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Wind effects on solid set sprinkler irrigation depth and yield of maize (*Zea mays*)

Received: 28 August 2002 / Accepted: 28 March 2003 / Published online: 25 June 2003
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Abstract A field experiment was performed to study the effect of the space and time variability of water application on maize (*Zea mays*) yield when irrigated by a solid set sprinkler system. A solid set sprinkler irrigation layout, typical of the new irrigation developments in the Ebro basin of Spain, was considered. Analyses were performed (1) to study the variability of the water application depth in each irrigation event and in the seasonal irrigation and (2) to relate the spatial variability in crop yield to the variability of the applied irrigation and to the soil physical properties. The results of this research showed that a significant part of the variability in the Christiansen coefficient of uniformity (CU), and wind drift and evaporation losses were explained by the wind speed alone. Seasonal irrigation uniformity (CU of 88%) was higher than the average uniformity of the individual irrigation events (CU of 80%). 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 variability was partly dictated by the water deficit resulting from the non-uniformity of water distribution during the crop season. The spatial variability of irrigation water depth when the wind speed was higher than 2 m s^{-1} was correlated with the spatial variability of grain yield, indicating that a proper selection of the wind conditions is required in order to attain high yield in sprinkler-irrigated maize.

Introduction

Two main irrigation technologies are currently being used to irrigate field crops such as maize (*Zea mays*): surface and sprinkler irrigation. Several authors have reported on the advantages of sprinkler irrigation over surface irrigation (Cuenca 1989; Fuentes-Yagüe 1996). These benefits 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 the period 1985 to 2000 the percentage acreage of sprinkler irrigation in the USA increased from 37% to 50%.

One of the most relevant parameters in sprinkler irrigation systems is the uniformity of water distribution (Merriam and Keller 1978). Field irrigation evaluations are used to establish irrigation performance, which for 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 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. 2003a). These references have led to two firm conclusions. First, applied water is lost partially by evaporation, particularly through drift out of the irrigated area. Second, under windy conditions, the water distribution pattern of an isolated sprinkler is distorted and narrowed. Therefore, the CU generally shows a tendency to decrease as wind speed increases.

The response of crop yield to irrigation water supply has been extensively analysed (Doorenbos and Kassam 1979; Hanks 1983). Several studies have confirmed the negative impact of irrigation non-uniformity on crop yield and deep percolation losses. Bruckler et al. (2000),

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summarising previous research findings, 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 in addition to variation in water application, water dynamics in the vertical (via deep percolation and capillary rise) and horizontal directions influence its availability to the crop root zone. Researchers differ in their interpretation of the effects of soil heterogeneity on water distribution in the profile; some consider that soil heterogeneity increases the variability in irrigation water distribution (Sinai and Zaslavsky 1977), while others report that soil heterogeneity diminishes the heterogeneity induced by the irrigation system (Hart 1972; Stern and Bresler 1983; Li 1998).

In the Ebro Valley of Spain, maize is one of the main irrigated crops. New irrigation projects and the modernisation of traditional irrigated areas are leading to a rapid increase in solid set sprinkler acreage. When the irrigated fields are larger than 20 ha, pivot irrigation is often used. Since most fields are smaller than 10 ha, solid set irrigation is the most common technical solution. Although triangular sprinkler spacings of 21×18 m were common 10 years ago (Dechmi et al. 2003b), nowadays the most frequently used spacings are triangular 18×15 m and 18×18 m.

Wind is a serious limiting factor to sprinkler irrigation in the Ebro Valley, due to its high frequency and intensity (Hernández-Navarro 2002). In fact, in some irrigated areas of Aragón more than 50% of the daily average wind speeds between April and September are greater than 2 m s⁻¹ (Oficina del Regante 2002). Regional crop water requirements for maize 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 reported locally when the irrigation supply has been limited (Cavero et al. 2000).

The purpose of this paper is to evaluate the effect of irrigation water distribution under variable environmental conditions on a maize crop irrigated with a solid set sprinkler system typical of the new developments in the Ebro basin. Particular objectives are: (1) to analyse the variability of the water application in each irrigation event and in the seasonal application; and (2) to relate the spatial variability in crop yield to the variability of applied irrigation and soil physical properties.

Materials 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 (41°43'N, 0°48'W, 225 m altitude). The climate is Mediterranean semi-arid, with mean annual maximum and

minimum daily air temperatures of 20.6°C and 8.5°C, respectively. The yearly average precipitation is 330 mm, and the yearly average reference evapotranspiration (ET₀) is 1,110 mm (Faci et al. 1994). The soil is a Typic Xerofluvent coarse loam, mixed (calcareous), mesic (Soil Survey Staff 1992). 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 the 1.5 m depth. The average pH was 8.2. Soil salinity levels (EC_e = 3.88 dS m⁻¹ on average) were found to be above the critical threshold values for maize (Ayers and Wescot 1989). Irrigation water is pumped from the Urdán canal, having been diverted from the Gállego river (a tributary of the Ebro river). The Urdán water carries a significant salt load (about 2 dS m⁻¹) during the summer. For this reason, the electrical conductivity of the irrigation water (EC_w) was monitored for each irrigation event.

Experimental layout

The experimental layout of the solid set sprinkler irrigation system was designed to achieve 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 above the soil surface. The sprinkler spacing was triangular, 18×15 m. The impact sprinklers and nozzles were manufactured in brass by Vyrsa (Briviesca, Burgos, Spain). The sprinkler model was a "VYR 70", with a vertical throw angle of 25°. The nozzle operating pressure was kept constant during the season at 300 kPa, and resulted in a wetted radius of 11 m. 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 discharge, irrigation time, and sprinkler spacing.

Maize (cv. Dracma) was planted on 17 May 2000, at a density of eight plants m⁻², with the rows 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 1 June. Pests and weeds were controlled according to best management practice in the area.

Two experimental plots (hereafter designated plot A and plot B) were selected in the field as shown in Fig. 1a. In each plot, twenty-five square parcels (each side measuring 1.5 m) 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 as 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 (Fig. 1b).

Crop water requirements and irrigation scheduling

Meteorological data were recorded daily by an automatic weather station (Campbell Scientific, Logan, Utah) located about 200 m from the experimental plots. The daily crop evapotranspiration (ET_C, mm day⁻¹) was estimated from daily values of reference evapotranspiration (ET₀) calculated using the FAO Penman-Monteith equation, and from tabulated crop coefficients (K_c) following the FAO approach (Allen et al. 1998). Throughout the experiment, 2-min averages of wind speed and direction were recorded at the above-mentioned meteorological station. For each irrigation event the average wind speed (\bar{W} , m s⁻¹) was determined, and a statistical analysis was performed on wind speed and direction.

An initial irrigation event (irrigation 0) applied 25 mm on 1 June. 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

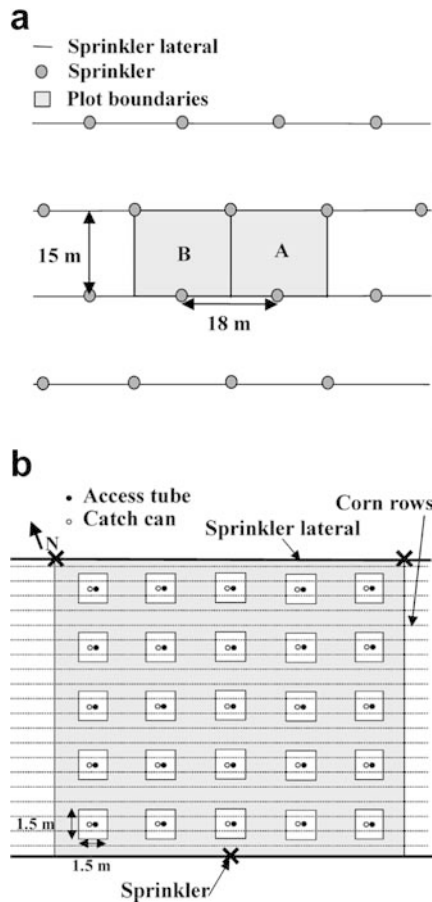


Fig. 1 Design of the field experiment: **a** general experimental layout and **b** detail of plot A

in approximately 25% of the plants. During the rest of the season, irrigations were performed when the calculated soil water balance reached 50% of the total available water. Each irrigation event lasted for the time required to regain field capacity. The daily estimate of the average soil water content (SWC_i) was determined based on the initial soil water content measured gravimetrically 13 days after planting. Daily soil water content was updated as:

$$SWC_i = SWC_{i-1} + P_i + ID_{C_i} - ET_{C_i} \quad (1)$$

where SWC_{i-1} is the average soil water content on day $i-1$ (mm); P_i is the precipitation for day i (mm); ID_{C_i} is the catch can irrigation depth for day i (mm); and ET_{C_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 likewise ignored for scheduling purposes. A total of 23 additional irrigation events were applied during the whole maize cycle. Figure 2 presents the cumulative ET_C and water applied (catch-can irrigation depth plus precipitation) during the growing season. At the beginning of the season, slight overirrigation was allowed. Towards the end of the maize cycle, irrigation was underapplied in order to avoid excess soil water at harvest, following the local farmers' practice.

Measured soil properties

Selected soil properties were analysed in each parcel of both plots in 0.3 m layers 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

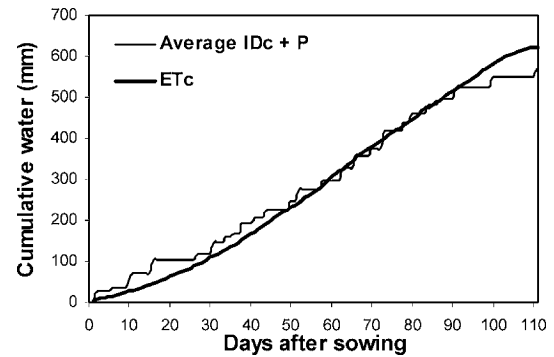


Fig. 2 Seasonal evolution of the cumulative average catch can irrigation depth plus precipitation ($ID_C + P$) and crop evapotranspiration (ET_C), used for irrigation scheduling purposes

measurements were determined at the laboratory using pressure plates. Values of 0.02 and 1.5 MPa were considered representative of field capacity and wilting point, respectively. The average bulk density obtained from the 18 samples collected during the calibration of the neutron probe was 1.45 Mg m^{-3} . 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 calibration 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 1 day before and 1 day after four irrigation events distributed throughout the season.

In all experimental parcels of both plots, the gravimetric water content and the 1:5 soil extract electrical conductivity ($EC_{1:5}$, dS m^{-1}) 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) from 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 depth (ID_C). The ID_C 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 ID_C applied to each parcel. The classification of CU values proposed by Keller and Bliessner (1991) was used in this work. The wind drift and evaporation losses (WDEL, %) produced during each irrigation event were computed from the irrigation depth applied by the sprinkler system (ID_D , obtained from the sprinkler discharge, the spacing and the duration of the irrigation event, and expressed in mm) and the average ID_C ($\overline{ID_C}$)

$$WDEL = \frac{ID_D - \overline{ID_C}}{ID_D} 100 \quad (2)$$

A deficit coefficient (C_D) was computed to express the water deficit in each irrigation event for parcels that were underirrigated (i.e. parcels receiving less water than ID_D). The deficit coefficient (C_D) and the seasonal deficit coefficient (C_{DS}) were computed using the expressions:

$$C_D = \frac{ID_D - ID_C}{ID_D} 100; \text{ for } ID_D > ID_C \quad (3)$$

$$C_{DS} = \frac{ID_{DS} - ID_{CS}}{ID_{DS}} 100; \text{ for } ID_{DS} > ID_{CS} \quad (4)$$

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

The root mean square error (RMSE, mm h⁻¹) of the application rate was determined as:

$$RMSE = \frac{1}{25t} \sqrt{\sum_{i=1}^{25} (ID_{CIA} - ID_{CIB})^2} \quad (5)$$

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

Maize yield and seasonal irrigation water applied

At crop maturity, the above-ground parts of maize plants from all parcels in plots A and B were hand-harvested. The ears were separated from the rest of the plants and oven dried at 60°C to constant weight. The grain was separated from the cob, its moisture was measured and the resulting weight was adjusted to represent a moisture content of 14%. The analysed crop yield parameters included maize grain yield at moisture content of 14% (GY), total dry matter (TDM) and harvest index (HI).

Table 1 Characteristics of the 23 evaluated irrigation events [days after sowing (DAS), phenological stage (PS), average wind speed (W), dominant wind direction (WD), water electrical conductivity (EC_w), sprinkler applied irrigation depth (ID_D), catch can irriga-

Irrigation number	DAS	PS ^a	W (m s ⁻¹)	WD (°)	EC_w (dS m ⁻¹)	ID_D (mm)	ID_C (mm)	WDEL (%)	CU_A (%)	CU_B (%)	RMSE (mm h ⁻¹)
1	23	1	4.8	90–135	1.60	19.2	11.6	39.6	66.2	63.5	1.27
2 ^b	29	1	3.2	225–270	1.13	44.8	32.4	27.7	75.4	74.3	0.64
3	36	1	1.4	225–270 ^c	1.73	38.4	31.3	18.5	93.7	94.2	0.40
4	40	1	2.7	180–225	–	12.8	10.8	15.6	82.8	80.2	0.92
5	44	1	1.1	135–180 ^c	1.75	32.0	26.7	16.6	94.5	94.1	0.55
6	47	1	2.0	90–135 ^c	1.71	19.2	14.8	22.7	89.3	85.9	0.62
7	49	1	2.6	135–180	1.89	12.8	9.7	23.8	82.9	79.8	0.52
8	51	1	4.2	315–360	1.81	32.0	23.0	28.1	73.1	77.0	0.75
9 ^b	57	1	5.3	315–360	2.02	26.1	16.6	36.4	51.6	57.8	1.13
10	63	1	1.2	135–180	2.07	25.6	21.3	16.8	91.4	91.8	0.39
11	65	1	2.4	180–225	1.31	38.4	29.6	22.9	73.8	73.6	0.44
12	71	1	0.6	0–45 ^d	1.71	25.1	20.0	–	92.9	92.7	0.39
13 ^b	76	2	3.1	135–180	1.92	38.4	32.4	15.5	70.2	70.4	0.51
14	79	2	6.5	315–360	1.86	38.2	27.4	28.3	53.2	59.6	1.15
15	83	2	1.1	135–180	1.90	20.3	17.3	14.7	93.7	94.2	0.39
16	86	2	1.3	0–45	1.77	35.2	30.2	14.1	86.8	87.5	0.50
17	91	3	0.8	0–45 ^d	1.82	26.7	22.9	14.0	89.2	87.1	0.63
18	93	3	1.2	45–90 ^d	1.75	25.6	22.7	11.3	86.1	86.1	0.40
19	97	3	0.6	45–90 ^d	1.71	19.2	18.0	6.0	89.8	88.2	0.51
20	100	3	0.7	0–45 ^d	1.83	19.2	17.6	8.1	90.8	89.5	0.45
21 ^b	104	3	1.0	0–45 ^c	1.76	32.0	28.3	11.4	88.7	87.4	0.63
22	113	3	6.2	270–315	–	32.0	21.9	31.4	51.3	57.3	0.79
23	124	4	1.8	225–270 ^c	2.29	25.6	21.7	15.2	81.2	80.4	0.41
Average	– ^e	– ^e	2.4	– ^e	1.78	27.8	22.1	19.9	80.4	80.6	0.63

^aPhenological stages were coded as: 1 = emergence to maximum LAI; 2 = maximum LAI to end anthesis; 3 = end anthesis to pasty grain; 4 = pasty grain to harvest

^bNeutron probe measurements were performed before and after the irrigation event

Data analysis

The statistical analyses were 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 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 2.1 m s⁻¹, the value reported by Faci and Bercero (1991) as the threshold for reducing CU in mid-Ebro valley conditions. In 22% of the irrigation events, wind blew from multiple directions and the average wind speed was lower than 2 m s⁻¹. Nearly 50% of the frequent high-wind directions corresponded to either north-west winds (*cierzo*, in the local terminology) or south-east winds (*bochorno*, in the local terminology). The highest average wind speeds corresponded to the *cierzo* conditions. This wind pattern is very common in the middle Ebro Valley area (Faci and Bercero 1991).

tion depth (ID_C), wind drift and evaporation losses (WDEL), Christiansen coefficient of uniformity 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]

^cA dominant wind direction was established, but wind blew from all directions during the irrigation event

^dCalm periods were recorded during the irrigation event

^e– Unavailable data

According to Ayers and Westcot (1989), irrigation water salinity (average EC_w of 1.78 dS m^{-1}) was above the threshold values for yield loss in maize ($EC_w = 1.1 \text{ dS m}^{-1}$). Under these conditions, the expected yield should be 90% of the potential yield. The ID_D ranged from 12.8 mm to 44.8 mm between irrigation events, while the average ID_C varied from 9.7 mm to 32.4 mm. The seasonal amount of irrigation water (ID_D) was 664 mm; crop evapotranspiration was 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 both plots was different in each irrigation event. The extreme values of CU did not correspond either to the highest average wind speed (irrigation 14, $W = 6.5 \text{ m s}^{-1}$) or to the lowest (irrigation 19, $W = 0.6 \text{ m s}^{-1}$). This may be explained by the frequent changes of wind speed and direction during these particular irrigation events. 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 Fig. 3, two cases of water distribution for two consecutive irrigation events of the same duration are

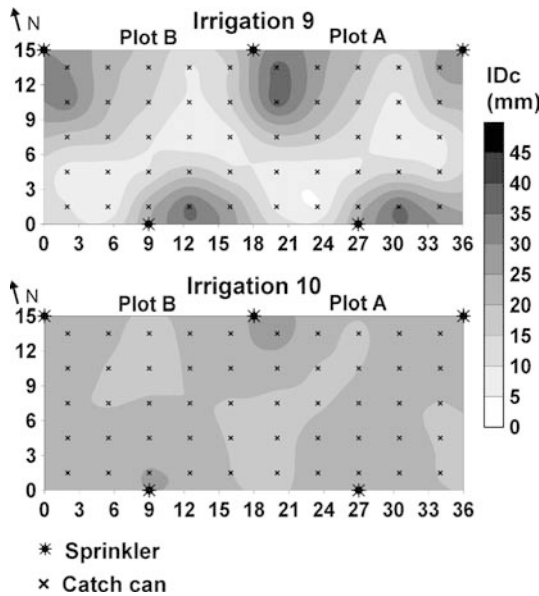


Fig. 3 Contour map of irrigation depth (ID_C) for two consecutive irrigation events with the same duration. The recorded average wind speeds were 5.3 m s^{-1} for irrigation 9 and 1.2 m s^{-1} for irrigation 10

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 concentrates precipitation in particular areas.

Except for one case, all CU values under low wind conditions ($< 2.1 \text{ m s}^{-1}$) were over 84%, which was Keller and Bliesner's (1991) threshold for "low" CU . The best fit between the wind speed and the CU of both plots was obtained with a third degree polynomial function (Fig. 4). This relationship explains 90% of the variation of the CU . For wind speeds beyond 2.1 m s^{-1} the value of CU is clearly affected by the wind speed. Urrutia (2000), under similar experimental conditions, found a decrease in the CU when the wind speeds 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 water loss increases with the wind speed, particularly beyond 2 m s^{-1} (Fig. 5). However, the variability of wind speed and direction during the irrigation time affects the fit of the

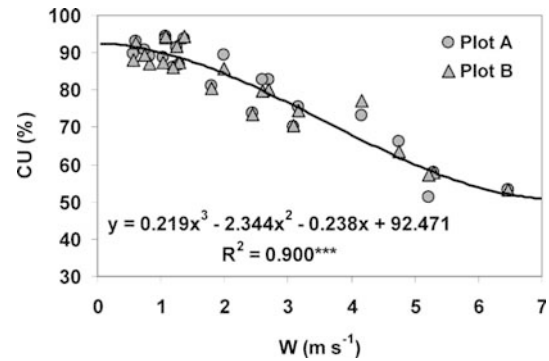


Fig. 4 Christiansen coefficient of uniformity (CU) measured in plots A and B vs wind speed (W)

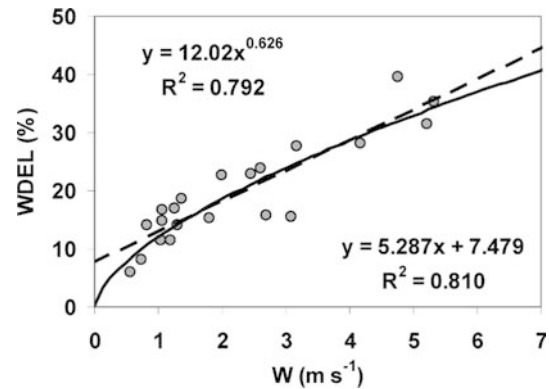


Fig. 5 Average wind drift and evaporation losses ($WDEL$) vs wind speed (W). Linear and potential regression equations are presented

data. Both the linear ($R^2=0.810$) and potential ($R^2=0.792$) regression equations showed adequate fitting to the experimental data. Predicted losses between both models for wind speeds below 0.5 m s^{-1} differ. For no-wind conditions the linear and potential regression equations estimate WDEL values of 7.5% and 0.0%, respectively. It would be difficult to assess which model is more appropriate in the Ebro Valley conditions, since calm periods lasting for a few hours are rare. The potential model may be inadequate for low wind conditions, since there are reasons to believe that WDEL will always be greater than zero. The linear model, however, may overestimate the WDEL under calm conditions.

The average CU for all irrigation events can be classified as low (80.5% on average for both plots), while the total seasonal irrigation had a high uniformity (CU of 88.0% on average for both plots). Indeed, differences in wind speed and direction between irrigation events lead to a process resulting in the seasonal uniformity being higher (7.5%) than the mean uniformity of the individual irrigation events. This is frequently found in sprinkler irrigation, due to the 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 seasonal data over the mean of the irrigation events. In our work, if DU values were used (data not presented), the difference would have been 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 for textural class in all soil layers (Table 2) with the upper layers (0–0.60 m) showing very low spatial variability. The volumetric water contents at field capacity (θ_{FC}) and wilting point (θ_{WP}) showed low variability among soil layers; the highest average values were observed at the upper 0.30 m layer. As soil depth increases, both θ_{FC} and θ_{WP} decrease. This could be attributed to the moderate increase in the sand fraction. In the top layers (0.0–0.60 m) the coefficient of variation of θ_{WP} and θ_{FC} is small. In deeper soil layers (0.60–1.50 m) the coefficients of variability are approximately double those found in the upper layers. The variability in these deeper layers should not have a relevant effect on the overall soil water regime, since the experimental ID_C (22 mm per irrigation event on average) is small in comparison with the TAW of top layers (which averaged 101.9 mm, with a CV of 8.6%). This circumstance downplays the effect of soil physics on yield in contrast to the results of Zapata et al. (2000), where this dependence was relevant in surface-irrigated maize.

The average EC_e was slightly higher in plot B at harvest than in plot A (Table 2). In both plots, the top layer (0–0.30 m) soil salinity decreased during the growing season, while in the 0.30–1.50 m layers, soil salinity moderately increased. The average profile increase in soil salinity from sowing to harvest time was 0.09 dS m^{-1} in plot A and 0.78 dS m^{-1} in plot B. The soil salinity level should have affected maize yield, since

Table 2 Textural class, volumetric water content at field capacity (θ_{FC}) and wilting point (θ_{WP}), total available water (TAW) and soil salinity at sowing (EC_{es}) and harvest (EC_{eh}), 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 parentheses

Soil layers (m)	Sand (%)	Silt (%)	Clay (%)	θ_{FC} (%)	θ_{WP} (%)	TAW (mm)	EC_{es} (dS m^{-1})	EC_{eh} (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	53.3 (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)

the average profile values exceed the threshold of 1.7 dS m^{-1} (Ayers and Westcot 1989). The expected yield should be reduced to 50–75% of the potential yield. However, other authors have reported that yield is less affected by salt stress at moderate water stress levels, and only becomes problematic under larger deficits (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 characterised using the Christiansen uniformity coefficient concept of soil water content (CU_{Sa}) as proposed by Li (1998). Figure 6a illustrates the relationship between the sprinkler uniformity (CU) and the uniformity of soil water content within the soil profile ($CU_{Sa1.5}$) for irrigations 2, 9, 13 and 21. $CU_{Sa1.5}$ values were very high (above 94%) for all the considered irrigation events, due to the large amount of water in the soil profile in comparison with the irrigation depth. There was no significant statistical relationship between sprinkler CU and $CU_{Sa1.5}$. The results obtained by Stern and Bresler (1983) and Li (1998) under similar experimental conditions showed that CU_{Sa} exceeded 90% even when the sprinkler CU was below 70%. In this research, however, $CU_{Sa1.50}$ reached values between 94 and 95% even for very low sprinkler uniformities ($CU = 51\%$).

The upper soil water uniformity values ($CU_{Sa0.3}$) were also higher than sprinkler CU values (Fig. 6b) and increased as the sprinkler CU increased ($R^2 = 0.924^*$).

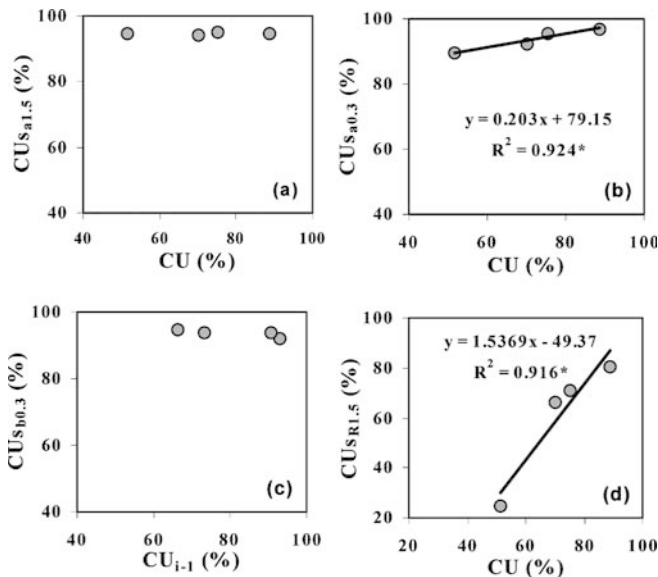


Fig. 6 Different soil water uniformity parameters vs sprinkler CU for irrigation events 2, 9, 13 and 21: **a** after the irrigation event for full soil profile ($CU_{Sa1.5}$); **b** after the irrigation event for the upper soil layer (0–0.30 m) ($CU_{Sa0.3}$); **c** before the irrigation event ($CU_{Sb0.3}$) vs the CU of the previous irrigation event; and **d** soil water recharge ($CU_{Sr1.5}$)

This relationship seems to be due to the limited soil depth, in comparison to the irrigation depth. Hart (1972), Li and Kawano (1996) and Li (1998) reported that sprinkler irrigation water was more uniformly distributed in the soil (CU_S) than in catch cans (CU) because of the redistribution of irrigation water in the soil.

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, Fig. 6c was prepared. A scatter plot presents the sprinkler CU of the previous irrigation event (CU_{i-1}) vs the soil coefficient of uniformity just before the next irrigation for the upper layer ($CU_{Sb0.30}$). The values of this last variable were systematically high (beyond 92%), and showed no statistical relationship with CU_{i-1} .

The average soil water recharge ($\bar{\theta}_s$, determined as $\theta_a - \theta_b$) for each of the four irrigation events showed a very good correlation with ID_C ($r = 0.995^{***}$), indicating the adequacy of the experimental procedures. $CU_{SR1.5}$ was always lower than the corresponding CU (Fig. 6d). This difference was particularly relevant for the lowest value of CU. The low values of ID_C in some parcels may have resulted in a very shallow water recharge, prone to evaporation and difficult to measure accurately with the neutron probe. 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 horizontal soil water redistribution was not relevant in this experiment. These findings may also indicate the possibility of explaining the spatial variability of crop yield using catch can data.

A correlation analysis was performed between ID_C , θ_b , θ_a and θ_R . 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 ID_C 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, characterised 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 soil water measurements. These findings suggest that the relationship between ID_C and θ_R heavily depends on irrigation uniformity. The relationship between ID_C and θ_a follows the same trend identified for ID_C and θ_R . Finally, as expected, no statistical relationship could be established between ID_C and θ_b in any of the four irrigation events.

An additional correlation analysis was performed to characterise the relationships between the considered irrigation events. The selected variables were θ_b and θ_a . The soil water content before irrigations i and j (θ_{bi} vs θ_{bj}) and after each irrigation (θ_{ai} vs θ_{aj}) 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

Table 3 Correlation matrix between catch can irrigation depth (ID_C), volumetric water content before (θ_b) and after (θ_a) the selected irrigation events and soil water recharge (θ_R)

	Irrigation 2 (CU = 74.8%)			Irrigation 9 (CU = 54.7%)			Irrigation 13 (CU = 70.3%)			Irrigation 21 (CU = 88.0%)		
	θ_b (%)	θ_a (%)	θ_R (%)	θ_b (%)	θ_a (mm)	θ_R (%)	θ_b (%)	θ_a (mm)	θ_R (mm)	θ_b (%)	θ_a (%)	θ_R (mm)
ID_C (mm)	0.306 ^{ns}	0.532**	0.426 ^{ns}	0.632***	0.662***	0.368 ^{ns}	0.386 ^{ns}	0.158 ^{ns}	0.527**	0.330 ^{ns}	0.568**	0.781***
θ_b (%)	–	0.831***	–	0.928***	0.068 ^{ns}	–	0.991***	0.008 ^{ns}	0.146 ^{ns}	–	0.945***	–0.031 ^{ns}
θ_a (%)	–	–	–	–	0.435*	–	–	0.142 ^{ns}	0.670***	–	–	0.296 ^{ns}

significant correlations with w_{FC} and w_{WP} , indicating that the water retention properties governed the local water content throughout the experiment.

Relationship between irrigation water distribution and deficit coefficient

The deficit coefficient (C_D) was determined for the parcels that received less water than ID_D 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 ID_C and ID_D , and corresponds to the average value of RMSE 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 WDEL values were high, deficits 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 adequate (with some CU values above 94%), there was a continuous, localised water deficit. An additional amount of irrigation water should be applied in this case in order to maximise yield if economic and environmental factors allow.

This finding suggests that in sprinkler irrigation, characterising 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 (Fig. 7). 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

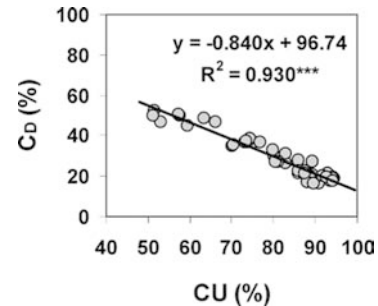


Fig. 7 Average deficit coefficient (C_D) vs sprinkler CU for each irrigation event. Only parcels with $C_D > 10\%$ were used to determine the average C_D

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 and expensive, and the meteorological conditions (wind speed and direction) are frequently challenging for sprinkler irrigation.

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

In some parcels, the seasonal irrigation depth exceeded the average ID_{CS} , however, the resulting yield (around $5,000 \text{ kg ha}^{-1}$) was well below the field average ($7,129 \text{ kg ha}^{-1}$) (Fig. 8). In some of these parcels the low yield could be attributed to a low plant density (20% lower). In the remaining parcels, the low yield was due to a very low infiltration rate, causing water stagnation leading to anaerobic conditions in the root system. The following analysis was restricted to the remaining parcels, i. e., the parcels marked in Fig. 8a were excluded.

The values of the seasonal deficit coefficient (C_{DS}), seasonal catch can irrigation depth (ID_{CS}), total dry matter (TDM), harvest index (HI) and maize 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 ID_{CS} , being slightly higher in plot A than in plot B. The CV of GY was slightly higher than the CV of TDM in both plots,

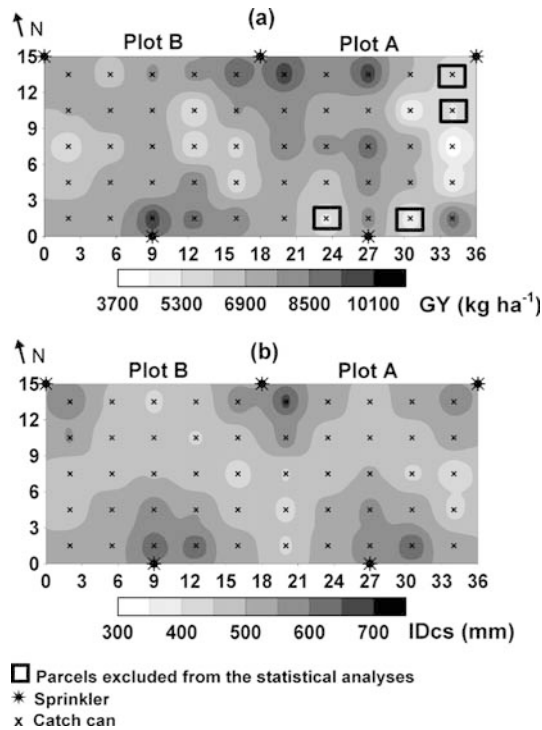


Fig. 8 Contour maps of: **a** grain yield; and **b** seasonal irrigation depth (ID_{CS})

Table 4 General statistics for the seasonal deficit coefficient (C_{DS}), the seasonal irrigation catch can depth (ID_{CS}), total dry matter (TDM), harvest index (HI) and grain yield (GY) in plots A and B

Plot	Value	C_{DS} (%)	ID_{CS} (mm)	TDM (kg ha ⁻¹)	HI	GY (kg ha ⁻¹)
A	Minimum	11	391	7,660	0.47	3,769
	Maximum	39	680	17,560	0.61	10,102
	Average	24	509	13,053	0.54	7,064
	CV	33	15	21	7.10	26
B	Minimum	12	399	10,024	0.44	4,831
	Maximum	37	654	17,490	0.60	10,013
	Average	24	508	13,459	0.53	7,195
	CV	31	14	15	19	19
A and B	Average	24	509	13,256	0.54	7,129
	CV	32	14	18	7.58	23

but more than three times that of the HI. In contrast, 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.

A correlation analysis was performed to characterise the effect on crop yield parameters (TDM, HI and GY) of seasonal irrigation depth (ID_{CS}), seasonal available water, C_{DS} , EC_e at sowing and EC_e at harvest. No significant correlation was found between GY and EC_e either at sowing nor at harvest. GY showed correlations with ID_{CS} ($r = 0.502^{**}$) 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 ID_{CS} , the value obtained in this work is similar to (though somewhat lower than) those reported for previous research performed with 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. However, the magnitude of this correlation is more related to the adequacy of the irrigation schedule than to the characteristics of the irrigation system.

As discussed previously, wind was the main cause of variability in water distribution. A correlation analysis was performed between crop yield parameters and the ID_C applied during all the season and during four crop development phases (phase 1: from emergence to maximum leaf area index (LAI); phase 2: from maximum LAI to end of anthesis; phase 3: from the end of anthesis to pasty grain; phase 4: from pasty grain to maturity). In all cases the correlations were performed separately for the ID_C applied when wind speed was higher or lower than the threshold value of 2.1 m s^{-1} (Table 5).

Considering all the crop season, GY and TDM were highly correlated with the irrigation water applied when the wind speed was higher than 2.1 m s^{-1} , but no correlation was found with the water applied when the wind speed was lower than this threshold. This result was the same when considering the different crop development phases. However, the highest correlation coefficient was obtained for phase 2 (around flowering) due to the high sensitivity of maize to water stress at that stage. In this phase the irrigation water applied when the wind speed was higher than 2.1 m s^{-1} was significantly correlated with HI. The correlation between ID_C and both GY and TDM was also high in phase 1, but decreased in phase 3 and especially in phase 4.

The effect of the spatial variability of seasonal ID_{CS} on the spatial variability of GY is shown in Fig. 9. The areas receiving an ID_{CS} above the average could attain potential values of GY. However, the areas with ID_{CS} below the average ID_{CS} never attained the potential values and showed a clear decrease in the maximum attainable values as the ID_{CS} decreased. Yields could be lower than the potential when irrigation water applied was greater than crop water requirements, due to the dynamic nature of water stress (even if the seasonal water applied was higher than needed, some water stress could happen during the season) but also to other factors. In any case, the average yield was 6.88 t ha^{-1} in those areas where the ID_{CS} was below the average ID_{CS} , but was 7.91 t ha^{-1} in those areas where the ID_{CS} was above the average ID_{CS} . The nature of the relationship between applied water and yield is 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.

Table 5 Results of the correlation analysis between yield parameters (GY, TDM and HI) and irrigation depth (ID_C) during all the season and during different crop phenological phases. In all cases the correlations were performed separately for the ID_C applied

	ID_C (mm)									
	All the season		Crop phenological phases							
	<2.1	>2.1	Phase 1		Phase 2		Phase 3		Phase 4	
W ($m s^{-1}$)	<2.1	>2.1	<2.1	>2.1	<2.1	>2.1	<2.1	>2.1	1.8	
GY ($kg ha^{-1}$)	0.257 ns	0.501***	0.143 ns	0.486***	0.278 ns	0.532***	0.243 ns	0.401**	0.303*	
TDM ($kg ha^{-1}$)	0.232 ns	0.530***	0.125 ns	0.522***	0.257 ns	0.547***	0.204 ns	0.432**	0.313*	
HI (-)	0.208 ns	0.258 ns	0.106 ns	0.235 ns	0.208 ns	0.318	0.237 ns	0.178 ns	0.163 ns	
ID_C (mm)	315	213	137	133	47	58	109	21	22	
CU (%)	89.5	68.7	92.0	72.3	90.5	63.3	88.3	54.3	80.8	

Phase 1 = Emergence to maximum LAI
 Phase 2 = Maximum LAI to end anthesis
 Phase 3 = End anthesis to pasty grain
 Phase 4 = Pasty grain to harvest

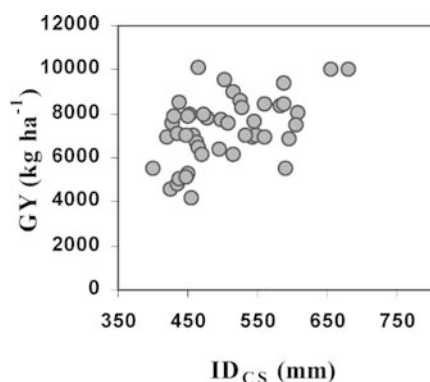


Fig. 9 Relationship between grain yield (GY) and seasonal irrigation depth (ID_{CS})

These results show clearly that the spatial variability of irrigation water induced by the effect of wind resulted in spatial variability of maize yield. If irrigation water is applied according to the crop water requirements but without considering the spatial variability induced by the wind, the average yield will decrease. The result is relevant for sprinkler systems management and design.

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 maize yield. The irrigation system design allowed high irrigation uniformity under low wind-speed conditions. Irrigation was scheduled to meet maize water requirements during all growth stages, but assumed no wind effects; light irrigations were applied. Irrigation did occur during varying meteorological conditions (wind speed and direction) inducing different spatial patterns of water distribution for each irrigation event. The following remarks and conclusions are supported by this study:

when wind speed was higher or lower than the threshold value of $2.1 m s^{-1}$. The average ID_C ($\overline{ID_C}$) and the sprinkler CU are presented for comparison purposes

- The CU values of 48% of the irrigation events were lower than an acceptable 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 80% of the wind drift and evaporation losses. The differences in wind speed and direction among irrigation events led to a compensation process resulting 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 maize water status and yield on the analysed soil properties was low. No evidence was found proving that the soil diminishes the horizontal 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 ($R^2 = 0.916^*$).
- 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 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 localised water deficit). As a conclusion, in sprinkler irrigation systems, characterising the variability of irrigation water application using sprinkler CU alone may not be an adequate choice. The average C_D was significantly related to

CU. This relationship can be used to determine the minimum CU required to ensure that all parts of the field receive a sufficient amount of water.

- GY presented more variability than TDM and HI in both plots, and both GY and TDM showed more variability than ID_{CS}. The variability of GY was partly due to the spatial and temporal variability of ID_C, 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}. The irrigation water applied when the wind speed was higher than 2.1 m s⁻¹ was significantly correlated with GY, particularly at the flowering stage. Therefore, farmers should be careful in selecting the right wind conditions for irrigation. Irrigations performed with wind speeds beyond the threshold will result in uneven water applications, leading to considerable yield losses, unless additional irrigation water is applied.

Acknowledgements This research was sponsored by the Research and Development programme of the Ministry of Science and Technology of the Government of Spain and the FEDER funds of The European Union, through grant 2FD97-0547, and by the CONSI+D of the Government of Aragón, through grant P028/2000. The International Agency of Cooperation (Government of Spain) awarded a research scholarship to F. Dechmi. Thanks are also due to Miguel Izquierdo, Jesús Gaudó and Enrique Mayoral for their technical assistance in the field experiment and to Tere Molina for her contribution to laboratory analyses.

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