# ASSESSING LOW-PRESSURE SOLID-SET SPRINKLER IRRIGATION IN MAIZE

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## ABSTRACT

Water and energy are limited and expensive resources. Conserving water and energy is a requirement to ensure the viability of modern pressurized irrigation systems. The objective of this research was to analyze the possibilities of reducing the nozzle operating pressure of impact sprinklers from 300 kPa (standard pressure) to 200 kPa (low pressure) in solid-set irrigation systems without reducing the sprinkler spacing and maintaining crop yield. Three treatments resulting from combinations of sprinkler type, and working pressure were analyzed: 1) Conventional impact sprinkler operating at 300 kPa (CIS300); 2) Conventional impact sprinkler operating at 200 kPa (CIS200); and 3) Modified deflecting plate impact sprinkler operating at 200 kPa (DPIS200). A randomized experimental design was applied to a maize crop during two seasons (2015 and 2016). Irrigation performance was measured by catch-can monitoring at one replicate of each treatment. Maize growth, yield and its components were measured. Differences between treatments in soil water, maize growth and yield variables were analyzed using ANOVA. Seasonal irrigation uniformity evaluated at the top of the canopy was larger for the standard pressure treatment (93%) than for the low pressure treatments (82% and 84% for DPIS200 and CIS200, respectively). The average wind drift and evaporation losses for the 2016 irrigation season were higher for the CIS300 treatment (17%) than for the low pressure treatments, DPIS200 (15%) and CIS200 (13%). Low pressure treatments did not reduce grain yield compared with the standard

pressure treatment. Differences in irrigation performance and maize yield between the low pressure treatments, DPIS200 and CIS200, were not statistically significant. The reduction in energy use by reducing the operating pressure from 300 kPa to 200 kPa would allow to increase the net farming benefit of individual and collective systems. This is particularly true if low pressure irrigation is considered at the design phase of the irrigation system.

**KEYWORDS**

Solid-set, sprinkler irrigation, energy efficiency, low pressure sprinklers, maize yield.

# INTRODUCTION

A number of countries have devoted intense efforts in the last years to modernize their irrigation systems. Among them, Spain, where new collective pressurized irrigation networks and on-farm irrigation systems have been designed to operate at the highest water management standards. Designs paid attention to energy dependence and to the resulting costs for the farmers. However, modernization projects did not foresee the sudden rise in agricultural electricity prices in 2008, resulting from the discontinuation of the specific electricity tariff for agricultural irrigation (Rocamora et al., 2013; Tarjuelo et al., 2015). This new situation forced Water Users Associations operating pressurized networks with pumping stations to optimize irrigation management and to apply water in the daily or weekly periods of relatively low tariffs (Moreno et al., 2010). In our days, being efficient in the use of water (applying irrigation when needed and in the amount that the crops need) is not sufficient when water is applied through energy-dependent pressurized irrigation systems. In these cases, farmers reduce the energy used per unit volume of water and schedule irrigation when energy cost is low. Taking these challenges into consideration, many recent research works have focused on improving the energy efficiency of irrigation facilities, optimizing pumping stations and irrigation network designs (Rodriguez-Diaz et al. 2009; Moreno et al. 2010; Fernandez-García et al., 2013). However, it is necessary to move forward in energy optimization, paying attention to irrigation in its agricultural context: the plot, the crop, its yield and the resulting economic profit.

Traditional solid-set irrigation systems are usually designed to operate at a minimum of 300 kPa at the nozzle of the impact sprinklers. As energy costs increase, there is a need to find ways to operate sprinkler systems at reduced pressure without reducing the sprinkler spacing and maintaining high irrigation uniformity (Kincaid, 1991). Farmers would find it difficult to accept narrower sprinkler spacings because this would increase the cost of the installation and make mechanization more difficult. Additionally, Playán et al. (2006) reported very small differences in uniformity in the range of sprinkler layouts commonly used for field crops (from 21 x 18 m to 18 x 15 m, triangular and rectangular).

With standard pressure, 300 kPa, the jet breaks up sufficiently to produce an adequate conical water distribution pattern. As pressure is reduced the pattern becomes annular or doughnut shape, reducing the uniformity of the overlapped configuration. Recently, new impact sprinklers have been commercialized which are specially designed to operate at reduced pressure. These new sprinklers are based on developments by Kincaid (1991) who proposed a modification of the impact-type sprinkler adding a deflector attached to the drive arm. The device diffuses the jet of a standard circular-orifice nozzle, maintaining the radius range and potentially improving the distribution pattern. Kincaid (1991) proposed an intermittent deflection of the jet to fill in the intermediate and lower irrigated portion of the annular pattern (the proximal region).

Reductions in the energy requirements of center pivot and lateral move irrigation machines have been successfully achieved by replacing the traditional impact sprinklers by spray sprinklers. These spray sprinklers operate at reduced pressure without affecting irrigation performance (Omary & Sumner, 2001). Kincaid (1982) analyzed the possibilities of reducing energy requirements of a sprinkler stationary system, the sideroll wheeline lateral. His results indicated that for 12.2 m to 15.2 m lateral move distances, a pressure of 206 kPa produced irrigation uniformities nearly equivalent to those resulting from 379 kPa. For longer lateral move distances, the low pressure configuration significantly reduced uniformity.

Encouraging results were presented by Playán et al. (2006) in solid-set sprinkler irrigation systems when reducing the nozzle pressure from 300 kPa to 200 kPa in two conventional impact-type sprinklers. Differences were analyzed in a solid-set sprinkler layout of 18 x 15 m with a 2 m sprinkler riser height. The radial application patterns were very similar, and Distribution Uniformity was slightly higher (< 5%) for the highest pressure. Paniagua (2015) analyzed the effect of reducing the pressure at the nozzle from 300 kPa to 200 kPa in modified impact sprinklers with a deflecting plate in the drive arm. The comparison was performed in two solid set sprinkler layouts commonly used to irrigate field crops (18 x 18 m and 18 x 15 m). The author concluded that for the experimental conditions, modified impact sprinklers operating at 200 kPa performed adequately and could substitute the traditional impact sprinklers operating at 300 kPa in solid-set layouts. Sahoo et al. (2008), working in solid-set spacings smaller than the previous authors (12 x 12 m or 6 x 12 m) and at pressures ranging from 100 kPa to 250 kPa, concluded that the nozzle pressure of 200 kPa performed better than the rest of analyzed nozzle pressures, using small and medium sized nozzles. For larger nozzles, the pressure of 200 kPa performed better than lower pressures and equal to the nozzle pressure of 250 kPa. These authors recommended selecting relatively large size nozzles for operating low pressure sprinklers in windy conditions.

Several variables affect the water distribution pattern of a solid-set sprinkler irrigation system: the spacing among sprinklers and laterals, wind speed and direction, sprinkler type, working pressure, nozzle size and sprinkler riser height (Tarjuelo et al. 1999; Playán et al. 2005). While the effect of reducing sprinkler nozzle pressure on irrigation performance of individual irrigation events has been analyzed in the literature (Kincaid, 1991; Playán et al., 2006; Sahoo et al., 2008; Paniagua, 2015), the seasonal effect on crop yield has not been assessed.

This research set out to analyze the possibilities of reducing energy requirements of solid-set sprinkler irrigation systems by reducing the pressure at the sprinkler nozzle from 300 kPa to 200 kPa, without reducing the sprinkler spacing and maintaining maize yield. A field experiment was designed to compare the irrigation performance and the crop yield of three treatments based on two sprinkler configurations (conventional impact sprinkler and modified impact sprinkler) and two operating pressures (300 kPa and 200 kPa).

# MATERIALS AND METHODS

## *Experimental site and design*

The experiment was conducted in a 2.0 ha solid-set facility located at the experimental farm of the Aula Dei Agricultural Research Centre in Montañana (Zaragoza, NE Spain). Geographical coordinates are 41°43’ N latitude and 0°49’ W longitude, and elevation is 225 m above mean sea level. The sprinkler layout of the irrigation system was square, with a spacing of 18 m between sprinkler lines and 18 m between sprinklers of the same line. Riser pipes were used to locate the sprinkler nozzle at an elevation of 2.5 m above the ground level. The irrigation system is composed by 14 irrigation blocks. Two linear blocks irrigate the borders of the experiment, while twelve square blocks correspond to the experimental plots. Each experimental plot is composed by four impact sprinklers (324 $m^2$) and is controlled by a hydraulic valve equipped with a pressure regulator. Blocks are named after the number of the valve irrigating them: from V1 to V14.

Three treatments were designed for this research, each of them with four replicates randomly distributed in the twelve experimental plots (Fig. 1). Two types of impact sprinklers were tested. The first one is a standard brass impact sprinkler, Costa RC-130 (CIS, Conventional Impact Sprinkler). The second one is a plastic impact sprinkler (NaanDanJain 5035) resulting from the application of the developments by Kincaid (1991). This modified impact sprinkler adds a deflecting plate to the drive arm (DPIS, Deflecting Plate Impact Sprinkler). Two nozzle pressures were evaluated: the standard 300 kPa and the low 200 kPa.

The three treatments are: 1) the standard brass impact sprinkler equipped with double brass nozzle (4.4 mm and 2.4 mm) operating at a pressure of 300 kPa (CIS300); 2) the standard brass impact sprinkler equipped with double plastic nozzle (5.16 mm and 2.5 mm) operating at a pressure of 200 kPa (CIS200); and 3) the modified plastic impact sprinkler equipped with double plastic nozzle (5.16 mm and 2.5 mm) operating at a pressure of 200 kPa (DPIS200). The treatments with low working pressure implement larger nozzles than the treatment with standard pressure to obtain a similar gross irrigation application rate, 5.2 mm $h^{-1}$.

The 14 irrigation blocks (including the 12 experimental plots) were irrigated from the same hydrant. Irrigation blocks of the field border, V1 and V14 (Fig. 1), were irrigated independently from the experimental plots. The 12 experimental plots were always irrigated at the same time. The collective irrigation network provided a quasi-constant pressure of 420-440 kPa upstream from the hydrant. The pressure at each experimental plot was manually adjusted using the pressure regulator of its hydraulic valve. Pressure was set according to the plot treatment (200 kPa or 300 kPa). A manometer was installed at each hydraulic valve to measure and verify pressure at each irrigation event. Additionally, a pressure transducer (Dickson, PR150) and a manometer were installed in one of the sprinkler risers of each irrigation block (Fig. 1). Pressure transducers were connected to a data logger recording measurements every five minutes.

*Soil characterization*

Soil samples were taken before sowing at each experimental plot in 2015 to determine field capacity (FC, %), wilting point (WP, %), soil water holding capacity (WHC, mm $m^{-1}$) and initial gravimetric soil water content (ISWC, %). ISWC was also determined in 2016 before sowing. Soil samples were also taken after harvesting in both crop seasons to determine the final gravimetric soil water content (FSWC, %). Two measurement points were selected at each plot for FC, WP, ISWC and FSWC (Fig. 2a). At each measurement point samples were collected every 0.3 m, to a depth of 1.2 m with a 5 cm diameter hand auger (Eijkelkamp Agriresearch Equipment BV, The Netherlands). Gravimetrical soil water content was determined for the samples. Soil fertility, including Nitrogen (N), phosphorus (P), and potassium (K) were determined after harvest in 2015. Two soil cores were taken from each experimental plot with a 5 cm diameter hand auger (Eijkelkamp Agriresearch Equipment BV, The Netherlands) to a depth of 1.2 m for N determination and to a depth of 0.3 m for P and K determination. The two samples were combined and fresh-sieved to pass a 2 mm sieve, and 10 g were extracted with 30 mL of KCl 2N solution for colorimetric determination of $NO3^{-}$–N concentration with a continuous flow analyzer (AA3, Bran+Luebbe, Norderstedt, Germany). Soil available phosphorus (Olsen method) and potassium (extraction in ammonium acetate and atomic absorption) concentrations were determined by an external laboratory. Differences between treatments in the measured soil variables were established using analysis of variance.

*Crop variety and fertilization*

The experiment was performed in a maize crop during two crop seasons, 2015 and 2016. Maize (Pioneer P1758) was sown in April 14, 2015 and April 13, 2016, in rows separated 0.75 m and with a density of 89,500 seeds $ha^{-1}$. In 2015, fertilization consisted in 64 kg $ha^{-1}$ of N, 120 kg $ha^{-1}$ of $P_2O_5$ and 120 kg $ha^{-1}$ of $K_2O$ applied before the planting date, and 100 kg $ha^{-1}$ of N as ammonium-urea-nitrate solution (32% N) applied with the irrigation water at the V9 growth stage. Alfalfa had been cropped in the field during the previous three years. In 2016, the same fertilization was applied before planting, but two applications of 100 kg $ha^{-1}$ of N as ammonium-urea-nitrate solution (32% N) were done at V6 and V12. Weeds and pests were controlled according to best management practices in the area during both experimental years.

*Irrigation requirements*

Maize evapotranspiration ($ET_c$) for 2015 and 2016 was computed from reference evapotranspiration ($ET_0$) data and crop coefficients (Allen et al. 1998). $ET_0$ data were obtained from the Montañana station, the nearest agrometeorological station of the SIAR agrometeorological network (www.magrama.gob.es/siar/informacion.asp). This station is located at a distance of 1.2 km from the experimental site. Maize crop coefficients were derived from the model of relative cumulative degree-days proposed by Martínez-Cob (2008) in the experimental area. Maize irrigation requirements (CIR) were weekly obtained as a balance between $ET_c$, effective precipitation (considered 75 % of weekly precipitation), soil water availability and net irrigation application. An irrigation efficiency of 85% was assumed in this work, in agreement with efficiency estimates reported in the literature for solid-set sprinkler irrigation systems (Clemmens and Dedrick, 1994). The three treatments were irrigated at the same time to ensure equal meteorological conditions. Since the irrigation application rate is constant among treatments, the seasonal irrigation volume was the same for the three treatments.

*Irrigation performance*

Short irrigation events (lasting for one hour) were applied at the beginning of the crop season to facilitate crop emergence. Once emergence was completed, irrigation events were scheduled to last for 2, 3 or 4 hours.

The water distribution pattern was evaluated by a 25 catch-can network (Fig. 2b) installed in one of the replicates of each irrigation treatment. The experimental plots monitored with catch-cans were not the same in 2015 and 2016 (Fig. 1). Catch-cans had a total height of 0.37 m and a diameter of the upper part of 0.016 m. Catch-cans were marked in mm for direct readout up to 0.045 m. The mouth of the catch-cans was installed at 1.0 m above ground level at the beginning of each season. During the 2016 irrigation season catch-cans were elevated as maize grew to be always above the crop canopy, until a maximum height of 2.3 m. Only six irrigation events were evaluated in 2015, while most of the irrigation events were evaluated in 2016. The Christiansen Uniformity Coefficient (CUC, %) (Christiansen, 1942) was determined for each evaluated irrigation event in 2015 and 2016. Seasonal CUC ($CUC_{seasonal}$) was also determined in 2016 by applying the CUC equation to the cumulative seasonal irrigation in each catch-can. Wind drift and evaporation losses (WDEL) were estimated as the difference between applied irrigation depth and collected irrigation depth at the catch-can network (Playán et al., 2005), expressed as percentage of the applied irrigation depth. WDEL were determined for each evaluated irrigation event in 2015 and 2016, and seasonally in 2016.

*Maize growth and yield variables*

Plant height was measured after tasseling (30 July in 2015 and 28 July in 2016), using a ruler with centimetric accuracy. Twenty measurement points were homogenously distributed at each experimental plot (Fig. 2a). The height of two plants was measured at each point. Plant height at an experimental plot was determined as the average of all measurements.

The photosynthetically active radiation (PAR, %) intercepted by the crop was measured at each experimental plot in both seasons. PAR intercepted by the crop was measured at R5 growth stage (17 August in 2015 and 18 July in 2016) with a 1-m-long ceptometer using 64 photodiodes (Sunscan, Delta-T, Cambridge, UK) and a PAR sensor (BF3 Sunshine sensor, Delta-T, Cambridge, UK). The PAR sensor continuously measured radiation above the crop canopy. Radiation at the soil surface was measured at each experimental plot by taking 12 readings with the ceptometer placed perpendicular to the plant rows and moving it across the rows of the plot, covering consecutive sections 1 m in length (Fig. 2a). Measurements were taken around 12:00 GMT. The fraction of PAR intercepted by the crop was computed as the percentage of the difference between the

BF3 readings and the ceptometer readings, to the BF3 readings. The PAR intercepted by the plants at each plot was determined as the average of the 12 measurements.

On 28 September (in both seasons) hand harvest was performed at each experimental plot to determine aerial biomass. The maize plants located in a 3-m-long section of two different rows (rows 6 and 12), a total of 4.5 $m^2$ in each experimental plot (Fig. 2a), were hand harvested by cutting them at the soil surface level. The grain was separated from the cob and both parts were dried at 60ºC. The final number of plants, number of ears, total biomass, kernel mass and harvest index (HI) were determined for each plot and treatment.

On 29 September 2016 an intensive hand harvest was performed at three experimental plots to determine the intra-plot spatial variability of grain yield. The three experimental plots, one replicate per treatment, were coincident with those of pluviometry measurements in 2016. The maize grain was manually harvested at 25 points in each experimental plot (Fig. 2b). The maize ears located in a 2-m-long section of two different rows (one at each side of the pluviometer) were hand harvested in each point. The grain was separated from the cob and dried to 60 ºC. Grain yield was adjusted to standard 140 g $kg^{-1}$ moisture content. The spatial variability of grain yield was established for the measured plot. Comparisons were performed between treatments and with the spatial variability of seasonal irrigation collected at the catch-can network for every treatment.

The experimental plots (18 × 18 m) were machine harvested on 30 September in 2015 and on 5 October in 2016 using a combine. Grain was weighed with a 1-kg-precision scale. A grain subsample was collected to measure grain moisture. Another subsample of the combine-harvested grain from each experimental plot was dried at 60° C to measure kernel mass. The number of grains per unit area was calculated from kernel mass and grain yield.

*Economic issues*

The effect of the irrigation pressure treatments (300 kPa and 200 kPa) on electricity cost depends on network topology. In this research, the results presented by Zapata et al. (2015) were used to illustrate the economic implication of reducing irrigation pressure. Zapata et al. (2015) analyzed the effect of reducing the pressure at the sprinkler nozzle form 300 kPa to 200 kPa in a collective pressurized sprinkler irrigation network. The topology of the studied collective network is considered representative of the conditions in the Ebro Valley.

*Data analysis*

The relationships between wind speed and irrigation uniformity and between wind speed and WDEL were analyzed for the three treatments using regression. Spatial variability in water distribution patterns and hand harvested grain yield was assessed using contour line maps produced with the SURFER software (copyright Golden Software Inc.). Differences between treatments in measured water application, maize growth variables, yield and its components were analyzed using ANOVA. Means were separated using Fisher's Protected LSD at $P = 0.05$.

## RESULTS AND DISCUSSION

### *Soil characterization*

The soil of the experimental farm was classified as a Typic Xerofluvent. The initial soil water content of the treatments was very similar between seasons, ranging from 23.9% to 26.7%. The final soil water content (after harvest) was higher in 2015 than in 2016. This can be explained by a more adjusted irrigation schedule to crop water requirements in 2016 (Fig. 3). Within each experimental season, significant differences were not found between treatments for WHC, ISWC or FSWC.

In 2015 the values of soil nitrogen, phosphorus and potassium were within normal bounds, and did not show fertility problems at the experimental plots. Statistically significant differences between the soils assigned to the different treatments were not found for phosphorus soil content and potassium soil content. Soil nitrogen for soils of treatment CIS200 was significantly lower than for the soils of the other two treatments.

### *Characterization of meteorology*

The meteorological characteristics of the experimental seasons, 2015 and 2016 (considered from April to September), were compared with the available semi-hourly meteorological data set in the area (ranging from 1995 to 2016). Both experimental seasons can be classified as average in terms of reference evapotranspiration, since the seasonal values (952 mm and 924 mm, for 2015 and 2016, respectively) were similar to the average season (927 mm). Both seasons were drier (116 mm and 130 mm of precipitation in 2015 and 2016 seasons, respectively) than the average season (170 mm). The inter-seasonal variability of precipitation is high in the area. Regarding the average daily wind speed, the values of both seasons (2.2.m $s^{-1}$ and 2.3 m $s^{-1}$, for 2015 and 2016, respectively) were slightly lower than the value of the average season (2.4 m $s^{-1}$).

### *Irrigation requirements and irrigation application*

The average soil available water at planting was 50 mm in 2015 and 40 mm in 2016. The rainfall from seeding date (April 13) to senescence (September 15) was 78 mm in 2015 and 126 mm in 2016. Fig. 3 presents the cumulative ETc, rainfall, crop irrigation requirements (CIR) and irrigation application as a function of time. In general, irrigation application was close to CIR (Fig. 3). Some differences can be observed during the seasons, mostly due to rainfall. In 2016 irrigation application was slightly below crop irrigation requirements (Fig. 3b), leading to a reduction of the soil water content at the end of the cropping season. The total volume of irrigation applied was similar in both seasons, 661 mm in 2015 and 659 mm in 2016. The total irrigation time (132.0 h and 131.5 h, in 2015 and 2016, respectively) was arranged in 43 irrigation events in 2015 and in 47 in 2016 (Appendix A). In both seasons 12 % of the irrigation time suffered wind speeds larger than or equal to 4 m $s^{-1}$. 33 % and 21 % of the irrigation time in 2015 and 2016, respectively, was performed under wind speeds between 2 m $s^{-1}$ and 4 m $s^{-1}$. Finally, 55 % and 67 % of the irrigation time in 2015 and 2016, respectively, was performed under wind speeds lower than 2 m $s^{-1}$. In general, irrigations in 2015 were applied under higher wind speeds than irrigations in 2016.

*Irrigation performance*

The average and standard deviation of the nozzle pressure measured with pressure transducers are presented in Fig. 4. The seasonal average and the standard deviation are presented for each treatment and for both seasons. Pressures were slightly higher in 2015 than in 2016. The inter-seasonal variation in pressure was also larger for the first season (larger error bars) than for the second. The control of the nozzle pressure by pressure regulation pilots at the hydraulic valves proved effective to maintain the required pressure of the different experimental plots and treatments.

*Irrigation uniformity*

Table 2 presents average and seasonal catch-can elevation, wind speed, temperature, relative humidity, irrigation uniformity and wind drift and evaporation losses for each treatment. Data for the 36 irrigation events evaluated in 2016 is presented in the Appendix A. The relationship between wind speed and irrigation uniformity for all evaluated irrigation events was stronger for the treatment with standard pressure (CIS300, correlation coefficient of 0.92) than for the low pressure treatments (correlation coefficients of 0.75 for DPIS200 and 0.72 for CIS200). This data set was plotted for each treatment and catch-can elevation (Figs. 5a, b and c). Differences in CUC between treatments increased as catch-can elevation increased. This was particularly evident for the irrigations performed under low wind speeds. At 1 m catch-can elevation, differences in CUC between treatments were not relevant. CIS300 treatments had slightly higher CUC (88%) than the low pressure treatments (85% and 87%, for CIS200 and DPIS200, respectively) for wind speeds lower than 2 m $s^{-1}$. These results are in agreement with the findings of Paniagua (2015) when comparing CUC of a DPIS operating at 300 and at 210 kPa over bare soil with catch-cans installed at 0.45 m above ground level. As catch-can elevation increases differences in CUC between treatments of standard pressure (CIS300) and low pressure (CIS200 and DPIS200) accentuate, particularly for low wind speeds (Figs. 5b and c). Under low wind speeds, the CUC of CIS300 did not change with catch-can elevation (87% and 89% for 2 m and 2.3 m catch-can elevation, respectively), but the CUC of low pressure treatments sharply decreased with increasing catch-can elevation (78% for both low pressure treatments at 2 m catch-can elevation and 74% and 73% for CIS200 and DPIS200, respectively at 2.3 m catch-can elevation).

When analyzing all the irrigations evaluated in 2016, $CUC_{seasonal}$ was higher in CIS300 than in CIS200 and DPIS200 (93, 84 and 82%, respectively). The large number of irrigations evaluated under high catch-can elevation determined the differences in $CUC_{seasonal}$. Sanchez et al. (2010b) reported that the vertical distance between the sprinkler nozzle and the opening of the catch-cans affects the estimation of both CUC and WDEL, particularly under high wind speed conditions. Dogan et al. (2008) stated that the accuracy of the water depth estimation increased with the vertical distance between the sprinkler nozzle and the collector. In fact, ISO standard 15886-3 states that the vertical elevation difference between sprinkler nozzle and collector should be larger than 300 mm. Sanchez et al. (2010b) reported that as the water interception plane raises, the sprinkler overlap worsens. In the present experimental conditions, this effect was noticeably larger for the low pressure treatments than for the standard pressure treatment, presumably owing to differences in jet trajectory.

Summarizing, at low catch-can elevation results are in agreement with the literature, and the uniformity of the three treatments shows small differences: the treatments can be ranked as CIS300, DPIS200 and CIS200, with respective CUCs of 86, 82 and 80% (Table 2). As catch-cans are raised, the difference between CIS300 and the low pressure treatments is magnified. It is to be assessed whether these differences in measured irrigation uniformity translate to differences in crop growth and yield.

Fig. 6 shows the intra-plot water distribution pattern of two irrigation events performed under low wind speed (1 m $s^{-1}$) and high wind speed (4.5 m $s^{-1}$) for the three treatments in 2015 (catch-can elevation of 1 m). Higher CUC was observed for CIS300 (92%) than for DPIS200 and CIS200 (89 and 88%, respectively) under low wind speed conditions. Lower CUC was observed under high wind (Fig. 6), but the differences between treatments followed a different pattern than those for low wind speed conditions. The uniformity of CIS300 (72%) was similar to CIS200 (73%), and both were higher than DPIS200 (67%). These results are in agreement with Fig. 5a.

Fig. 7 presents contour maps of the seasonal water distribution pattern corresponding to each treatment (adding the observations of the 36 evaluated irrigation events in 2016). DPIS200 (Fig. 7a) and CIS200 (Fig. 7b) showed common traits, with under irrigation near the center and over irrigation near the sprinkler. The correlation coefficient between both seasonal water distribution patterns was 0.55. CIS300 (Fig. 7c) showed a homogenous water distribution pattern, and no correlation with the distribution patterns of the low pressure treatments.

*Wind drift and evaporation losses*

Figures 5d, 5e and 5f present the relationship between wind speed and WDEL for the three treatments and the different catch-can elevations. As in the case of CUC, the differences in WDEL between pressure treatments change with catch-can elevations. For catch-cans installed at the lowest elevation (1 m, Fig. 5d), treatment DPIS200 resulted in WDEL (25%) noticeably larger than the other two treatments (19% and 17% for CIS300 and CIS200, respectively). As catch-can elevation increases WDEL decreases for all the treatments (Table 2), but particularly for low pressure treatments. Sanchez et al (2010b) measured WDEL at 1 and 2 m catch can elevations at the same time over an alfalfa crop, and reported that under wind speeds higher than 2 m $s^{-1}$, measurements at 2 m catch-can elevation overestimated WDEL. For wind speeds lower than or equal to 2 m $s^{-1}$, these authors reported a slight decrease in WDEL with increasing catch-can elevation, similar to what was observed for the CIS300 treatment. For wind speeds lower than 2 m $s^{-1}$, as catch-can elevation increases the WDEL of CIS300 slightly varied (18%, 18% and 15% for 1 m, 2 m and 2.3 m catch-can elevation, respectively), while the WDEL of CIS200 (16%, 13% and 10% for 1 m, 2 m and 2.3 m catch-can elevation, respectively) and particularly DPIS200 (23%, 13% and 13% for 1 m, 2 m and 2.3 m catch-can elevation, respectively) showed relevant decreases (Fig. 5d, e and f).

Differences in WDEL were observed between the two low pressure treatments. Treatment CIS200 presented the lowest WDEL for the lowest and the highest catch can elevations. Treatment DPIS200 presented the largest WDEL for the lowest catch-can elevation, and showed a sharp WDEL decrease as catch-can elevation increased from 1 to 2 m.

The average WDEL for the 2016 irrigation season was higher for the CIS300 treatment (17%) than for the low pressure treatments, DPIS200 (15%) and CIS200 (13%). The large number of irrigations evaluated under high catch-can elevation determined the seasonal differences in WDEL. As nozzle diameter decreases and pressure increases, the number of drops with small diameter increases and the number of drops with large diameter decreases (Kincaid et al., 1996). The increase in drop surface area per unit volume of water delivered with the smaller droplets increases evaporation. At the same time, small drops are more likely to be drifted by wind (Kincaid and Longley, 1986; Kincaid, 1996). The deflecting plate of the DPIS sprinkler diffuses the jet, reducing drop size. This contributed to explain the differences in WDEL between both low pressure treatments, particularly for the 1 m catch-can elevation.

Literature can explain the seasonal differences in WDEL between treatments obtained in this research as previously discussed. It can also explain the reduction in WDEL as catch-can elevation increases (smaller distance for the drops to be evaporated and drifted). However, it is difficult to explain why the reduction in WDEL and CUC with increasing catch-can elevation was mainly observed for low pressure treatments. These results suggest that the use of catch-can networks over the crop canopy of tall crops (such as maize) to estimate sprinkler irrigation performance (CUC and WDEL) could introduce noise as the elevation of the catch-cans approximates the sprinkler nozzle height. This seems particularly relevant when the sprinkler operating pressure is lower than 300 kPa.

*Crop height and PAR interception*

A remarkable delay in maize emergence was observed in plots V13 and V11 in 2015, compared to the other plots. This delay affected crop development variables and yield components in these plots. Measurements of soil water content and soil fertility could not explain the different behavior of experimental plots V13 and V11 compared to the rest. In 2015 both plots were excluded for the ANOVA analysis. In 2016, no emergence problems were observed, and all the plots were included in the ANOVA analysis.

Table 3 presents the average and standard deviation of crop height and PAR interception, per treatment and season. Differences in crop height were observed between seasons: in 2016 maize height (2.15 m) was higher than in 2015 (1.96 m). In 2015 the irrigation treatment did not affect crop height.. In 2016, the crop height of DPIS200 was significantly lower than for the other two treatments.

The experimental season had a significant effect on PAR interception, with values in 2016 (96.5 %) being higher than those in 2015 (91.8 %) (Table 3). The irrigation treatment did not affect the intercepted PAR in any of the seasons.

*Crop yield and components*

Grain yield and biomass per experimental plot are presented in Table 4 per treatment and season. Maize grain yield presented differences between seasons, with 2016 being more productive than 2015 (17.4 *vs.* 15.2 Mg ha$^{-1}$). The effect of the irrigation treatment on grain yield was not statistically significant in 2015 neither in 2016 (Table 4). Low pressure treatments did not reduce yield, neither in 2015 nor in 2016.

Aerial biomass did not show differences between seasons. The irrigation treatments did not affect maize biomass in 2015, but did so in 2016 (Table 4). The statistically significant biomass differences in 2016 between CIS200 and the other two treatments were not associated to differences in maize grain yield.

Yield components: plant density, number of grains per square meter, kernel mass (KM) and harvest index (HI) for each treatment and season are presented in Table 5. Differences in grain yield between seasons (Table 4) were due to differences in kernel mass, since the number of grains per square meter and plant density were not significantly different between seasons. Differences in HI between seasons could be explained by differences in grain yield, since aerial biomass was not significantly different.

The irrigation treatment had no effect on plant density, kernel mass and harvest index in 2015 and 2016 (Table 5).The irrigation treatment did not affect the number of grains per square meter in 2016, but did so in 2015. The number of grains per square meter of the CIS300 treatment resulted significantly lower than the number of grains of the treatment DPIS200 in 2015 (Table 5)..

The results of the intensive hand harvest performed in one of the replicates of each treatment to analyze intra-plot yield variability are presented in Fig. 8. The grain yield variability of low pressure treatments (Fig. 8a and b) was slightly higher than that of the standard pressure treatment (Fig. 8c). However, the Christiansen coefficients of uniformity of grain yield were very high, and similar for the three experimental plots (94.0%, 94.5% and 95.0%, for DPIS200, CIS200 and CIS300, respectively).

*Seasonal irrigation and crop yield*

When comparing maize plot yield maps (Fig. 8) with seasonal water distribution maps (Fig. 7), no clear associations could be observed, except for the DPIS200 treatment. This treatment had the lowest $CUC_{seasonal}$ (82%), also the correlation performed between the measured seasonal irrigation depth and the hand harvested grain yield was significant (0.42). DPIS200 and CIS300 showed no intra-plot correlation between measured seasonal irrigation depth and measured hand harvest grain yield.

Following the discussion on Tables 4 and 5, low pressure treatments did not reduce maize grain yield respect to the standard pressure treatment. However, seasonal irrigation uniformity was about ten points higher in the standard pressure treatment than the low pressure treatments. This important difference in $CUC_{seasonal}$ was expected to have an effect on maize grain yield.

Many studies have been published about the impact of irrigation non-uniformity on crop yield. Some of these studies have reported low impacts (Mateos, 1997; Allaire-Leung et al., 2001; Li and Rao, 2003), but others have found crop yield to be notably influenced by the decrease of irrigation uniformity (Stern and Bresler, 1983; Mantovani et al., 1995; Cavero et al., 2001; Dechmi et al., 2003; Salmerón et al., 2012; Urrego-Pereira et al., 2013). The conclusions of these studies seem to be affected by the amount of irrigation applied to the crop and by the crop sensitivity to water stress. If the irrigation applied to the crop is lower than its water requirements, irrigation uniformity will influence crop yield (Mantovani et al., 1995; Dechmi et al., 2003; Montazar and Sadeghi, 2008; Urrego-Pereira et al., 2013). If the crop is over irrigated non-uniformity may not show its effect on crop yield (Sanchez et al., 2010a, 2010b). These authors concluded that the effect of irrigation performance on maize growth and yield depends on irrigation depth, uniformity and irrigation scheduling. The influence of irrigation uniformity on maize yield increases with water stress, and it is particularly significant during the earliest growth period and during the tasseling stage (Dechmi et al., 2003). Sprinkler irrigation water is partitioned by the crop canopy in three components: stemflow, throughfall and interception storage (Lamm and Manges, 2000). The crop canopy redistributes the irrigation water (Steiner et al., 1983; Paltineanu and Starr, 2000; DeBoer et al., 2001) and reduces the effect of non-uniformity on crop yield.

Low pressure treatments showed lower seasonal WDEL than the standard pressure treatment (15%, 13% and 17% for DPIS200, CIS200 and CIS300, respectively).The differences between DPIS200 and CIS300 are mostly based on data measured with catch-can installed at tall elevation (2 m and 2.3 m), since differences based on 1 m catch-can elevations are different (25%, and 19% for DPIS200, and CIS300, respectively). WDEL of CIS200 treatment were the lowest for all the evaluated conditions.

Maize was selected for this experiment because it is the main crop irrigated by solid-set sprinkler systems in the central Ebro river basin and because of its sensitivity to water stress. The irrigation depth and scheduling were adjusted to gross crop water requirements in both experimental seasons. The methodology used to estimate irrigation CUC using catch-cans installed over the crop canopy has been shown to reduce its accuracy as the distance between the sprinkler nozzle and the catch-can reduces, particularly for low operating pressures (200 kPa). Taking into account the quantitative importance of stemflow and interception storage, keeping the catch-cans below the crop canopy would result in even more methodological problems. Given the difficulty in obtaining adequate estimates of the spatial variability of irrigation depth in maize, grain yield variability or even soil water variability stand as interesting alternatives to indirectly assess irrigation performance.

*Integrating low pressure solid-set sprinkler irrigation in commercial farming*

Net economic benefits are the major criteria for determining acceptability of changes in design and operation of irrigation systems for energy use reduction (Allen et al., 1984). In this research we proved the feasibility of reducing energy requirements by reducing the sprinkler operating pressure from 300 kPa to 200 kPa without affecting crop yield. Anticipating the application of low-pressure irrigation, Zapata et al. (2015) presented a simulation study analyzing the economic implications of reducing the pressure at the sprinkler nozzle from 300 kPa to 200 kPa in a collective pressurized sprinkler irrigation network. The study area had an irrigation electricity cost of 200 € $ha^{-1}$ $yr^{-1}$ for maize operating at 300 kPa. This cost was reduced by 21% (42 € $ha^{-1}$ $yr^{-1}$) when pressure was reduced to 200 kPa. Further cost reductions could have been obtained through the consideration of related infrastructure, such as the pumping station.

The issue is how to implement low pressure sprinkler irrigation in the commercial solid-sets of the central Ebro valley and beyond, ensuring an increase in farmers' net benefit. Most of these irrigation systems are connected to collective pressurized networks and large pumping stations belonging to Water Users Associations (WUA). Two different situations arise in this discussion: irrigation management and irrigation design.

In the management arena, existing solid-sets can be converted into low pressure irrigation by reducing the target pressure downstream from the pumping station. In order to be able to apply crop water requirements at the farm level, the sprinkler nozzles may need to be enlarged to maintain the irrigation application rate. If the change of nozzles is needed, this can be paid for in a crop season, capitalizing the savings of about 42 € $ha^{-1}$ $yr^{-1}$ in the electricity bill. No further changes will be required at the farm level or at the collective network.

In the design arena, the potential of low pressure irrigation is much more important, particularly when designing the modernization of WUAs and their collective networks. Low on-farm pressure requirements represent an increase of the area that can be irrigated by natural pressure (the areas of the WUA with low elevation respect to the water source). In these areas, the full cost of the electricity bill can be saved. In other cases, the pressure requirements of a few elevated farms dictate the target pumping pressure of a WUA network. Reducing the operating pressure of these few elevated farms will extend the energy savings to the whole WUA. Finally, any reduction in the target pressure or area of the collective pressurized network will imply a reduction in the cost of the pumping station.

# CONCLUSIONS

1. For catch-cans installed at an elevation of 1.0 m, under low wind speed conditions the standard pressure treatments had slightly higher CUC than the low pressure treatments. Under high wind speed conditions differences in irrigation uniformity between low and standard pressure treatments were not clear. At this catch-can elevation, differences in irrigation uniformity of individual events between the two sprinkler models operating at 200 kPa (CIS and DPIS) were not clear. In 2016 the seasonal irrigation uniformity ($CUC_{seasonal}$) for the treatment with standard pressure was higher than for the low pressure treatments, with differences between 9-11%.
2. Differences in CUC between treatments increased with the elevation of the catch-cans, apparently penalizing the uniformity of low pressure treatments as the distance between sprinkler nozzle and catch-can was reduced. These differences could have led to unrealistic estimates of CUC for individual irrigation and for complete seasons. Similar results were found in the estimation of WDEL in individual irrigations. The methodology used to determine irrigation performance indexes, CUC and WDEL, using catch-cans installed above the crop canopy and at elevations near the sprinkler nozzles, should be specifically assessed for reliability.
3. Low pressure treatments, using conventional brass impact sprinklers or modified plastic impact sprinklers, did not reduce maize grain yield compared to a standard pressure (300 kPa) treatment using conventional brass impact sprinklers. Differences in maize grain yield could not be established between the two low pressure treatments, CIS200 and DPIS200.
4. In order to evaluate seasonal irrigation performance of sprinklers operating at low pressure and irrigating tall crop canopies, agronomical determinations, such as maize grain yield and its variability, were more adequate than uniformity estimates. Detailed soil water analyses could have supported the information obtained from grain yield.
5. It is possible to save energy on-farm by reducing the sprinkler operating pressure from 300 to 200 kPa in maize and in the experimental conditions, without reducing the sprinkler spacing and maintaining crop yield.

**6.** The present research leads to improved net economic benefits in commercial maize farms. Benefits will be much more important when considering low pressure irrigation at the time of designing collective pressurized networks for water users’ associations.

# APPENDIX A

Figure 1A. Date, catch-can elevation, irrigation time, wind speed, temperature, relative humidity, irrigation uniformity and wind drift and evaporation losses measured in each experimental treatment for each of the 36 evaluated irrigation events in 2016.

| Date | Catch-can height (m) | Irrig. time (h) | WS ($m\ s^{-1}$) | Tª (ºC) | RH (%) | CUC (%) | | | WDEL (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | DPIS200 | CIS200 | CIS300 | DPIS200 | CIS200 | CIS300 |
| 6/7/2016 | 1.0 | 3.0 | 1.2 | 22 | 66 | 88 | 85 | 91 | 25 | 13 | 17 |
| 6/10/2016 | 1.0 | 4.0 | 1.0 | 20 | 72 | 86 | 84 | 91 | 20 | 7 | 13 |
| 6/14/2016 | 1.0 | 2.0 | 4.5 | 19 | 53 | 67 | 73 | 72 | 30 | 21 | 23 |
| 6/15/2016 | 1.0 | 2.0 | 1.6 | 18 | 61 | 86 | 82 | 88 | 22 | 21 | 20 |
| 6/17/2016 | 1.0 | 2.0 | 1.1 | 16 | 69 | 85 | 78 | 87 | 26 | 23 | 23 |
| 6/24/2016 | 2.0 | 4.0 | 0.8 | 19 | 68 | 78 | 80 | 94 | 14 | 11 | 17 |
| 6/28/2016 | 2.0 | 4.0 | 0.6 | 17 | 75 | 75 | 75 | 89 | 14 | 13 | 16 |
| 6/29/2016 | 2.0 | 2.5 | 1.9 | 20 | 70 | 78 | 80 | 87 | 13 | 18 | 18 |
| 7/1/2016 | 2.0 | 4.0 | 1.1 | 20 | 76 | 79 | 76 | 79 | 10 | 11 | 21 |
| 7/5/2016 | 2.0 | 2.7 | 2.3 | 21 | 85 | 81 | 82 | 84 | 20 | 23 | 25 |
| 7/6/2016 | 2.0 | 4.0 | 2.6 | 20 | 78 | 74 | 76 | 78 | 10 | 13 | 14 |
| 7/12/2016 | 2.0 | 3.5 | 3.0 | 20 | 66 | 69 | 66 | 70 | 18 | 26 | 21 |
| 7/13/2016 | 2.0 | 4.0 | 4.5 | 17 | 58 | 62 | 63 | 65 | 17 | 16 | 22 |
| 7/15/2016 | 2.0 | 4.0 | 1.1 | 14 | 71 | 77 | 81 | 86 | 11 | 5 | 21 |
| 7/19/2016 | 2.0 | 4.0 | 1.1 | 19 | 63 | 77 | 80 | 84 | 13 | 15 | 19 |
| 7/20/2016 | 2.0 | 4.0 | 1.0 | 21 | 70 | 80 | 79 | 86 | 14 | 14 | 18 |
| 7/22/2016 | 2.0 | 4.0 | 2.7 | 20 | 70 | 68 | 64 | 77 | 8 | 16 | 9 |
| 7/26/2016 | 2.0 | 4.0 | 1.3 | 20 | 75 | 77 | 75 | 87 | 14 | 16 | 12 |
| 7/27/2016 | 2.3 | 4.0 | 2.4 | 21 | 69 | 77 | 75 | 83 | 12 | 16 | 16 |
| 7/29/2016 | 2.3 | 4.0 | 0.4 | 19 | 75 | 72 | 72 | 88 | 12 | 12 | 13 |
| 8/2/2016 | 2.3 | 4.0 | 0.6 | 18 | 72 | 71 | 72 | 92 | 17 | 13 | 14 |
| 8/3/2016 | 2.3 | 3.0 | 0.5 | 21 | 70 | 71 | 73 | 89 | 13 | 12 | 10 |
| 8/5/2016 | 2.3 | 4.0 | 4.7 | 20 | 59 | 53 | 55 | 54 | 19 | 19 | 21 |
| 8/9/2016 | 2.3 | 3.0 | 2.4 | 20 | 69 | 73 | 70 | 77 | 13 | 14 | 16 |
| 8/10/2016 | 2.3 | 3.0 | 4.0 | 17 | 58 | 59 | 62 | 66 | 19 | 17 | 20 |
| 8/12/2016 | 2.3 | 4.0 | 0.8 | 13 | 79 | 68 | 72 | 88 | 14 | 10 | 12 |
| 8/16/2016 | 2.3 | 4.0 | 1.0 | 19 | 82 | 74 | 76 | 91 | 13 | 8 | 14 |
| 8/17/2016 | 2.3 | 3.0 | 0.8 | 20 | 81 | 73 | 76 | 90 | 13 | 9 | 16 |
| 8/19/2016 | 2.3 | 3.0 | 0.8 | 21 | 80 | 71 | 72 | 90 | 15 | 16 | 15 |
| 8/23/2016 | 2.3 | 2.0 | 0.6 | 22 | 75 | 70 | 75 | 90 | 14 | 4 | 17 |
| 8/24/2016 | 2.3 | 2.0 | 0.8 | 21 | 70 | 71 | 74 | 87 | 13 | 7 | 17 |
| 8/26/2016 | 2.3 | 2.0 | 0.9 | 20 | 63 | 69 | 74 | 89 | 18 | 8 | 17 |
| 8/30/2016 | 2.3 | 2.0 | 1.4 | 17 | 70 | 78 | 80 | 91 | 10 | 6 | 17 |
| 8/31/2016 | 2.3 | 2.0 | 1.2 | 20 | 78 | 80 | 77 | 86 | 8 | 9 | 17 |
| 9/2/2016 | 2.3 | 2.0 | 1.2 | 20 | 78 | 79 | 73 | 86 | 8 | 7 | 16 |
| 9/7/2016 | 2.3 | 3.0 | 0.6 | 18 | 81 | 78 | 74 | 87 | 7 | 9 | 14 |

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**Table 1.** Main characteristics of the irrigations, the irrigation evaluations and the wind during irrigation in each experimental season. Variables include the number of irrigation events, the number of evaluated irrigation events, the seasonal irrigation time, the average wind speed during irrigation, and the percentage of irrigation time in three wind speed classes.

**Table 2.** Average and seasonal catch-can elevation, wind speed, WS, temperature, T$^a$, relative humidity, RH, irrigation uniformity, CUC and wind drift and evaporation losses, WDEL, measured in each experimental treatment for the irrigation applied in 2016 season.

**Table 3**. Average and standard deviation values of measured plant height and photosynthetically active radiation intercepted by the crop (PAR) for each treatment and crop season. Average values are also presented for all treatments.

**Table 4**. Average grain yield and biomass for each treatment and crop season. Average values are also presented for all treatments.

**Table 5.** Plant density, number of grains, kernel mass (KM) and harvest index (HI) for the three treatments and the two irrigation seasons (2015 and 2016). Average seasonal values are also presented.

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m catch-cans elevation correspond to irrigations evaluated in 2015 and 2016 (a and d). Data for the other catch-cans elevation correspond only for irrigations evaluated in 2016.

**Figure 6.** Water distribution patterns of two individual irrigation events, one under low wind speed (upper figures) and the other under high wind speed conditions (lower figures), for the three treatments.

**Figure 7.** Water distribution pattern of the accumulated irrigation applied in 2016 to one replicate of each treatment: DPIS200 (a), CIS200 (b) and CIS300 (c).

**Figure 8.** Spatial variability of grain yield obtained by the intensive hand harvest performed in one replicate of each treatment: DPIS200 (a), CIS200 (b) and CIS300 (c), in 2016 crop season.

**Table 1**. Main characteristics of the irrigations applied, the irrigation evaluated and the wind during irrigation in each experimental season. Variables include the number of irrigation events, the number of evaluated irrigation events, the seasonal irrigation time, the average wind speed during irrigation, and the percentage of irrigation time in three wind speed classes.

| | Irrigation | | | | Irrigation time (%) | | |
|---|---|---|---|---|---|---|---|
| Season | No. (-) | Evaluated (-) | Time (h) | Avg. Wind Speed (m $s^{-1}$) | < 2 m $s^{-1}$ | 2 ≤ WS <4 | ≥ 4 m $s^{-1}$ |
| 2015 | 43 | 6 | 133 | 2.2 | 55 | 33 | 12 |
| 2016 | 47 | 36 | 130 | 1.8 | 67 | 21 | 12 |

**Table 2.** Average and seasonal catch-can elevation, wind speed, temperature, relative humidity, irrigation uniformity and wind drift and evaporation losses measured in each experimental treatment for the irrigation applied in 2016.

| | Catch-can height (m) | WS (m s$^{-1}$) | Tª (ºC) | RH (%) | CUC (%) | | | WDEL (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | DPIS200 | CIS200 | CIS300 | DPIS200 | CIS200 | CIS300 |
| Average | 1 | 1.9 | 18.9 | 64.2 | 82 | 80 | 86 | 25 | 17 | 19 |
| | 2 | 1.8 | 18.9 | 71.0 | 75 | 75 | 82 | 13 | 15 | 18 |
| | 2.3 | 1.4 | 19.1 | 72.6 | 72 | 72 | 85 | 13 | 11 | 16 |
| | All | 1.6 | 19.0 | 70.9 | 74 | 74 | 84 | 15 | 13 | 17 |
| Seasonal | All | 1.6 | 19.0 | 70.9 | 82 | 84 | 93 | 15 | 13 | 17 |

**Table 3**. Average and standard deviation values of measured plant height and photosynthetically active radiation intercepted by the crop (PAR) for each treatment and crop season. Average values are also presented for all treatments.

| Treatment | 2015 | | | | 2016 | | | |
|---|---|---|---|---|---|---|---|---|
| | Plant Height (m) | | PAR (%) | | Plant Height (m) | | PAR (%) | |
| | Avg. | SD | Avg. | SD | Avg. | SD | Avg. | SD |
| **DPIS200** | 2.00$^{a}$ | 0.05 | 90.8$^{a}$ | 1.85 | 2.08$^{a}$ | 0.06 | 96.2$^{a}$ | 0.87 |
| **CIS200** | 1.94$^{a}$ | 0.06 | 94.1$^{a}$ | 0.63 | 2.20$^{b}$ | 0.04 | 97.1$^{a}$ | 0.21 |
| **CIS300** | 1.95$^{a}$ | 0.00 | 92.8$^{a}$ | 2.31 | 2.20$^{b}$ | 0.02 | 96.1$^{a}$ | 0.51 |
| **All** | 1.96 | 0.05 | 92.5 | 2.10 | 2.15 | 0.07 | 96.4 | 0.71 |

For each variable and year, numbers followed by different letters are significantly different after ANOVA according to a Fisher's Protected LSD test at the 0.05 level.

**Table 4**. Average grain yield and biomass for each treatment and crop season. Average values are also presented for all treatments.

| Treatment | 2015 | | 2016 | |
|---|---|---|---|---|
| | Yield (Mg ha$^{-1}$) | Biomass (Mg ha$^{-1}$) | Yield (Mg ha$^{-1}$) | Biomass (Mg ha$^{-1}$) |
| **DPIS200** | 15.7$^{a}$ | 25.8$^{a}$ | 16.9$^{a}$ | 24.1$^{a}$ |
| **CIS200** | 15.0$^{a}$ | 26.4$^{a}$ | 17.6$^{a}$ | 28.1$^{b}$ |
| **CIS300** | 14.6$^{a}$ | 25.5$^{a}$ | 17.6$^{a}$ | 25.8$^{a}$ |
| Average | 15.2 | 26.0 | 17.4 | 26.0 |

For each variable and year, numbers followed by different letters are significantly different after ANOVA according to a Fisher's Protected LSD test at the 0.05 level

**Table 5**. Plant density, number of grains, kernel mass (KM) and harvest index (HI) for the three treatments and the two irrigation seasons (2015 and 2016). Average seasonal values are also presented.

| Treatment | Plant density (plants ha$^{-1}$) | | No. of grains (grains m$^{-2}$) | | KM (mg kernel$^{-1}$) | | HI (-) | |
|---|---|---|---|---|---|---|---|---|
| | 2015 | 2016 | 2015 | 2016 | 2015 | 2016 | 2015 | 2016 |
| **DPIS200** | 83,889$^{a}$ | 86,667$^{a}$ | 3,699$^{a}$ | 3,695$^{a}$ | 364$^{a}$ | 393$^{a}$ | 0.48$^{a}$ | 0.57$^{a}$ |
| **CIS200** | 85,556$^{a}$ | 86,667$^{a}$ | 3,625$^{ab}$ | 3,918$^{a}$ | 357$^{a}$ | 387$^{a}$ | 0.49$^{a}$ | 0.53$^{a}$ |
| **CIS300** | 86,667$^{a}$ | 90,000$^{a}$ | 3,462$^{b}$ | 3,909$^{a}$ | 363$^{a}$ | 387$^{a}$ | 0.49$^{a}$ | 0.56$^{a}$ |
| **Average** | 85,371 | 87,778 | 3,621 | 3,841 | 361 | 389 | 0.49 | 0.55 |

For each variable and year, numbers followed by different letters are significantly different according to Fisher´s Protected LSD test at the 0.05 level.

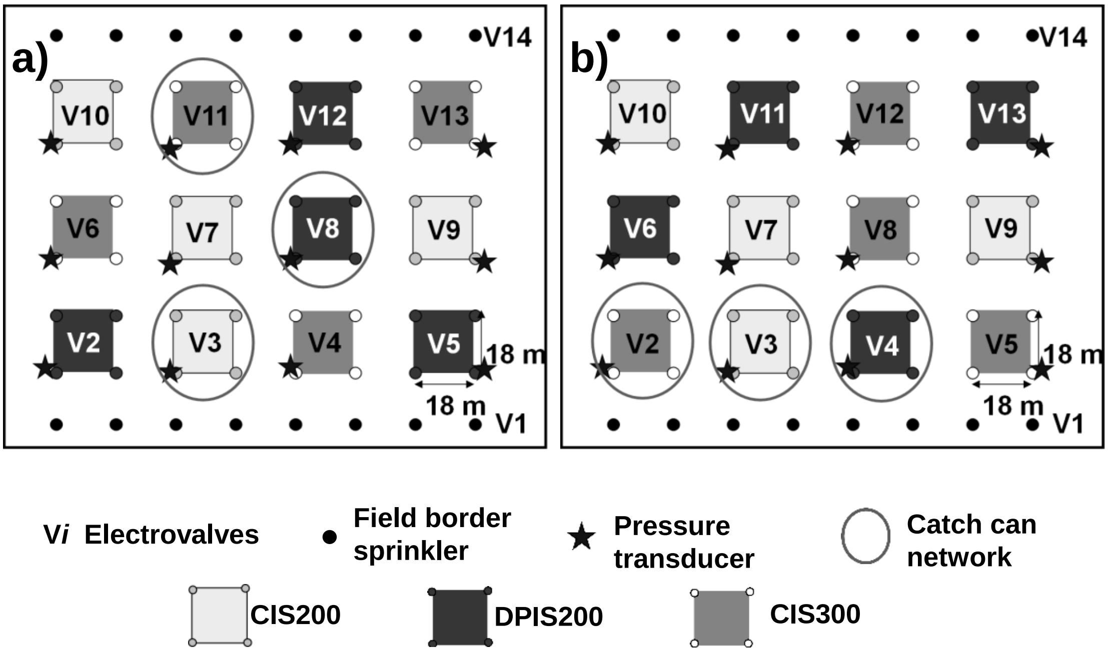


**Figure 1**. Experimental design configuration, location of the three treatments and four replicates in 2015 season (Fig. 1a) and in 2016 season (Fig. 1b). Treatments are: CIS300, standard pressure treatment; CIS200, low pressure treatment; and DPIS200, low pressure treatments with modified sprinkler. Location of the pressure transducer in each experimental plot and the experimental plots selected for catch-cans evaluation in each season are also shown.

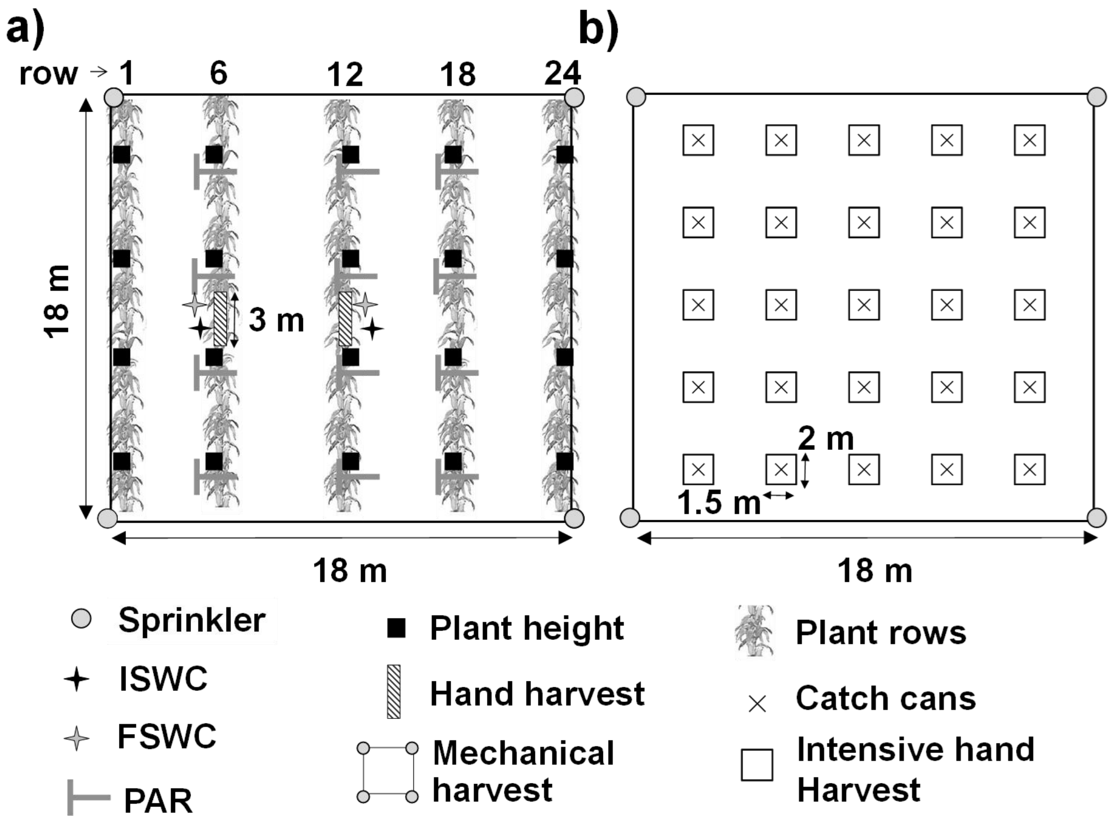


**Figure 2.** Location of the measurement points for plant height, photosynthetically active radiation intercepted by the crop (PAR) and hand harvest for biomass and yield components determination at each experimental plot (Fig. 2a). Arrangement of the 25 catch-cans network and intensive hand harvest area at the three experimental plots were irrigation uniformity and yield variability was measured, was also presented (Fig. 2b).

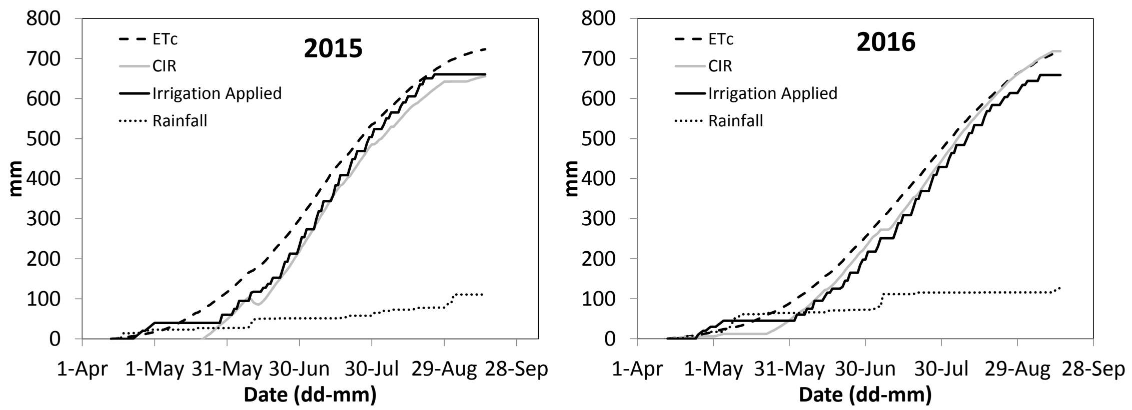


**Figure 3.** Cumulative calculated crop evapotranspiration (ETc), rainfall, crop irrigation requirement (CIR) and irrigation applied water as a function of time during the season 2015 and 2016.

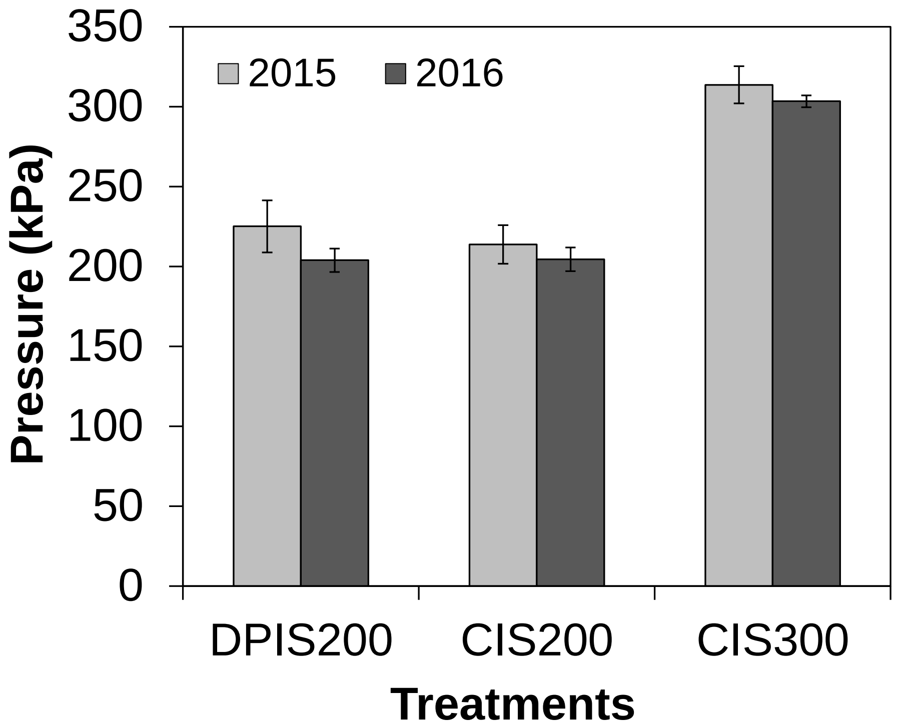


**Figure 4**. Seasonal average of the water pressure measured with the pressure transducer at the sprinkler riser for each treatment during the 2015 and 2016 irrigation seasons. Error bars represents one standard deviation.

**Figure 5**. Relationships between wind speed and uniformity coefficient, CUC, (a, b and c) and between wind speed and wind drift and evaporation losses, WDEL, (d, e and f) for each treatment and catch-cans elevation (1 m, 2 m and 2.3 m). Data presented for 1 m catch-cans elevation correspond to irrigations evaluated in 2015 and 2016 (a and d). Data for the other catch-cans elevation correspond only for irrigations evaluated in 2016.

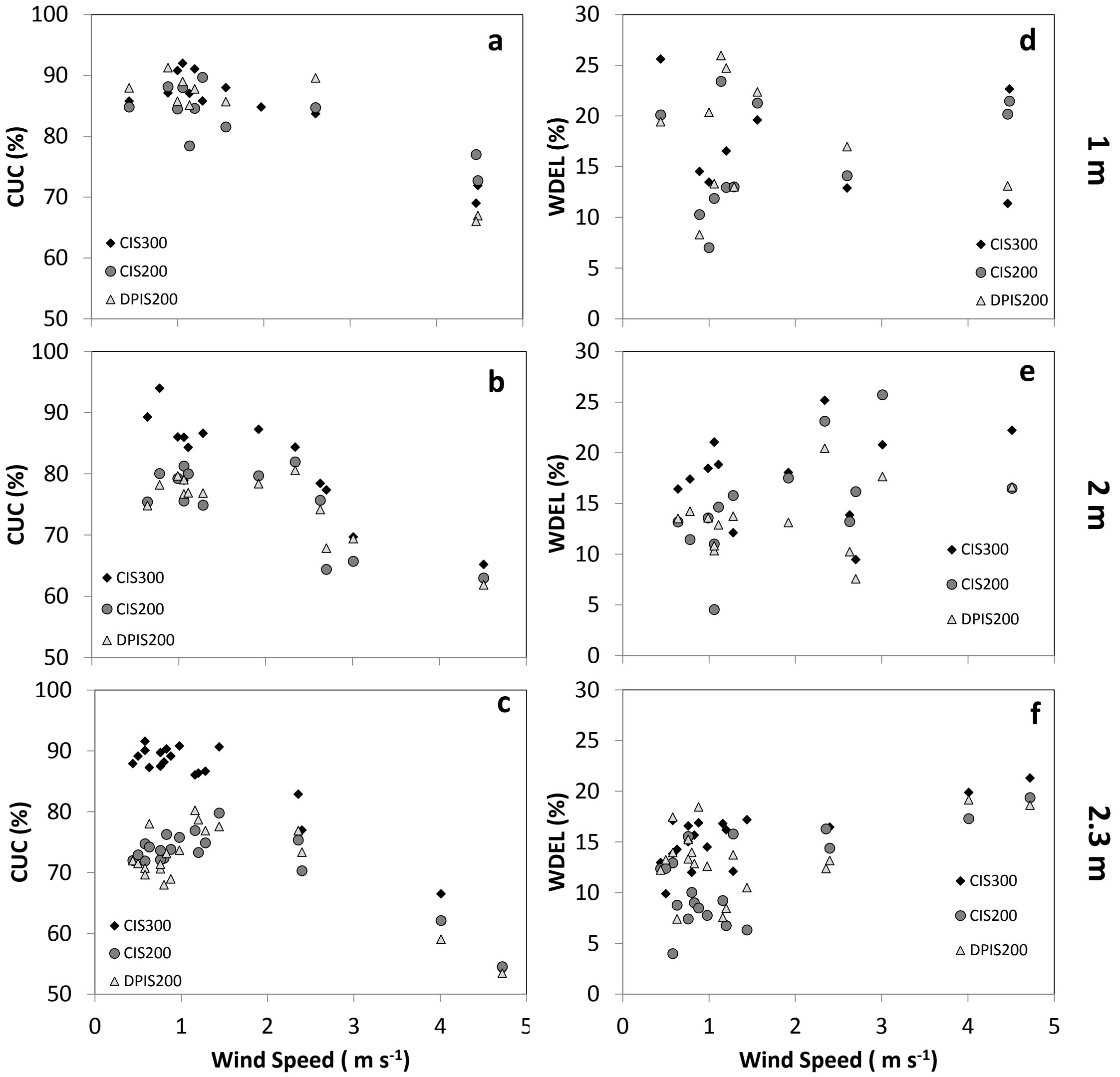


**Figure 5**. Relationships between wind speed and uniformity coefficient, CUC, (a, b and c) and between wind speed and wind drift and evaporation losses, WDEL, (d, e and f) for each treatment and catch-cans elevation (1 m, 2 m and 2.3 m). Data presented for 1 m catch-cans elevation correspond to irrigations evaluated in 2015 and 2016 (a and d). Data for the other catch-cans elevation correspond only for irrigations evaluated in 2016.

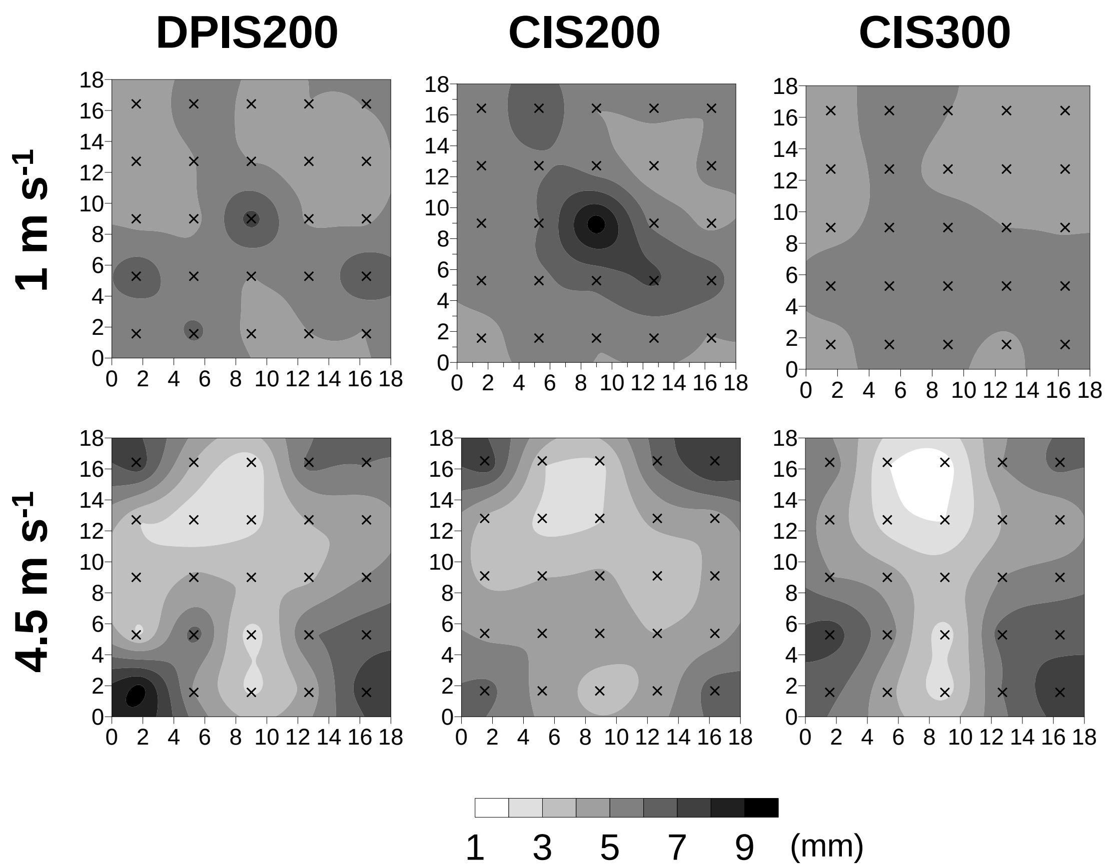


**Figure 6**. Water distribution patterns of two individual irrigation events, one under low wind speed (upper figures) and the other under high wind speed conditions (lower figures), for the three treatments.

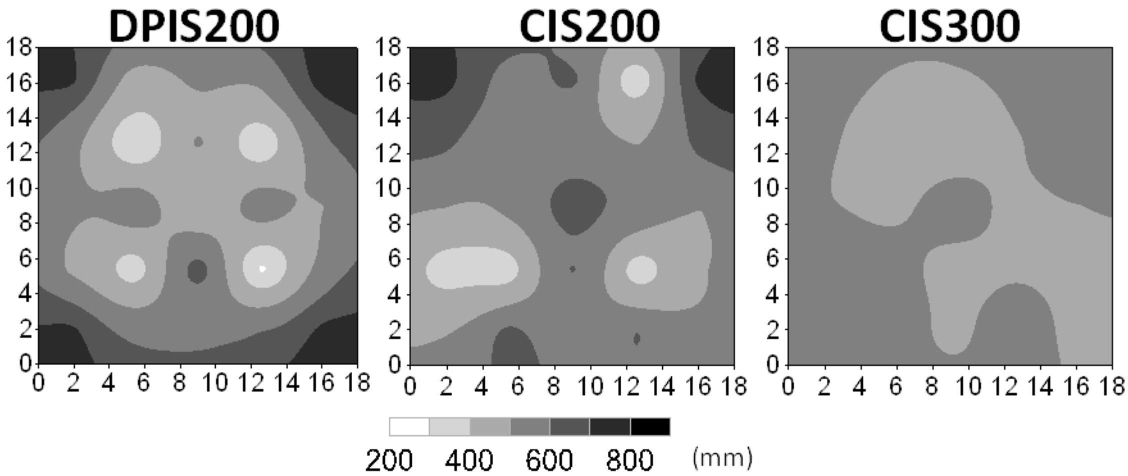


**Figure 7.** Water distribution pattern of the accumulated irrigation applied in 2016 to one replicate of each treatment: DPIS200 (a), CIS200 (b) and CIS300 (c).

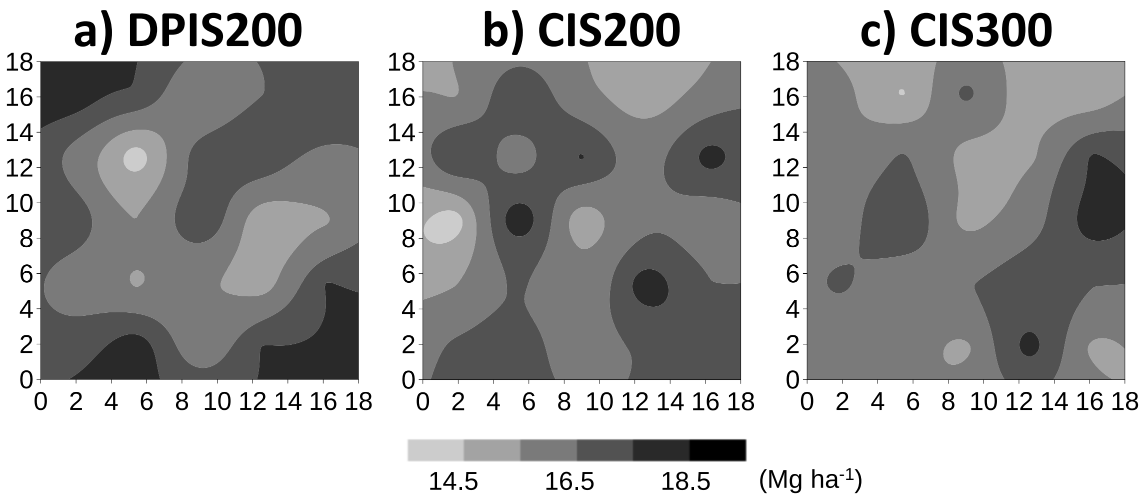


**Figure 8.** Spatial variability of grain yield obtained by the intensive hand harvest performed in one replicate of each treatment: DPIS200 (a), CIS200 (b) and CIS300 (c), in 2016 crop season.