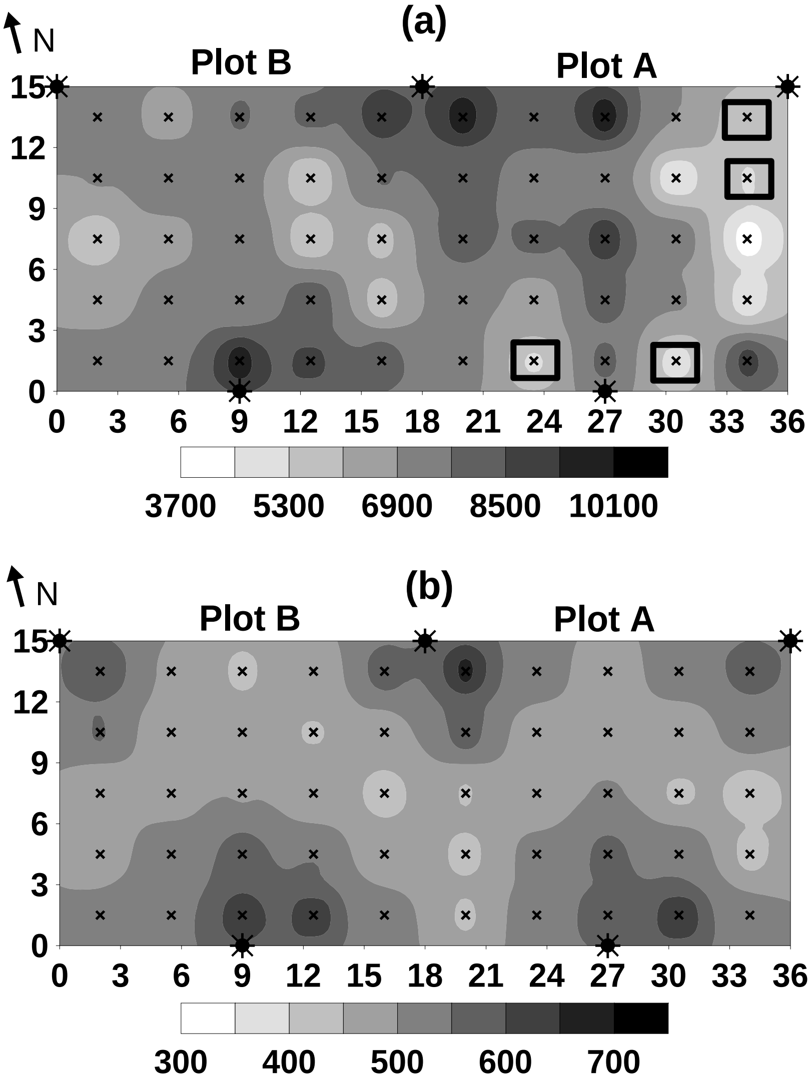

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