Sprinkler irrigation frequency affects maize yield depending on irrigation time

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Abbreviations: CIR, crop irrigation requirement; CU, Christiansen coefficient of uniformity; EC: electrical conductivity; ETo, reference evapotranspiration; ETc, crop evapotranspiration; GMT, Greenwich Mean Time; PAR, photosynthetically active radiation; VPD, vapor pressure deficit; WDEL, wind drift and evaporation losses; WUE, water use efficiency.

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ABSTRACT

34 Sprinkler irrigation with solid-set systems easily allows changing irrigation
35 frequency. We studied, under field conditions and during three years, the effects
36 of irrigation frequency (two events per week or daily) and daytime vs. night-time
37 irrigation on microclimatic changes, soil matric potential, growth, yield, and
38 water use of maize (*Zea mays* L.). Microclimatic changes (decrease of air
39 temperature and vapor pressure deficit, and of canopy temperature) were
40 slightly larger and lasted for more time after the irrigation event with low
41 frequency irrigation. Increasing irrigation frequency during daytime resulted in a
42 lower soil matric potential. Irrigating at night-time resulted in higher maize height
43 (+3%) and yield (+10%) than irrigating at daytime. The high irrigation frequency
44 decreased maize height (-7%) and yield (-5%) compared with the low irrigation
45 frequency when irrigation was performed at daytime but not at night-time. The
46 Na⁺ content of the plant was doubled with daytime sprinkler irrigation compared
47 with night-time irrigation, and was increased by 30% when the irrigation
48 frequency was increased. Water use efficiency (WUE) was not affected by
49 irrigation frequency when irrigating at night-time, but it decreased with the
50 increase of irrigation frequency when irrigation was applied during daytime.
51 Sprinkler irrigation with solid-set must be applied at night to obtain the maximum
52 maize yield and WUE. Irrigation frequency is not relevant for sprinkler irrigation
53 of maize applied at night, but high irrigation frequency should be avoided when
54 maize is sprinkler irrigated during daytime to avoid yield and WUE decreases.

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Sprinkler irrigation with solid-set systems easily allows changing irrigation frequency. In the Ebro River Valley (Spain) sprinkler irrigation is scheduled at one to five days intervals (Salvador et al., 2011). In some fields, a high irrigation frequency is necessary due to limitations on water infiltration in soil (López-Bruna and Aragüés, 1995). However, sometimes it is just a farmer's preference. A higher irrigation frequency has generally been considered as advantageous when irrigating crops (Rawlins and Raats, 1975), but in the case of sprinkler irrigation some factors must be taken into account.

In each sprinkler irrigation event some water is lost by evaporation during and after irrigation (Tolk et al., 1995). The water lost after the irrigation application (interception losses) mainly depends on the canopy architecture, leaf characteristics, and the development stage of the crop, and has been found fairly constant in the different irrigation events (Steiner et al., 1983a). Consequently, a higher irrigation frequency will result in higher interception losses due to a higher number of irrigation events (Seginer, 1967). In maize, reported interception losses ranged from 0.4 to 2.7 mm per irrigation event (Steiner et al., 1983a), but Martínez-Cob et al. (2008) found that considering the transpiration reduction after irrigation, the interception losses decreased to 0.3 mm for daytime irrigation and 0.1 mm for night-time irrigation events.

Sprinkler irrigation modifies the microclimatic conditions where plants grow and their physiology: decreasing the crop canopy temperature (Steiner et al., 1983b; Tolk et al., 1995; Saadia et al., 1996; Caverro et al., 2009; Caverro et al., 2016), transpiration (McNaughton, 1981; Martínez-Cob et al., 2008; Caverro et al., 2009) and photosynthesis (Urrego-Pereira et al., 2013a), and increasing the leaf water potential (Howell et al., 1971; Caverro et al., 2009). These

changes are more important for day than night irrigation (Cavero et al., 2009; Cavero et al., 2016) and could be affected by irrigation frequency because at higher irrigation frequency the application rate at each irrigation event is lower but the plant wetting-drying events increase.

Sprinkler irrigation results in the absorption by the leaves of different ions present in the irrigation water (Isla and Aragüés, 2010). A higher irrigation frequency could increase ion absorption due to a higher number of wetting events (Maas et al., 1982), which could be positive for plant growth (if the irrigation water contains beneficial ions) or negative (if the irrigation water contains toxic ions, such as Na^+ and Cl^-). Leaf ion absorption is affected by leaf wettability (Fernández and Eichert, 2009) and the irrigation time of the day (Isla and Aragüés, 2010). FAO (1985) recommends to avoid sprinkler irrigation when the salinity of water is moderate (electrical conductivity (CE) $> 1 \text{ dS m}^{-1}$) and the content of toxic ions (Na^+ and Cl^-) is higher than 10 meq L^{-1} . Irrigation water in the Ebro River Valley is generally below these thresholds (Isidoro and Aragüés, 2007).

A positive effect of higher irrigation frequency is that the soil water content is more stable. However, that results in a shallower root system, which could be harmful if the irrigation is stopped due to problems with the irrigation system. The effect of irrigation frequency on the yield of crops has been scarcely studied under sprinkler irrigation. Faci and Fereres (1980) reported that when irrigation was applied below that needed to fulfill the crop requirement, the higher frequency sprinkler irrigation decreased the yield of sorghum (*Sorghum bicolor* (L.) Moench). Fischbach and Somerhalder (1974) tested several irrigation frequencies (1.5 vs. 3 days), (3.5 vs. 7 days) and did not find

differences in maize yield. Lyle and Bordovsky (1995) using low energy precision application did not find differences in maize yield when the irrigation interval was 3 or 6 days, but yield decreased when the irrigation interval was 9 or 12 days. However, the irrigation rates that provided the highest maize yield in the work of Fischbach and Somerhalder (1974) (<300 mm), and the irrigation rates used by Lyle and Bordovsky (1995) (300-450 mm), are much lower than those required in the Ebro River Valley (>600 mm) and other semiarid areas (Farré and Faci, 2006). Moreover, none of the previous studies has looked into whether the irrigation time of the day affects to the effect that the irrigation frequency can have in the growth and yield of maize.

The objective of this work was to study if the irrigation frequency of sprinkler irrigation with a solid-set system affects the growth and yield of maize. Given that the sprinkler irrigation time of the day affects the maize growth and yield (Cavero et al., 2008; Urrego-Pereira et al., 2013b) the effect of irrigation frequency was studied for daytime and night-time irrigation.

MATERIALS AND METHODS

Experimental Site

The field experiment was carried out during three years (2015-2016-2017) in a 2.34 ha field irrigated with a solid-set sprinkler system, located at Zaragoza, Spain (41°43'N, 0°48'W, 225 m altitude). The climate is Mediterranean semiarid with long-term annual averages of 14.1 °C for air temperature, 298 mm for precipitation, and 1243 mm for grass reference crop evapotranspiration (ET_o) (FAO Penman-Monteith method, (Allen et al., 1998)). The soil is a clay loam and classified as Typic Xerofluvent. A more detailed

description of the soil characteristics of the experimental field can be found in Cavero et al. (2009).

Experimental Layout

The experimental field was divided into twelve irrigation sectors which were irrigated independently by four sprinklers (Fig. 1). The borders of the field were irrigated independently of the main twelve irrigation sectors. The sprinkler spacing was a square of 18 m x 18 m, i.e., each sector had a surface area of 324 m². The impact sprinkler and nozzles were manufactured in brass (RC-130, Riegos Costa, Lérida, Spain). The sprinkler has a vertical throw angle of 25°, the nozzle diameters were 4.4 mm (main) and 2.4 mm (auxiliary), and the nozzle height was 2.50 m above the soil surface. The nozzle operating pressure was kept constant at 0.3 MPa with a hydraulic pressure control valve. Sprinkler application rate was 5 mm h⁻¹ and the wetted radius was 15 m. The irrigation volume was measured with an electromagnetic flow meter (Promag 50, Endress+Hauser, Reinach, Switzerland) with ±0.5% measurement error.

Maize cv. Pioneer P1758 was planted on 14 Apr. 2015, 13 Apr. 2016 and 3 Apr. 2017 in rows 0.75 m apart at a planting density of 89,500 seeds ha⁻¹. The previous crop had been alfalfa (*Medicago sativa* L.) during three years (2012-2014). Fertilization consisted of 64 kg ha⁻¹ N, 120 kg ha⁻¹ P₂O₅, and 120 kg ha⁻¹ K₂O applied before sowing, and 200 kg ha⁻¹ N applied with the irrigation water in two dates (at V6 and V12), except in 2015 when only 100 kg ha⁻¹ N was applied with the irrigation water at V12 because of the carryover N effect of the previous alfalfa crop. Weed and pest control were carried out following the best management practices of the area.

The soil gravimetric water content was determined on disturbed soil samples (0.3-m intervals to the 1.5-m depth) each year before maize planting and at maize harvest by sampling in the center of each experimental plot.

The meteorological data recorded at a weather station over grass located 1 km southwest of the experimental field were used to compute the reference ET_o . Crop coefficients (K_c) were calculated as a function of thermal time using an equation developed at the same location of the experiment (Martínez-Cob, 2008). Thermal time was computed as the cumulative daily difference between daily mean air temperature and a basal air temperature of 8 °C (Kiniry, 1991). Daily crop evapotranspiration of maize (ET_c) was then obtained as the ET_o multiplied by the K_c . The crop irrigation requirements (CIR) were determined weekly as the difference between the ET_c and the effective precipitation, assumed as 75% of total weekly precipitation (Dastane, 1978). The initial soil water content above the wilting point at the 0-0.9 m depth was considered as available for the crop and subtracted from the CIR at the beginning of the crop season. The irrigation amount applied to the crop was equal to the CIR and irrigation was applied at night-time to all the experimental plots until the crop was well established (V6 to V8 growth stage) in order to have the same plant density and because limitations for irrigation scheduling at night-time are generally not relevant during the period of lower CIR.

Two factors, irrigation time and irrigation frequency (with two levels each), were tested in a factorial design. For irrigation time the levels were daytime or night-time. For irrigation frequency the levels were: two irrigation events per week (low frequency) or daily irrigation (high frequency). Therefore, four irrigation treatments were established: a) daytime irrigation and low

frequency (day&low); b) daytime irrigation and high frequency (day&high); c) night-time irrigation and low frequency (night&low); and d) night-time irrigation and high frequency (night&high). Each treatment was replicated three times, so 12 irrigation plots were used. Each year the treatments were randomly established to avoid any cumulative effect. The same amount of irrigation water was applied to all the treatments and was calculated weekly, as explained. The starting time for irrigation was generally 1000 h Greenwich Mean Time (GMT) for daytime irrigations and 2200 h GMT for night-time irrigations. The irrigation duration of the high frequency treatment was at least 1 h, so if the weekly CIR was lower than 7 h, irrigation was not applied daily.

Irrigation efficiency was evaluated in the low frequency treatments by determining the wind drift and evaporation losses (WDEL) (Frost and Schwalen, 1955) and the uniformity of application through the coefficient of uniformity (CU) (Christiansen, 1942). For this, one grid of catch cans was placed at each of two different irrigation sectors, one irrigated during daytime and low frequency, and another irrigated during the night and low frequency (Fig. 1). Each grid was formed by 25 catch cans, which were arranged in five rows and five columns with a distance of 3.6 m between catch cans. The catch cans were made of plastic, with an opening diameter of 0.18 m and a maximum capacity of 45 L m⁻². The catch cans were marked in mm with a resolution of 1 mm, in order to directly read irrigation depth just after each irrigation event. The catch cans were placed above the crop and they were moved up (three times each season) as the crop height increased.

206 The WDEL were calculated as:

$$207 \quad WDEL = 100 \left(\frac{I_{fm} - I_{cc}}{I_{fm}} \right) \quad (1)$$

208 where I_{fm} (mm) is the applied irrigation depth measured with the flow meter; and
209 I_{cc} (mm) is the mean value of collected water depth in the catch cans.

210 The CU was computed using the methodology described by Christiansen
211 (1942) as:

$$212 \quad CU = 100 \left[1 - \frac{\sum (x_i - I_{cc})}{I_{cc} n} \right] \quad (2)$$

213 where $x_i - I_{cc}$ is the deviation of the individual observations from the mean
214 value of collected water depth in the catch cans, and n is the number of catch
215 cans of the grid.

216 Irrigation water was analyzed each year on three dates to determine the
217 electrical conductivity (EC) and the content of Na^+ (ICP-OES) and Cl^- (ion
218 chromatography).

219 **Soil Matric Potential**

220 The soil matric potential was measured with a granular matrix sensor
221 (Watermark, Irrrometer Company, Riverside, CA). One irrigation sector of each
222 irrigation time & irrigation frequency combinations was monitored, so four
223 irrigation sectors were monitored (Fig. 1). Eight sensors were installed in each
224 of these four irrigation sectors at the same positions within the square defined
225 by the four sprinklers (Fig. 1): four within the plant rows (two at 0.2 m depth and
226 two at 0.6 m depth) and four at the centre of the inter-plant row space (two at
227 0.2 m depth and two at 0.6 m depth). The eight sensors in each irrigation sector

were connected to a datalogger (Microsis, Progres, Bellpuig, Lérida, Spain) which recorded the measurements each hour.

It is well established that the allowable soil water depletion to avoid water stress depends on the crop species and the climate (Martin et al., 1990; Allen et al., 1998). A soil matric potential threshold of -0.080 MPa, which corresponded to a 30% soil water depletion, has been found adequate to indicate probable water stress in our experimental site for maize (Urrego-Pereira et al., 2013b).

Microclimatic Changes Due to Sprinkler Irrigation

Sensors to record the temperature and vapor pressure deficit (VPD) of the air and the crop canopy temperature during the crop season were installed just at the border of four experimental plots (one irrigation sector of each irrigation time & irrigation frequency combinations) in order not to interfere with cultural labors. Sensors were: one temperature and relative humidity probe (HMP45C, Vaisala, Helsinki, Finland) installed inside a shield URS1 (Campbell Scientific, Logan, USA), which protected it from irrigation water, and an infrared thermometer (IR120, Apogee Instruments Inc., Roseville, CA, USA) to measure the crop canopy temperature. They were placed progressively higher above ground as the crop height increased during the season, so they were always at 0.5 m above the crop canopy. The accuracy of the temperature and relative humidity probe was ± 0.3 °C for temperature and ± 3 % for relative humidity. The infrared thermometer has an accuracy of ± 0.2 °C, was located with an angle of 45 °, and was oriented towards the south measuring inside the experimental plot. The air temperature and relative humidity, and the canopy temperature were measured every 10 s and the 5-min mean values were recorded in a datalogger (CR1000, Campbell Scientific Inc, Logan, UT). The VPD was

calculated from the air temperature and relative humidity data (Allen et al., 1998).

These sensors were used to record the temperature and VPD of the air and the crop canopy temperature during the crop season so for each irrigation frequency level comparisons could be made between the plot that was irrigated and the plot that was not irrigated at that time.

Maize Growth and Yield

The percentage photosynthetically active radiation (PAR) intercepted by the maize crop was determined using a 1-m long ceptometer (Sunscan, Delta-T, Cambridge, UK) and a PAR sensor (BF3 , Delta-T, Cambridge, UK). The measurements were performed at the R2-R3 growth stage. All the measurements were taken around 1000 h GMT. The PAR sensor continuously measured the incoming PAR above the crop canopy every 30 s. The transmitted PAR below the canopy was measured with the ceptometer in three plant rows (6, 12 and 18) of each irrigation sector making four readings at different locations in each row; thereby twelve readings of transmitted PAR were recorded in each irrigation sector. The fraction of the PAR intercepted by the maize crop at each of the 12 sampling spots was calculated as the ratio of the difference between the PAR sensor reading (above the crop) and the simultaneous ceptometer reading (below the crop). The average intercepted PAR per irrigation sector was obtained. For each year, the plant height was measured after tasseling in five plants of the rows 6, 12 and 18 within each irrigation sector. Plant height was measured with a wood ruler as the distance between the soil surface and the top highest leaf.

Maize ear leaves were collected just before tasselling (V12-V14) and at R1, R2, and R5. At each experimental plot, eight leaves from different plants were taken from rows 3, 7, 11 and 15. They were dried at 60 °C and ground. The Na⁺ content was analysed by ionic chromatography and the Cl⁻ content by ICP-OES.

The harvest was conducted on 30 September 2015, 5 October 2016 and 28 September 2017. For each irrigation sector, the final number of plants, total biomass, and harvest index were determined by hand harvesting the plants in a 3-m long section of two rows. The plants were clipped at the soil level, the grain was separated from the cob and stover and both parts dried at 60 °C. The biomass was analyzed for N content by combustion (TruSpec CN, LECO, St. Joseph, MI, USA) and for Na⁺ and Cl⁻ content as explained before. Each irrigation sector (18m x 18m) was also harvested with a combine, and the grain weighed with a 1-kg precision scale. A subsample of grain was collected from each irrigation sector to measure the grain moisture to adjust the grain yield to a standard 14% moisture content. Another subsample of the combine harvested grain from each irrigation sector was dried at 60 °C to measure kernel mass and to determine the N, Na⁺, and Cl⁻ content. The number of grains per unit area was calculated from the kernel mass and the grain yield.

Water Use Efficiency

The water balance was used to calculate the actual maize ET at each plot during each season. Irrigation applied, rainfall and the change in soil gravimetric water content between maize planting and maize harvest were used. The water use efficiency (WUE) was calculated for each plot as the ratio between the maize grain yield and the seasonal actual maize ET.

Statistical Analysis

The effect of year, irrigation time and irrigation frequency on maize growth and yield, N content and N uptake, Na^+ and Cl^- content of biomass and grain, seasonal actual ET and water use efficiency were analyzed with ANOVA at a level of significance of $P = 0.05$ considering all the factors as fixed effects. The year was not considered as a factor in ANOVA when analyzing the effect of irrigation time and irrigation frequency on Na^+ and Cl^- content of leaves because they were not collected all years at the same phenological stage. Multiple comparisons among treatments were performed using Fisher's Protected LSD test at $P = 0.05$.

For each month, the average daily values of the soil matric potential from some irrigation time & irrigation frequency treatments were compared using a paired t -test and level of significance of $P = 0.05$: day&low vs. night&low; day&high vs. night&high; day&low vs. day&high; and night&low vs. night&high. Considering each irrigation frequency, for each irrigation event the air temperature and VPD and the crop canopy temperature of the experimental plot that was irrigated (daytime or night-time) were compared with that of the experimental plot that was not irrigated at that time (night-time or daytime). A comparison was made of the average values for the periods: during the irrigation, and 1 and 2 h after the irrigation event. Comparison was made using a paired t -test and a level of significance of $P = 0.05$.

RESULTS

Irrigation Applied and Characteristics of Irrigation Events

The effective seasonal precipitation was similar all years (Table 1). The available soil water at planting for the crop was similar all years, ranging from 49 mm in 2015 to 64 mm in 2016. The ET_c and the CIR were similar all years (Table 1). The irrigation applied for crop establishment accounted for 11% to 14% of the total irrigation applied (Table 1). The seasonal irrigation applied was close to the calculated CIR with a difference of 1 to 8 mm, which represents less than 1.5% of CIR (Table 1, Fig. 2). In general, the weekly applied irrigation amount was close to that required (Fig. 2), but some discrepancies occurred during the season, mostly due to rainfall.

The mean EC values of the irrigation water were 0.58 (2015), 0.31 (2016) and 0.85 $dS\ m^{-1}$, its Na^+ contents were 1.22 (2015), 1.12 (2016) and 1.31 (2017) $meq\ L^{-1}$, and its Cl^- contents were 0.82 (2015), 1.00 (2016) and 1.26 (2017) $meq\ L^{-1}$.

The average wind speed during the low frequency irrigation events was higher during daytime irrigation events (Table 2). However, the difference of wind speed between daytime and night-time irrigation events was lower in 2017 because this year's daytime wind speed was lower than in previous years. The average wind speed during the high frequency irrigation treatments was slightly lower (0 to 12%) than in the low frequency irrigation treatments (data not shown). Faci and Bercero (1991) reported a threshold value of 2.1 $m\ s^{-1}$ for adequate irrigation uniformity in the region. In 2015 and 2016 this threshold was surpassed on the low frequency irrigation treatments much more on the daytime

irrigation events (52 to 62%) than in the night-time irrigation events (17 to 31%). Similarly, this threshold was surpassed on the high frequency irrigation treatments on 52% of daytime irrigations and 22% of night-time irrigations. However, in 2017 this threshold was surpassed on the low frequency irrigation treatments more on the night-time irrigation events (38%) than in the daytime irrigation events (29%), and in the high frequency irrigation treatments this threshold was surpassed on 36% of daytime irrigation events and 22% of night-time irrigation events.

All years, the average values of WDEL for daytime irrigations were greater than for night-time irrigations (Table 2). The WDEL of the daytime irrigation events ranged from 0 to 32%, while the WDEL of the night-time irrigation events ranged from 0 to 21%. In general, greater losses of water occurred with higher wind speeds during daytime irrigations, but the relationship was not so clear for the night-time irrigations. For daytime irrigation events, lower WDELs were found in 2017 (Table 2), probably due to the lower wind speed. In general, WDEL was slightly lower after maize tasseling (Table 2).

The average CU was lower for daytime irrigation events than for night-time irrigation events in 2015 and 2016, but it was similar in 2017 probably because this year's wind speed at daytime and night-time were closer (Table 2). The lower average CU for night-time irrigation events in 2017 compared with previous years was related to the higher wind speed in 2017. In general, the difference of CU between daytime and night-time increased after maize tasseling (Table 2). When considering the seasonal irrigation amounts collected at each catch can, the seasonal CU was 5% higher for the night-time irrigation all years (Table 2).

Soil Matric Potential

In general, the soil matric potential of the day&high treatment after mid-June was lower than that of the other treatments (Fig. 3). In all years, this treatment surpassed the threshold value considered to affect maize growth in our experimental conditions. The daily soil matric potential of the day&low treatment was lower than that of the night&low treatment during July of the first year, August of all years, and September of 2016 and 2017 (Table 3). When the irrigation time treatments were compared for the high irrigation frequency, the soil matric potential was always lower for the daytime treatment, except during June 2015 (Table 3). These results were due to the higher WDEL for daytime irrigation compared with night-time irrigation (Table 2).

Increasing the irrigation frequency during the daytime resulted in a lower soil matric potential all years, except during September 2016 (Table 3). Thus, the 3-yr mean number of days that the soil matric potential was lower than the water stress threshold in July and August was 44 for the day&high treatment compared with 17 for the day&low treatment. However, increasing the irrigation frequency during the night-time did not change the soil matric potential in a clear trend (Table 3), although the 3-yr mean number of days that the soil matric potential was lower than the water stress threshold in July and August was 11 for the day&high treatment compared with 3 for the night&low treatment.

Microclimatic and Crop Canopy Temperature Changes

Microclimatic and crop canopy temperature changes during night-time irrigation were small, so only changes during the daytime irrigations are shown.

During daytime irrigation the air temperature at the crop canopy height significantly decreased (Table 4). The decrease of air temperature due to the

irrigation was lower with the higher irrigation frequency. During the hour following the irrigation events the decrease of air temperature was significant and similar at the high and low irrigation frequencies, and its magnitude (1.6°C) was lower than during the irrigation events (Table 4). The decrease of air temperature 2 h after the irrigation event finished was only of 0.5°C and was similar at the two irrigation frequencies.

During the daytime irrigation events the air VPD significantly decreased, and the magnitude of the decrease was lower with the higher irrigation frequency (Table 4). During the hour following the irrigation events the decrease of air VPD was significant and similar at the high and low irrigation frequencies, but its magnitude was lower than during the irrigation event. The decrease of air VPD disappeared 2 h after the irrigation event finished at the high irrigation frequency.

Maize canopy temperature was significantly reduced during the daytime sprinkler irrigation events (Table 4). The mean reduction was around 4.5°C for the low frequency irrigations but smaller at the high irrigation frequency (2.8°C to 3.2°C , Table 4). Once the daytime irrigation finished, the decrease of maize canopy temperature due to irrigation lasted for 2 h for the low irrigation frequency but only for one hour for the high irrigation frequency (Table 4).

Maize Growth and Yield

The plant density at harvest was affected by the year but was not affected by irrigation time and irrigation frequency (Table 5). The percentage of intercepted PAR was affected by the year, and irrigation time and frequency (Table 5). Night-time irrigation and low frequency irrigation increased the percentage of intercepted PAR. The plant height was affected by the year and

by the interaction of the irrigation time and irrigation frequency (Table 5). The high irrigation frequency decreased the plant height compared with the low frequency irrigation only when irrigation was applied during daytime.

The Cl^- content of maize leaves during the crop season was not affected by the irrigation time of the day nor by the irrigation frequency or their interaction. However, the Na^+ content of leaves was increased all years by two to three times with daytime irrigation compared with night-time irrigation (Table 6). Moreover, the Na^+ content of leaves was significantly increased by 15 to 33% with the high frequency compared with low frequency irrigation in two years (Table 6).

Maize yield was affected by the year and by the interaction of irrigation time and irrigation frequency (Table 7). Significant differences were found between the three years, and the lowest yield was found in 2015 when the plant density was lowest. Irrigating at night-time resulted in higher maize yield than at daytime. The irrigation frequency did not affect maize yield when irrigation was applied at night. However, the high frequency irrigation decreased maize yield when irrigation was applied during the daytime. Considering the mean yield obtained with night-time irrigation (16.4 Mg ha^{-1}), daytime irrigation at low frequency decreased the maize yield by 8.5%, and daytime irrigation at high frequency decreased the maize yield by 12.8%. The aboveground biomass was affected by the year and the irrigation time (Table 7). Daytime irrigation decreased the aboveground biomass by 11.5% compared with night-time irrigation (Table 7). The harvest index was affected by the year but was not affected by the irrigation time nor by the irrigation frequency (Table 7). The number of grains per unit area was affected by the year and by the interaction

of irrigation time and irrigation frequency. Daytime irrigation decreased the number of grains per unit area compared with night-time irrigation. Increasing the irrigation frequency slightly increased the number of grains per unit area with night-time irrigation but the contrary was found for daytime irrigation, although differences were not significant at $P = 0.05$. The kernel mass was affected by the year and the irrigation time (Table 7). Daytime irrigation slightly decreased (-2.5%) the kernel mass.

The Na^+ content of maize stover at harvest was affected by the interaction of irrigation time and irrigation frequency and by the interaction of year and irrigation time (Table 8). Daytime irrigation doubled the Na^+ content of maize stover compared with night-time irrigation and the effect of irrigation time was higher in 2016. Increasing the irrigation frequency increased the Na^+ content of maize stover by 38% when irrigating at daytime and by 31% when irrigating at night-time. The Cl^- content of maize stover was affected by the interaction of year and irrigation frequency (Table 8). In one year (2016) increasing the irrigation frequency decreased Cl^- content of maize stover, while the contrary occurred in 2017 and no effect was observed in 2015. The Na^+ content of maize grain was not affected by any factor studied. However, the Cl^- content of maize grain was affected by the year, the irrigation time and the irrigation frequency (Table 8). Night-time irrigation slightly increased the Cl^- content compared to daytime irrigation, and the low irrigation frequency slightly increased the Cl^- content compared to high frequency irrigation.

The N content of maize stover and grain at harvest was affected by the year but was not affected by the irrigation time of the day nor by the irrigation frequency or their interaction (Table 8). The N uptake was affected by the year

and the irrigation time (Table 8). The N uptake was higher with night-time irrigation as compared to daytime irrigation (Table 8).

Water Use Efficiency

The actual seasonal evapotranspiration calculated with the water balance was affected by the interaction of the year and the irrigation time (Table 9). The actual seasonal evapotranspiration was higher with daytime irrigation compared to night-time irrigation in two out of three years. The irrigation frequency did not affect the actual seasonal evapotranspiration (Table 9). The WUE was affected by the interaction of irrigation time and irrigation frequency and by the interaction of year and irrigation time (Table 9). The WUE was higher with night-time irrigation as compared to daytime irrigation, but the increase ranged between 23% (2015) to 10% (2017). The irrigation frequency affected the WUE only when irrigation was performed at daytime, so the higher irrigation frequency decreased the WUE by 5% as compared to the low irrigation frequency.

DISCUSSION

Previous work (Cavero et al., 2008; Urrego-Pereira et al., 2013b) has shown that sprinkler irrigation time has a relevant effect on maize yield, with daytime irrigation decreasing maize yield around 10% compared to night-time irrigation. The reasons for this decrease were the higher WDEL, the lower CU and the decrease of photosynthesis during daytime irrigation (Cavero et al., 2008; Urrego-Pereira et al., 2013a; Urrego-Pereira et al., 2013b). The results of the present work confirm this 10% decrease of maize yield with daytime sprinkler irrigation but provide an additional cause for it. Benes et al. (1996)

showed that leaf uptake accounted for 98% of total Na^+ content in maize sprinkler irrigated with saline waters ($\text{EC}=4.1 \text{ dS m}^{-1}$), and concluded that maize lacked the ability to selectively exclude Na^+ when sprinkler irrigated. Isla and Aragües (2010) reported that accumulation of Na^+ in maize leaves tended to be higher in diurnal than in nocturnal irrigations. According to these authors, the increase of Na^+ content in the plant is related to a decrease in maize yield. We found that daytime sprinkler irrigation doubled the Na^+ content of the ear leaf during the season and of maize stover at harvest compared to night-time sprinkler irrigation. This is a relevant result because the Na^+ content of irrigation water was low (1.1 to 1.3 meq L^{-1}) and is probably due to the high wettability of maize leaves (Urrego-Pereira et al., 2013a; Revilla et al., 2016) which could favor the entry of Na^+ to the leaves. Considering the 3-yr mean of Na^+ content of the ear leaf for the R2 stage and the equation provided by Isla and Aragües (2010) a 3.8% yield reduction could be predicted with daytime sprinkler irrigation compared to 1.7% yield reduction with night-time sprinkler irrigation, so the increase of Na^+ content due to daytime irrigation could explain a 2.1% maize yield decrease over night-time irrigation.

The higher irrigation frequency resulted in lower and less lasting (usually one hour after the irrigation event) microclimatic and canopy temperature changes at each irrigation event. When considering that the number of irrigation events tripled at the higher irrigation frequency, the seasonal changes could be higher at the higher irrigation frequency because more post irrigation hours occurred at the higher irrigation frequency. The decrease of maize canopy temperature during daytime irrigation has been related to a decreased photosynthesis (Urrego-Pereira et al., 2013a). Although in the high irrigation

frequency treatment the post irrigation hours were higher than at the low irrigation frequency, the high irrigation frequency resulted in a lower and less lasting canopy temperature decrease compared to the low irrigation frequency, so this temperature change probably did not result in a difference of photosynthesis due to the irrigation frequency. In any case, the decrease of CO₂ diffusion through the water layer that covers the maize leaves during the irrigation event and sometime after seems to be the main reason of the decrease of photosynthesis when sprinkler irrigation is performed in daytime (Urrego Pereira et al., 2013a), so if this time is increased with the high irrigation frequency, a higher reduction of photosynthesis is expected.

The high irrigation frequency decreased maize yield compared to the low irrigation frequency when irrigation was performed at daytime but not at night-time. The grain number per unit area was the yield component more affected by the irrigation frequency, similarly as it was found previously for the irrigation time ((Urrego-Pereira et al., 2013b). This reduction of maize yield with the higher irrigation frequency agrees with the decrease of intercepted PAR and plant height. It is well established that water stress can reduce the maize intercepted PAR and height (Denmead and Shaw, 1960; Bradford and Hsiao, 1982; Çakir, 2004; Farré and Faci, 2006). Thus, the soil matric potential was the lowest in the day&high treatment with an average of 70% of days during the July and August months below the threshold of water stress, while in the day&low treatment this threshold was surpassed on 27% of the days. The reported decrease of sorghum yield when sprinkler irrigation frequency was increased (Faci and Fereres, 1980) agrees with our results, but other authors (Fischbach and Somerhalder, 1974; Lyle and Bordovsky, 1995) reported no

effect of irrigation frequency on maize, probably because irrigation was applied above the CIR or the CIR was much lower than at our site.

Sprinkler irrigation frequency affected to the Na^+ content of maize leaves and maize stover at harvest, which was increased around 30% with the higher irrigation frequency. Although this increase is much lower than that due to irrigation time, it agrees with the maize yield results in the sense that increasing the irrigation frequency increased the Na^+ content, which could result in lower yield, as it occurred in the daytime irrigation treatment. Bernstein and Francois (1975) also found an increase of the Na^+ content of bell pepper (*Capsicum frutescens* L.) leaves when increasing the frequency of sprinkler irrigation with water of similar Na^+ content as in our experiment. These authors also found that increasing the irrigation frequency resulted in a decrease of pepper yield when saline water ($\text{EC} = 2.5 \text{ dS m}^{-1}$) was applied, that they attributed to the increased foliar absorption of Na^+ and Cl^- .

The seasonal ET calculated with the water balance was increased with the daytime irrigation compared to the night-time irrigation in two years by 2 to 8%. This is related to the higher WDEL measured during daytime irrigation. However, the water balance did not show an increase in ET due to the higher irrigation frequency, which should occur because the interception losses will increase as the irrigation events increase. The water balance computes the ET between the planting and harvest date so if the maize vegetative growth was decreased by the high irrigation frequency, as it was shown by the decreased intercepted PAR and height, the transpiration component of the ET could be reduced with the high irrigation frequency although the interception losses were higher with this treatment. This counter effect should be more relevant with

daytime irrigation due to the higher WDEL. Besides, Martinez-Cob et al. (2008) found that interception losses during night-time irrigation are a third than those at daytime irrigation.

The null effect on maize yield of irrigation frequency when sprinkler irrigation is performed at night-time and its relevant effect when sprinkler irrigation is performed at daytime is probably due to several reasons. First, WDEL are higher during the daytime so any additional water loss, as the interception losses that occur after the irrigation event, should be more detrimental to the plant. Second, interception losses are higher during daytime than during night-time (Martinez-Cob et al., 2008). Third, daytime sprinkler irrigation doubled the Na^+ content of the plant compared to night-time irrigation, and the further increase due to the higher irrigation frequency could have more than an additive effect. Fourth, as it was found previously (Urrego-Pereira et al., 2013a) the photosynthesis of maize is reduced during the daytime irrigation events and during the following two hours, so a higher decrease will occur with the higher irrigation frequency because the time after the irrigation events is increased.

Given the different effect of irrigation frequency depending on irrigation time on the maize growth and yield and on the ET, the WUE was not affected by the irrigation frequency when irrigating at night-time, but it decreased with the higher irrigation frequency when irrigation was applied during the daytime.

Considering that previous work with maize (Cavero et al., 2008; Urrego-Pereira et al., 2013b) and alfalfa (Cavero et al., 2016) has shown that the effect of sprinkler irrigation time on the crop yield depends on the species, the results

of this work suggest that the effect of sprinkler irrigation frequency should be studied in other crops.

CONCLUSIONS

The results of the present work confirm the 10% decrease of maize yield with daytime sprinkler irrigation with solid-set found previously (which was due to the higher WDEL, the lower CU and the decrease of photosynthesis during daytime irrigation), but provide an additional cause for it: the doubling of plant Na^+ content with daytime sprinkler irrigation.

The high irrigation frequency (daily) decreased maize yield compared to the low irrigation frequency (two irrigations per week) when irrigation was performed at daytime but not at night-time.

Sprinkler irrigation with solid-set must be applied at night to obtain the maximum maize yield and WUE. The irrigation frequency is not relevant for night-time sprinkler irrigation of maize, but high irrigation frequency should be avoided when maize is sprinkler irrigated during the daytime to avoid yield and WUE decreases.

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REFERENCES

- Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. Irrigation and Drainage Paper 56. FAO, Rome.
- Benes, S.E., R. Aragüés, S.R. Grattan, and R.B. Austin. 1996. Foliar and root absorption of Na^+ and Cl^- in maize and barley: Implications for salt tolerance screening and the use of saline sprinkler irrigation. *Plant and Soil* 180:75-86.
- Bernstein, L., and L.E. Francois. 1975. Effects of frequency of sprinkling with saline waters compared with daily drip irrigation. *Agron. J.* 67:185-190.
- Bradford, K.J., and T.C. Hsiao. 1982. Physiological responses to moderate water stress. p. 263–324. *In* O.L. Lange et al. (ed.) *Physiological plant ecology II: Water relations and carbon assimilation*. Springer-Verlag, Berlin.
- Çakir, R. 2004. Effect of water stress at different development stages on vegetative and reproductive growth of corn. *Field Crops Res.* 89:1-16.
- Cavero, J., L. Jiménez, M. Puig, J.M. Faci, and A. Martínez-Cob. 2008. Maize growth and yield under daytime and nighttime solid-set sprinkler irrigation. *Agron. J.* 100:1573-1579.
- Cavero, J., E.T. Medina, M. Puig, and A. Martínez-Cob. 2009. Sprinkler irrigation changes maize canopy microclimate and crop water status, transpiration, and temperature. *Agron. J.* 101:854-864.
- Cavero, J., J.M. Faci, and A. Martínez-Cob. 2016. Relevance of sprinkler irrigation time of the day on alfalfa forage production. *Agric. Water Manage.* 178:304-313.
- Christiansen, J.E. 1942. Irrigation by sprinkling. *Agric. Exp. Stn. Bull.* 670. Univ. of California, Berkeley.

1 Dastane, N.G. 1978. Effective rainfall in irrigated agriculture. Irrigation and
2 Drainage Paper 25. FAO, Rome.

3 Denmead, O.T., and R.H. Shaw. 1960. The effects of soil moisture stress at
4 different stages of growth on the development and yield of corn. Agron. J.
5 52:272-274.

6 Faci, J.M., and A. Bercero. 1991. Efecto del viento en la uniformidad y en las
7 pérdidas por evaporación y arrastre en el riego por aspersión. Inv. Agric.
8 Prod. Prot. Veg. 6:171–182.

9 Faci, J.M., and E. Fereres. 1980. Responses of grain sorghum to variable water
10 supply under two irrigation frequencies. Irrig. Sci. 1:149-159.

11 FAO. 1985. Water quality for agriculture. Ayers, Westcot (eds.). FAO Irrig.
12 Drain. Paper 29, Rev. 1, Rome, Italy. 182 pp.

13 Farré, I., and J.M. Faci. 2006. Comparative response of maize (*Zea mays* L.)
14 and sorghum (*Sorghum bicolor* L. Moench) to deficit irrigation in a
15 Mediterranean environment. Agric. Water Manage. 83:135-143.

16 Fernández, V., and T. Eichert. 2009. Uptake of hydrophilic solutes through plant
17 leaves: Current state of knowledge and perspectives of foliar fertilization.
18 Crit. Rev. Plant Sci. 28:36-68.

19 Fischbach, P.E., and B.R. Somerhalder. 1974. Irrigation design requirements
20 for corn. Trans. ASAE. 17:162-171.

21 Frost, K.R., and H.C. Schwalen. 1955. Sprinkler evaporation losses. Agric. Eng.
22 36:526–528.

23 Howell, T.A., E.A. Hiler, and C.H.M. van Bavel. 1971. Crop response to mist.
24 Trans. ASAE 14:906-910.

- 1 Isla, R., and R. Aragüés. 2010. Yield and plant ion concentrations in maize (*Zea*
2 *mays* L.) subject to diurnal and nocturnal saline sprinkler irrigations. *Field*
3 *Crops Res.* 116:175-183.
- 4 Isidoro, D., and R. Aragüés. 2007. River water quality and irrigated agriculture
5 in the Ebro River Basin: An overview. *Int. J. Water Resour. Develop.* 23:91-
6 106.
- 7 Kiniry, J.R. 1991. Maize phasic development. p. 55–70. *In* J. Hanks and J.T.
8 Ritchie (ed.) *Modeling plant and soil systems.* Agron. Mongr. 31. ASA, CSA,
9 and SSSA, Madison, WI.
- 10 López-Bruna, D., and R. Aragüés. 1995. Estabilidad estructural de cinco suelos
11 de Monegros II regados con un simulador de lluvia: Efecto de la calidad del
12 agua de riego y del acolchado. *Invest. Agr.: Prod. Prot. Veg.* 10:441-462.
- 13 Lyle, W.M., and J.P. Bordovsky. 1995. LEPA corn irrigation with limited water
14 supplies. *Trans. ASAE.* 38:455-462.
- 15 Maas, E.V., R.A. Clark, and L.E. Francois. 1982. Sprinkling induced foliar injury
16 to pepper plants: effects of irrigation frequency, duration and water
17 composition. *Irrig. Sci.* 3:101-109.
- 18 Martin, D.L., E.C. Stegman, and E. Fereres. 1990. Irrigation scheduling
19 principles. *In:* G.J. Hoffman et al., editors, *Management of farm irrigation*
20 *systems.* Am.Soc. Agric. Eng., St. Joseph, MI. p. 155–203.
- 21 Martínez-Cob, A. 2008. Use of thermal units to estimate corn crop coefficients
22 under semiarid climatic conditions. *Irrig. Sci.* 26:335-345.
- 23 Martínez-Cob, A., E. Playan, N. Zapata, J. Cavero, E.T. Medina, and M. Puig.
24 2008. Contribution of evapotranspiration reduction during sprinkler irrigation
25 to application efficiency. *J. Irrig. Drain. Eng.* 134:745-756.

- McNaughton, K.G. 1981. Net interception losses during sprinkler irrigation. *Agric. For. Meteorol.* 24:11-27.
- Rawlins, S.L., and P.A.C. Raats. 1975. Prospects for high-frequency irrigation. *Science.* 108:604-610.
- Revilla, P., V. Fernández, L. Alvarez-Iglesias, E.T. Medina, and J. Caverro. 2016. Leaf physico-chemical and physiological properties of maize (*Zea mays* L.) populations from different origins. *Plant Phys. and Biochem.* 107:319-325.
- Saadia, R., L. Huber, and B. Lacroix. 1996. Modification du microclimat d'un couvert de maïs au moyen de l'irrigation par aspersion en vue de la gestion des stress thermiques des organes reproducteurs. *Agronomie* 16:465-477.
- Salvador, R., B. Latorre, P. Paniagua, and E. Playán. 2011. Farmers' scheduling patterns in on-demand pressurized irrigation. *Agric. Water Manage.* 102:86-96.
- Seginer, I. 1967. Net losses in sprinkler irrigation. *Agric. Meteorol.* 4:281-291.
- Steiner, J.L., E.T. Kanemasu, and R.N. Clark. 1983a. Spray losses and partitioning of water under a center pivot sprinkler system. *Trans. ASAE* 26: 1128-1134.
- Steiner, J.L., E.T. Kanemasu, and D. Hasza. 1983b. Microclimatic and crop responses to center pivot sprinkler and to surface irrigation. *Irrig. Sci.* 4:201-214.
- Tolk, J.A., T.A. Howell, J.L. Steiner, D.R. Krieg, and A.D. Schneider. 1995. Role of transpiration suppression by evaporation of intercepted water in improving irrigation efficiency. *Irrig. Sci.* 16:89-95.

- 1 Urrego-Pereira, Y., A. Martínez-Cob, V. Fernández, J. Caveró. 2013a. Daytime
2 sprinkler irrigation effects on net photosynthesis of maize and alfalfa. Agron.
3 J. 105:1515-1528.
- 4 Urrego-Pereira, Y., A. Martínez-Cob, and J. Caveró. 2013b. Relevance of
5 sprinkler irrigation time and water losses on maize yield. Agron. J. 105:845-
6 853.

Figure 1. General experimental layout, with 12 irrigation sectors (1-12) irrigated independently by four sprinklers each. The shaded areas are the experimental plots where irrigation events were characterized and maize yield was measured. IE, experimental plots where irrigation was characterized. The irrigation sectors where the soil matric potential was monitored and the location of sensors to measure microclimatic and canopy changes are shown.

Figure 2. Cumulative weekly values of calculated evapotranspiration of the crop (ET_c), rainfall, crop irrigation requirement (CIR), and irrigation amount applied to maize during the 2015, 2016 and 2017 seasons.

Figure 3. Weekly average values of soil matric potential for the different irrigation time & irrigation frequency treatments during the 2015, 2016 and 2017 seasons. Each value is the mean of eight probes: four at 0.2 m depth and four at 0.6 m depth; for each depth two probes were installed within the plant row, and another two probes installed halfway between two plant rows. The dashed line indicates the soil matric potential that can cause water stress in maize for the soil at this experiment location. VT: maize tasselling.

Table 1. Effective precipitation (P_{ef}), calculated crop evapotranspiration (ET_c), crop irrigation requirement (CIR) and water applied before the irrigation treatments were started (from planting to maize V6–V8 growth stages), during the sprinkler irrigation treatments, and for the whole season in 2015, 2016 and 2017.

Irrigation season		P _{ef}	ET _c	CIR	Irrigation applied
Year	Period				
-----mm-----					
2015	Planting to 31 May†	20	131	62	79
	31 May to maturity‡	65	610	544	535
	All season	85	741	606	614
2016	Planting to 1 June†	48	135	40	65
	1 June to maturity‡	50	637	569	536
	All season	98	772	609	601
2017	Planting to 24 May†	24	125	66	80
	24 May to maturity‡	77	615	519	506
	All season	101	740	585	586
†	Crop establishment.				
‡	Irrigation treatments.				

Table 2. Average values of wind speed, wind drift and evaporation losses (WDEL), and Christiansen coefficient of uniformity (CU) for the daytime (Day) and night-time (Night) irrigations events of the low frequency treatments in the three years of the experiment. Values are the means for each group of irrigation events. The seasonal CU is also given.

Irrigation		Wind speed		WDEL		CU	
Year	No.	Day	Night	Day	Night	Day	Night
		----- m s ⁻¹ -----		----- % -----		----- % -----	
2015	1-9 †	2.38	1.49	18.5	5.1	84	87
	10-23 ‡	2.77	1.41	12.7	1.4	81	87
	All	2.62	1.44	15.0	2.8	82	87
	Seasonal					87	92
2016	1-10 †	2.59	1.42	15.8	1.8	82	89
	11-26 ‡	2.67	1.72	10.5	0.6	78	87
	All	2.64	1.61	12.5	1.1	80	88
	Seasonal					87	93
2017	1-7 †	1.49	1.03	7.9	2.8	87	87
	8-24 ‡	2.46	2.05	10.0	1.9	81	82
	All	2.18	1.75	9.4	2.2	83	83
	Seasonal					85	91

† Before maize tasseling (6 July 2015, 15 July 2016, 1 July 2017).

‡ After maize tasseling.

Table 3. Average difference between the daily values of soil matric potential (mean of 0.20 and 0.60 m depth) recorded at the different irrigation time-irrigation frequency treatments during the months of 2015, 2016 and 2017.

Average difference of soil matric potential									
Day&Low - Night&Low		Day&Low- Day&High		Day&High - Night&High		Night&Low - Night&High			
-----MPa-----									
2015									
June	-0.004	ns†	0.011	s	0.002	ns	0.014	s	
July	-0.011	s	0.014	s	-0.018	s	0.007	s	
August	-0.021	s	0.014	s	-0.041	s	-0.005	s	
September	0.012	s	0.016	s	-0.036	s	-0.032	s	
2016									
June	0.010	s	0.031	s	-0.022	s	-0.002	ns	
July	0.002	ns	0.027	s	-0.026	s	0.001	ns	
August	-0.020	s	0.018	s	-0.025	s	0.013	s	
September	-0.025	s	-0.019	s	-0.018	s	-0.012	s	
2017									
June	-0.002	ns	0.014	s	-0.013	s	0.003	ns	
July	-0.003	ns	0.031	s	-0.047	s	-0.012	s	
August	-0.033	s	0.045	s	-0.034	s	0.044	s	
September	-0.042	s	0.015	s	-0.021	s	0.035	s	

†s For each year, month and treatments compared, the daily values are different according to a paired *t*-test at the 0.05 level.

ns For each year, month and treatments compared, the daily values are not different according to a paired *t*-test at the 0.05 level

Table 4. Average air temperature and vapor pressure deficit (VPD) measured at the crop canopy height and canopy temperature of maize in the irrigated (Irrig) and not irrigated (Not irrig) plots of the low and high frequency irrigation treatments during and after the daytime irrigation events for each year.

Irrigation frequency and year		During irrigation		1 h after irrigation		2 h after irrigation	
	N†	Irrig	Not irrig	Irrig	Not irrig	Irrig	Not irrig
Air temperature (°C)							
Low frequency							
2016	26	25.1 b‡	27.7 a	28.9 b	30.4 a	30.5 b	31.0 a
2017	24	25.6 b	28.3 a	29.4 b	31.1 a	31.3 b	31.8 a
High frequency							
2015	78	25.5 b	27.1 a	27.0 b	28.7 a	29.2 b	29.8 a
2016	82	24.3 b	25.5 a	26.0 b	27.1 a	28.5 a	28.4 a
2017	75	25.0 b	27.3 a	27.0 b	29.1 a	29.8 b	30.4 a
VPD (kPa)							
Low frequency							
2016	26	1.35 b	2.02 a	2.28 b	2.69 a	2.76 b	2.86 a
2017	24	1.13 b	1.98 a	2.11 b	2.71 a	2.78 b	2.97 a
High frequency							
2015	78	1.24 b	1.72 a	1.75 b	2.10 a	2.37 a	2.42 a
2016	82	1.26 b	1.68 a	1.65 b	2.05 a	2.31 a	2.37 a
2017	75	1.28 b	1.79 a	1.75 b	2.23 a	2.54 a	2.59 a
Canopy temperature (°C)							
Low frequency							
2016	25	23.3 b	27.9 a	27.5 b	29.4 a	28.8 a	29.3 a
2017	24	24.4 b	28.9 a	28.3 b	30.9 a	30.0 b	31.1 a
High frequency							
2015	78	23.9 b	26.7 a	27.1 b	27.8 a	28.9 a	28.5 b
2016	82	24.0 b	26.9 a	26.5 b	28.0 a	28.5 a	28.9 a
2017	75	24.3 b	27.5 a	27.5 b	28.7 a	29.5 a	29.4 a

† Number of irrigation events.

‡ For each variable, irrigation frequency, year and period of measurement the values followed by different letters are significantly different according to a paired *t*-test at the 0.05 level.

Table 5. Plant density at harvest, percentage intercepted photosynthetically active radiation (PAR) and plant height as affected by the year (Y), irrigation time (IT) and frequency (IF) for the 2015, 2016 and 2017 experiments. The interactions are shown when significant.

Effect	Levels	Plant density	Intercepted PAR	Plant height
		-- Plants ha ⁻¹ --	-----%-----	-----m-----
Year		S‡	S	S
	2015	73,333 b§	86.0 c	2.08 b
	2016	84,444 a	88.6 b	2.12 ab
	2017	84,722 a	93.3 a	2.19 a
Irrigation time		NS	S	S
	Day	80,000	88.3 b	2.10 b
	Night	81,667	90.4 a	2.16 a
Irrigation frequency		NS	S	S
	Low†	80,557	90.4 a	2.17 a
	High	81,111	88.3 b	2.08 b
IT x IF		NS	NS	S
	Day-Low			2.15 a
	Day-High			2.02 b
	Night-Low			2.19 a
	Night-High			2.17 a
Y x IT		NS	NS	NS
Y x IF		NS	NS	NS
Y x IT x IF		NS	NS	NS

† Low: two irrigation events per week; High: daily irrigation.

‡ S, significant at the 0.05 probability level; NS, not significant.

§ For each effect and variable the numbers with different letters are significantly different according to Fisher's Protected LSD test at $P = 0.05$ level.

Table 6. Na⁺ content of maize leaves at different growth stages as affected by the irrigation time and frequency for the 2015, 2016 and 2017 experiments. The interaction between the two factors was not significant.

		Na ⁺ content											
		V12-V14			R1			R2			R4-R5		
Factor	Level	2015	2016	2017	2015	2016	2017	2015	2016	2017	2015	2016	2017
		----- meq kg ⁻¹ -----											
Irrigation time	Day	12.2 a‡	17.8 a	11.3 a	21.3 a	18.3 a	16.1 a	33.9 a	25.2 a	23.4 a	47.8 a	42.6 a	64.3 a
	Night	6.1 b	7.8 b	4.8 b	10.9 b	8.7 b	6.5 b	15.2 b	11.7 b	9.1 b	26.1 b	21.3 b	26.1 b
Irrigation frequency	Low†	7.8 b	10.9 b	8.3 a	13.9 b	11.7 b	11.3 a	20.9 b	17.4 b	14.3 a	34.8 a	30.0 b	40.9 a§
	High	10.4 a	14.8 a	8.3 a	18.3 a	14.8 a	11.7 a	27.8 a	19.6 a	18.3 a	39.1 a	34.3 a	49.6 a

† Low: two irrigation events per week; High: daily irrigation.

‡ For each factor and variable the numbers with different letters are significantly different according to Fisher's Protected LSD test at $P = 0.05$ level.

§ $P = 0.059$.

Table 7. Grain yield (14% moisture content), aboveground biomass, harvest index and yield components as affected by the year (Y), irrigation time (IT) and frequency (IF) for the 2015, 2016 and 2017 experiments. The interactions are shown when significant.

Effect	Levels	Yield	Biomass	Harvest index	Grains per m ²	Kernel mass
		-- Mg ha ⁻¹ --	--Mg ha ⁻¹ --		-----no.-----	-----mg-----
Year		S†	S	S	S	S
	2015	14.1 c§	21.9 b	0.56 b	3268 b	371 b
	2016	15.8 b	22.4 b	0.59 a	3346 b	378 a
	2017	16.7 a	24.7 a	0.57 b	3995 a	358 c
Irrigation time		S	S	NS	S	S
	Day	14.7 b	21.6 b	0.57	3392 b	364 b
	Night	16.4 a	24.4 a	0.57	3680 a	373 a
Irrigation frequency		NS	NS	NS	NS	NS
	Low†	15.5	23.2	0.57	3526	371
	High	15.5	22.8	0.58	3547	367
IT x IF		S	NS	NS	S	NS
	Day-Low	15.0 b			3440 b	
	Day-High	14.3 c			3345 b	
	Night-Low	16.1 a			3616 a	
	Night-High	16.6 a			3749 a	
Y x IT		NS	NS	NS	NS	NS
Y x IF		NS	NS	NS	NS	NS
Y x IT x IF		NS	NS	NS	NS	NS

† Low: two irrigation events per week; High: daily irrigation.

‡ S, significant at the 0.05 probability level; NS, not significant.

§ For each effect and variable the numbers with different letters are significantly different according to Fisher's Protected LSD test at $P = 0.05$ level.

Table 8. Na⁺, Cl⁻ and N content of maize stover and grain and N uptake in the aboveground biomass as affected by the year (Y), irrigation time (IT) and frequency (IF) for the 2015, 2016 and 2017 experiments. The interactions are shown when significant.

Effect	Levels	Stover			Grain			Nuptake
		Na ⁺	Cl ⁻	N	Na ⁺	Cl ⁻	N	
		----- meq kg ⁻¹ -----		-----%-----	----- meq kg ⁻¹ -----		-----%-----	--kg ha ⁻¹ --
Year		S‡	NS	S	NS	S	S	S
	2015	11.8 b§	148	0.78 b	0.097	47.9 a	1.26 b	231 b
	2016	15.5 a	121	0.77 b	0.071	41.3 b	1.24 b	238 b
	2017	11.3 b	122	0.83 a	0.134	44.3 b	1.30 a	275 a
Irrigation time		S	NS	NS	NS	S	NS	S
	Day	17.0 a	140	0.80	0.086	42.9 b	1.27	234 b
	Night	8.7 b	121	0.79	0.114	46.0 a	1.27	262 a
Irrigation frequency		S	NS	NS	NS	S	NS	NS
	Low†	10.9 b	134	0.80	0.094	46.3 a	1.27	251
	High	14.8 a	126	0.78	0.107	42.6 b	1.26	245
IT x IF		S	NS	NS	NS	NS	NS	NS
	Day-Low	14.3 b						
	Day-High	19.8 a						
	Night-Low	7.5 d						
	Night-High	9.8 c						
Y x IT		S	NS	NS	NS	NS	NS	NS
	2015-Day	15.5 b						
	2015-Night	8.0 c						
	2016-Day	21.6 a						
	2016-Night	9.4 c						
	2017-Day	14.0 b						
	2017-Night	8.3 c						
Y x IF		NS	S	NS	NS	NS	NS	NS
	2015-Low		161 a					
	2015-High		134 ab					
	2016-Low		142 a					
	2016-High		99 c					
	2017-Low		104 bc					

2017-High		145 a					
Y x IT x IF	NS	NS	NS	NS	NS	NS	NS
†	Low: two irrigation events per week; High: daily irrigation.						
‡	S, significant at the 0.05 probability level; NS, not significant.						
§	For each effect and variable the numbers with different letters are significantly different according to Fisher's Protected LSD test at $P = 0.05$ level.						

Table 9. Seasonal maize actual evapotranspiration (calculated with a water balance) and water use efficiency (WUE) as affected by the year (Y), irrigation time (IT) and frequency (IF) for the 2015, 2016 and 2017 experiments. The interactions are shown when significant.

Effect	Levels	Evapotranspiration	WUE
		----- mm-----	--- kg ha ⁻¹ mm ⁻¹ -----
Year		S‡	S
	2015	754 a§	18.8 c
	2016	749 a	21.1 b
	2017	734 b	22.7 a
Irrigation time		S	S
	Day	758 a	19.4 b
	Night	733 b	22.3 a
Irrigation frequency		NS	NS
	Low†	744	20.9
	High	747	20.8
IT x IF		NS	S
	Day-Low		19.8 b
	Day-High		18.9 c
	Night-Low		22.1 a
	Night-High		22.6 a
Y x IT		S	S
	2015-Day	782 a	16.8 e
	2015-Night	726 d	20.7 c
	2016-Day	756 b	19.6 d
	2016-Night	742 c	22.5 b
	2017-Day	736 cd	21.7 bc
	2017-Night	732 cd	23.8 a
Y x IF		NS	NS
Y x IT x IF		NS	NS

† Low: two irrigation events per week; High: daily irrigation.

‡ S, significant at the 0.05 probability level; NS, not significant.

§ For each effect and variable the numbers with different letters are significantly different according to Fisher's Protected LSD test at $P = 0.05$ level.