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Effects of two types of sprinklers and height in the irrigation of sugar beet with a centre pivot

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Abstract

The main objective of this paper is to analyse the effects of sprinkler type and height above the ground on soil water uniformity (CUs) and sugar beet yield. Irrigation was performed with a centre pivot operating under field conditions with two types of sprinklers, one with a stationary plate (SPS) and the other with a moving plate (MPS), at two heights (1 and 2.5 m). The average coefficient of uniformity (CU) of water application of individual irrigation events with SPS ranged from 74 to 81%, compared to nearly 90% from MPS. The value of the cumulative coefficient of uniformity for the set of irrigation events (CUa) for all sprinkler-height combinations exceeded 90%, a value similar to that obtained for CU_S. Results do not show a clear advantage in the final crop response by using sprinklers with MPS or SPS. However, MPS, and especially those located at 1 m in height with a spacing of 1.5 m, have higher water application uniformity, achieving higher yield and yield indexes, as well as higher water use efficiency. The final yield of sugar beet was more influenced by the amount of soil water available for the crop than the small differences in soil water uniformity obtained with the centre pivot.

Additional key words: *Beta vulgaris* L.; fixed spray plate sprinklers; rotating spray plate sprinklers; soil water uniformity; water application uniformity.

Resumen

Efecto de dos tipos de aspersores y alturas en el riego de remolacha azucarera con un equipo pivot

El objetivo principal de este trabajo es analizar el efecto del tipo de emisor y la altura sobre el suelo sobre la uniformidad de agua del suelo (CUs) y la producción de remolacha azucarera. El riego se realizó con un equipo pivot funcionando en condiciones de campo con dos tipos de aspersores, uno con una placa fija (SPS) y el otro con una placa giratoria (MPS), a dos alturas (1 y 2,5 m). La media del coeficiente de uniformidad de agua aplicada (CU) en los riegos individuales con SPS varió entre 74 a 81%, en comparación con casi el 90% con los MPS. El valor del coeficiente de uniformidad acumulado para el conjunto de riego (CUa) para todas las combinaciones de aspersor-altura fue superior al 90%, un valor similar al obtenido para la CUs. Los resultados no muestran una clara ventaja en la respuesta final del cultivo mediante el uso de aspersores con MPS o SPS. Sin embargo, los MPS, y especialmente los situados a 1 m de altura, colocados a un espaciamiento de 1,5 m, tienen una mayor uniformidad en la aplicación del agua, logrando un mayor rendimiento y sus correspondientes índices, así como una mayor eficiencia del uso del agua. El rendimiento final de la remolacha azucarera estuvo más influenciado por la cantidad de agua disponible del suelo para el cultivo que por las pequeñas diferencias en la uniformidad de agua del suelo obtenido con el equipo pivot.

Palabras clave adicionales: aspersores con placa fija; aspersores con placa giratoria; *Beta vulgaris* L.; uniformidad de agua del suelo; uniformidad de aplicación del agua.

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Abbreviations used: CU (uniformity coefficient of Heermann & Hein); CU_a (accumulated coefficient of uniformity); CU_s (soil water uniformity); DMr (dry matter of the roots); EDLs (evaporation and drift losses); ET (estimated evapotranspiration); ETo (reference evapotranspiration); EWRc (efficiency of water received by the crop); FEI (farmer's economic index); HI (harvest index); ITV (industrial technological value); IWU (irrigation water use); MPS (moving plates sprinkler); PAR (photosynthetically active radiation); Pe (effective precipitation); RUE (radiation use efficiency); SPS (stationary plates sprinkler); TDM (total dry matter); TR (total solar global radiation); TWU (total water use); WERc (water efficiency received by the crop); WP (water productivity).

Introduction

One third of the sugar produced worldwide (114.3 million tons) comes from sugar beet and two thirds are from sugar cane (Kaffka & Hill, 2004). Decreasing water availability for agriculture in most regions of the world, along with high water requirements for sugar beet, makes it necessary to develop research that can contribute to water conservation. The long sugar beet cycle requires irrigation when it is cultivated in a semi-arid climate, usually using sprinkler irrigation systems, and centre pivots when plots are over 15 to 20 ha (Tarjuelo, 2005).

The most modern sprinklers typically used in centre pivot systems are low pressure sprinklers with stationary or moving plates that deflect the water ejected through the nozzle. The aim is to obtain a large proportion of medium-sized droplets (between 1.5 and 4 mm in diameter) and broader throw (8 to 12 m or more) while working at low pressure (less than 200 kPa) (Allen *et al.*, 2000).

The distribution of water applied on the surface by a sprinkler irrigation system has been extensively investigated. However, the response of crop yield depends on the available water in the root area. Several field experiments have been developed to study the relationship between the uniformity of soil water and uniformity of water applied with solid set sprinkler irrigation systems (Li & Kawano, 1996; Li, 1998), but there are few studies that evaluate the uniformity of soil water and water application uniformity with centre pivot. Previous work has shown that the uniformity of soil water is generally higher than the uniformity of water applied with the irrigation system (Stern & Bresler, 1983; Li & Kawano, 1996; Chen *et al.,* 2004).

In an experiment with sugar beet (*Beta vulgaris* L.) in semi-arid areas, Fabeiro *et al.* (2003) show that moderate restriction of water in plant growth and root thickening followed by severe restriction in the maturation period can produce high yields (up 117.64 t ha^{-1}) with relatively moderate irrigation water application (6,898 m^3 ha^{-1}). In a test of deficit irrigation, where the water applied ranges from 50, 75, and 100% of the estimated evapotranspiration (ET), Tognetti *et al.,* (2003) indicate that increasing the amount of water gives benefits in terms of sugar beet root yield and sucrose accumulation.

A continued reduction in water availability for agriculture makes it necessary to increase water use efficiency by the plant (Hatfield *et al.*, 2001; Topak *et al.* 2010, 2011). Given the difficulty of measuring the water a crop truly consumes, most publications refer to the relationship between yield and water received by the crop from irrigation and rain to calculate the efficiency of water received by the crop (EWRc).

Water productivity (WP) can be defined as the ratio between the actual yield achieved and the total water use (Lorite *et al.*, 2005; Rodrigues & Pereira, 2009; Topak *et al.,* 2010, 2011). Water use efficiency is commonly used as a synonym of WP (Steduto, 1996), but recently the term biomass WP was introduced to clearly refer to the physiological and ecophysiological processes of biomass production (Steduto *et al.*, 2007). When referring to irrigation, it is preferable to assess WP relative to either total water use (TWU) or irrigation water use (IWU) when an assessment aims to evaluate the performance of a given irrigation system (Rodrigues & Pereira, 2009; Hassanli *et al.,* 2010).

Moreover, the biomass and yield of a crop are closely related to the amount of radiation intercepted (Monteith, 1977; Milford *et al.,* 1980, 1985; Martin, 1986). Brown *et al.* (1987) measured radiation interception in sugar beet under different conditions of deficit irrigation and found that it was lower in treatments wherein plants underwent stress. Damay & Le Gouis (1993) studied radiation use efficiency (RUE) on sugar beet in northern France, finding values between 2.96 and 3.76 g of dry matter MJ^{-1}, while the average value for sugar was 2.31 g MJ^{-1} of absorbed radiation. López-Bellido (2003) indicates that sugar beet can produce 1.72 g of dry matter per MJ of intercepted radiation, and when leaf cover is fully established, it can accumulate 1 g of sugar per MJ of intercepted radiation.

The main objective of this paper is to analyze the effects of sprinkler type and height above the ground on soil water uniformity (CUs) and sugar beet yield. To achieve this, crops are irrigated with a centre pivot system operating under field conditions with two types of sprinklers, one with stationary plates (SPS) and the other with moving plates (MPS), at two heights (1 and 2.5 m).

Material and methods

Experimental design

The climate classification of Papadakis (1966), placed the study area in a warm Mediterranean climate. The field experiment was performed during three seasons (2004-2006), in an 18.4 ha plot irrigated with a centre pivot, located in Albacete, Spain (39°00'N, 1°52'W). The centre pivot, of 242 m in length, has four spans, which are 50 m long, one 38 m long span and an overhang of 4 m. Two types of sprinklers were installed: a) moving plate sprinklers (MPS; Rotator® with brown plate), and b) stationary plate sprinklers (SPS; D3000® with brown plate). SPS were placed at 2.5 m height (SPS 2.5) in the second span (S-II), and 1 m (SPS 1) in the third span (S-III). MPS were placed at 2.5 m height (MPS 2.5) in the fourth span (S-IV) and 1 m (MPS 1) in the fifth span (S-V). In all cases, the sprinklers had pressure regulators with an output of 140 kPa, and pressure at the fixed pivot point was 210 kPa. The pipe was 168.3 mm in diameter. Additional information is available in Ortiz *et al.* (2010).

This research was field-oriented and designed to be performed with equipment operating under field conditions. Although the proposed testing methodology admittedly had some weaknesses, its most important strength was that it reproduced field conditions. The main advantages of this experimental design is that it reproduces field conditions of irrigation with a centre pivot, increasing the nozzle diameter and the discharge with the distance from the centre pivot.

The experiment was performed on a sugar beet crop that covered a quarter of the area watered by the centre pivot. Due to crop soil requirements, it was necessary to rotate the crop for the different experimental years, which slightly changed the soil characteristics in each year, mainly the texture. Sugar beet was directly sowed (120,000 plants ha^{-1}). Before sow, 100 kg ha^{-1} of N, 150 kg ha^{-1} of P_2O_5 and 200 kg ha^{-1} of K_2O were applied. In May, another 100 kg ha^{-1} N were applied in two times. Pest control as well as other farm tasks and crop operations were those normally carried out by farmers in the area (de Juan *et al.,* 2003).

The typical soil was Xeric torriorthent (Soil Taxonomy) with a loam texture (4% coarse sand, 28% fine sand, 44% silt and 24% clay) according to the USDA (2006). The estimated available water in the first 0.60 m of the soil profile was around 0.09 mm^{-1}. The area is characterised by flat topography and the soils are well-drained, with medium thickness (> 0.60 m).

In order to avoid the border effect between treatments, only 30 m in the centre of each treatment were considered, meaning that 10 m at each end of the 50 m span were avoided. In the last span, of only 38 m in length, it was necessary to place two 3 m × 1.5 m rectangular plates covered with thin plastic mesh to avoid the border effect between treatments.

Irrigation was scheduled using a simplified water balance method within the root area, following the FAO methodology (Pereira & Allen, 1999). In order to compute reference evapotranspiration (ETo), the necessary climatic variables were measured by an automatic meteorological station located at a distance of 150 m from the plot.

Effective precipitation (Pe) was calculated from the moisture variation in the upper 0.5 m of the soil, which was considered to be the effective rooting depth according to samples taken in the field. In order to relate the applied water with the final crop yield, only the water measured at the catch cans located within the testing area was considered.

Control of water application

Evaluations were carried out following the methodology proposed by Merrian & Keller (1978), Merrian *et al.* (1980) and Heermann (1990), as well as International ANSI/ASABE Standards S436.1 (2001) and ISO 11545 (2001). In field tests, plastic catch cans with 0.16 m diameter opening and 0.15 m in height were spaced 2 m apart in along the radius and placed over the canopy, which was 0.5 m above the ground when the crop reached total development.

In each evaluation, flow was measured at the entrance of the centre pivot and at the beginning of each span using a portable ultrasonic flow meter (Panametrics® PT 868, Ireland) with 2% precision after calibration. In addition, a pressure transducer was located at the pivot point and at the beginning of each span for measuring the pressure during irrigation to relate it to discharge.

For each evaluation of the system, the uniformity coefficient of Heermann & Hein (1968) (CU) for each sprinkler-height combination was calculated. The accumulated coefficient of uniformity (CUa) and for all evaluations were also calculated from the accumulated water volume in each catch can.

Although the effective root depth was established at 0.5 m, soil moisture was measured at depths from 0 to 0.6 m in the soil profile. It was measured before and after each irrigation event by means of a sensor based on the frequency domain reflectometry (FDR) technology (Diviner 2000TM, Sentek Pty Ltd., Stepney, Australia). The equipment was calibrated in the laboratory following the methodology described by Sentek (2000) and Martinez (2004). Soil moisture was measured for the last two experimental seasons because the equipment was not available in 2004.

In order to quantify soil moisture uniformity during the 2005 and 2006 seasons, 16 PVC access tubes were installed next to the catch cans along 30 m in the middle of each sprinkler–height combination, spaced 2 m apart in the radius direction. They measured the water applied by the centre pivot. In each of these points, soil moisture measurements were taken every 0.1 m, to 0.5 m in depth. The measurements were recorded before each irrigation event, at 20:00 h for overnight irrigation and one hour before the centre pivot moved over the catch can line transect for daytime irrigation. The post irrigation measurements were taken 24-30 h following irrigation. Given that the objective was only to quantify soil moisture uniformity, we did not consider the loss of soil moisture due to crop evapotranspiration during this period.

The soil water uniformity for each sprinkler-height combination has been calculated using Eq. [1].

$$CU_s = \left(1 - \frac{\sum_{i=1}^{n} \left| \theta_i - \theta_m \right|}{\theta_m \cdot n} \right) * 100 \qquad [1]$$

where: CU_s is the uniformity coefficient of soil water content to a certain depth (%); θ_i is the volumetric water content at that depth (mL mL^{-1}) corresponding to the access tube *i*; and θ_m is the average water content in that depth (mL mL^{-1}) corresponding to n = 16 access tubes of a same sprinkler-height combination.

Yield control

In order to determine sugar beet crop yield, root yield and sugar yield, four parcels of 10 m^2 each (4 rows of 5 m of length) for each sprinkler-height combination were selected. In each of these parcels, water collected by the catch cans plus the effective rainfall was monitored to calculate the water efficiency received by the crop (WERc).

Samples for determining industrial quality parameters were analysed by the laboratory of the Association of Research for the Improvement of Sugar Beet (AIMCRA), located in Valladolid, Spain. The method used to determine the parameters of industrial quality was flame photometry for sodium and potassium. Colorimetry (blue number) was used for α-aminoacid N and reducing sugar (glucose, fructosa, etc.) determination and polarimetry for sugar richness. The method described by Wieninger & Kubadinow (1971) was used to establish the internal quality of sugar beet. The industrial technological value (ITV) was calculated with Eq. [2] (Salvo, 1999; Rosso, 2000; Morillo-Valverde, 2001):

$$\mathrm{ITV} = \frac{\left(\mathrm{Sw} - \mathrm{Sm} - 0.7\right)}{\mathrm{Sw}} * 100 \qquad [2]$$

$$\mathrm{Sw} = 0.14(\mathrm{Na} + \mathrm{K}) + 0.25(\alpha \mathrm{Am}) + 2.54\,\mathrm{RS} + 0.3 \qquad [3]$$

where: Sw is sugar richness (%); Sm is the sugar in molasses (%); Na, K, αAm, are sodium, potassium and alpha-amino, respectively, expressed in millimoles per 100 g of sugar beet; and RS is reducing sugar (g per 100 g of sugar beet).

Reference values of elements in sugar beet molasses considered by López-Bellido (2003) were used for the qualitative assessment of alpha-amino, potassium and sodium.

The RUE for the years 2004 and 2005 was obtained with Eq [4]. This is related with net photosynthesis or net assimilation (Major *et al.*, 1991).

$$\mathrm{RUE} = \frac{\mathrm{TDM}}{\mathrm{PAR_{ac}}} \qquad [4]$$

where: RUE is the radiation use efficiency (g MJ^{-1}); TDM is the total dry matter (g m^{-2}); and PAR_{ac} is the accumulated photosynthetically active radiation absorbed by the crop PAR_a (MJ m^{-2}). In this study, RUE values for TDM (RUE_{TDM}) and sugar yield (RUEs) (Scott *et al.*, 1973) were calculated. To calculate the PAR_a, it was necessary to previously obtain a balance to calculate the PAR_a using the Eq. [5] (Gallo & Daughtry, 1986; Gosse *et al.*, 1986):

$$\mathrm{PAR_a} = \mathrm{PAR_o} + \mathrm{PAR_{rs}} - \mathrm{PAR_t} - \mathrm{PAR_r} \qquad [5]$$

where: PAR_o is the PAR reaching the crop; PAR_{rs} is the PAR reflected by the soil; PAR_t is the PAR transfer to the soil; and PAR_r is the PAR reflected by the joint crop-soil.

Measurements were taken every 2 weeks in each of the four sprinkler-height treatments to get the components of the radiation balance. The components of the balance were measured at 5 equidistant points within the central 30 m in each span of the centre pivot. The value of each component was obtained as the average of 5 measurements. This procedure was repeated 10 times during the crop cycle in each year. All measurements were taken very close to solar 12:00 h and on cloudless days. For measuring these components, we used SunScan (Delta-T Devices, Cambridge, UK) equipment.

The efficiency of the crop canopy to absorb solar energy (ε_a) can be calculated using Eq [6] (Gosse *et al.,* 1986):

$$\varepsilon_a = \frac{PAR_a}{PAR_o} \quad [6]$$

The ε_a value ranges from zero for bare soil to a value of around 0.95 when the crop reaches total leaf development (Major *et al.*, 1991).

The PAR_{ac} during the crop cycle was calculated as the sum of the daily values of total solar global radiation (TR) multiplied by 0.48 and by daily ε_a (Major *et al.*, 1991). Daily values of TR, measured with a SKYE SP1110 pyranometre (Campbell Scientific Inc, Logan, UT, USA), were taken from a meteorological station located 150 m from the test area. The fraction of TR considered PAR was the average value given by different authors: 0.48 (Gosse *et al.*, 1986; Major *et al.*, 1991); 0.45 (Kiniry & Knievel, 1995); 0.50 (Villalobos *et al.*, 2002). Daily ε_a was obtained by relating the ε_a measured in each sprinkler-height combination with the time from emergence (t) using the polynomial function in Eq. [7]. The results are shown in Table 1.

$$\varepsilon_a = at^3 + bt^2 + ct + d \quad [7]$$

The harvest index (HI) (Andrade *et al.*, 1996), was calculated by relating the dry matter of the roots (DMr) with the total dry matter of the plant (TDM) obtained at harvest, using Eq. [8]:

$$HI = \frac{DMr}{TDM} * 100 \quad [8]$$

An analysis of variance (ANOVA) was performed by considering the variables related with water distribution (CU, CU_a, CU_s), and the variables related with root and sugar yield to estimate the effect of sprinkler type and height above the ground on water distribution uniformity and crop yield. For this, we used Statgraphics Plus™ software (v. 5.1 for Windows, Statistical Graphics Corp., 1 Herndon, VA, USA). Fisher's Least Significant Difference (LSD) test was used to determine the significant differences between average groups in the ANOVA.

Results and discussion

Water application uniformity on the surface and in the soil

A gross water depth of 8 to 25 mm per irrigation event took place, with an irrigation frequency of 1.5 to 3 days. Eighteen irrigation events were evaluated in the first season, 18 in the second season and 24 in the third season.

In order to illustrate the behaviour of individual and accumulated irrigation values, Figure 1 shows an example of the evolution of CU and CU_a in the four sprinkler-height combinations studied for the last irrigation season. Remarkable improvement is observed when considering accumulated irrigation, mainly in the SPS, where the variability obtained in CU values disappears. Variations in wind speed and direction during different irrigation events leads to a CU_a higher than the average uniformity coefficient of individual irrigation events (CU) (Dechmi, 2002; Martinez, 2004).

Table 1. Adjustment parameters of efficiency of the crop canopy to absorb solar energy (ε_a) [Eq. 7], for different sprinkler-height combinations

Coefficients	2004				2005			
	SPS 2.5	SPS 1	MPS 2.5	MPS 1	SPS 2.5	SPS 1	MPS 2.5	MPS 1
a	2.90E-7**	3.19E-7**	3.01E-7**	3.35E-7**	4.24E-7**	4.01E-7**	4.12E-7**	5.14E-7**
b	–1.36E-4**	–1.43E-4**	–1.38E-4**	–1.48E-4**	–1.68E-4**	–1.63E-4**	–1.60E-4**	–1.90E-4**
c	0.0201**	0.0206**	0.0202**	0.0209**	0.0219**	0.0217**	0.0209**	0.0230**
d	–0.0058^{ns}	–0.0048^{ns}	–0.0058^{ns}	–0.0028^{ns}	–0.0031^{ns}	–0.0061^{ns}	–0.0022^{ns}	–0.0063^{ns}
R^2 (%)	99.22**	98.48**	99.03**	99.30**	99.63**	99.64**	99.88**	99.68**
SE	0.0298	0.0415	0.0311	0.0255	0.0212	0.0207	0.0115	0.0189

SPS 2.5, SPS 1: sprinkler of stationary plate placed at 2.5 m or 1 m height. MPS 2.5, MPS 1: sprinkler of moving placed at 2.5 m or 1 m height. a, b, c and d: adjustment parameters of the function. SE: standard error of the estimation. R^2 = coefficient of determination. ns: not significant; **: $p < 0.01$.

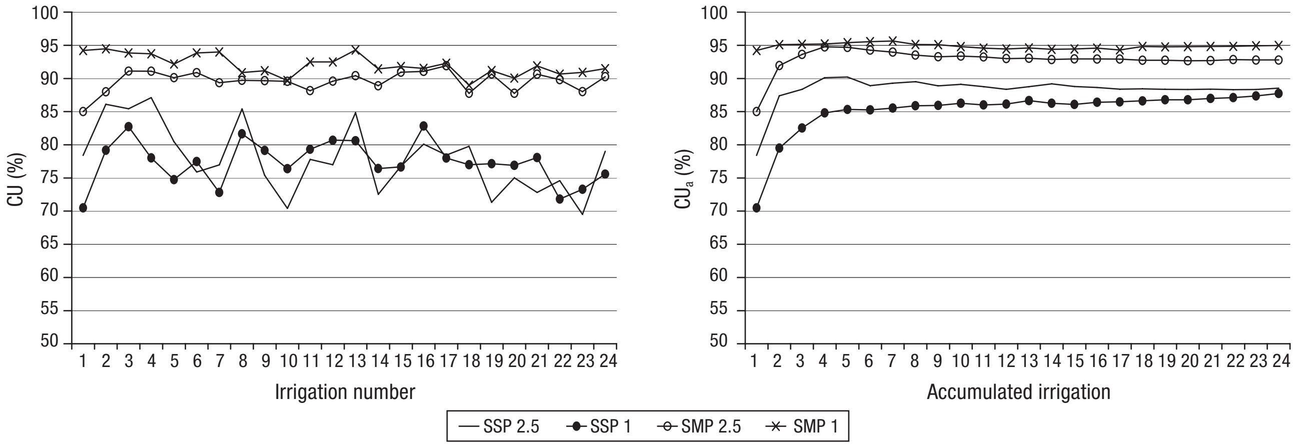

Figure 1. Progression of coefficient of uniformity values in individual (CU, left) and accumulated (CU_a, right) irrigation depths during the last season in the four sprinkler-height combinations. SPS 2.5, SPS 1: sprinkler of stationary plate placed at 2.5 m or 1 m height. MPS 2.5, MPS 1: sprinkler of moving placed at 2.5 m or 1 m height.

Table 2 shows the average CU values during the three experimental seasons, as well as the values of soil water uniformity after irrigation events (CU_{sa}) at 0-0.35 m in depth (which represents the area of greatest root activity) for the four sprinkler-height combinations with their respective coefficient of variation. It is necessary to indicate that the values of uniformity on the surface and in the soil correspond to the same points on the ground, highlighting higher uniformity in soil water than water applied to the surface. In the MPS, CU and CU_{sa} values in 0-0.35 m in depth are very similar. This is logical because they are very high uniformity values. In the SPSs, there is a great improvement in water uniformity in the soil versus on the surface. This is a consequence of low water application uniformity with this type of sprinkler.

Soil water uniformity at 0-0.35 m in depth had similar behaviour in the two years studied. It should be noted that greater values of soil water uniformity were obtained with MPS 1, showing significant differences with all other combinations ($p < 0.001$). However, in the area irrigated with SPS at 1 m high, soil water had lower uniformity (but with values greater than 88% for CU_{sa}). However, as will be seen in the yield analysis, this lower soil water uniformity did not have an influence on final yield.

Yield and its component

Table 3 shows the root yield for the different combinations sprinkler-height studied. In 2004, higher root yield was obtained with MPS at 1 m and the lowest yield was obtained with the SPS at 2.5 m, with significant differences between them. In the 2005 season, the lowest root yield was with MPS at 2.5 m, which was statistically different from SPS for both heights, but not different from MPS at 1 m. The lower root yield

Table 2. Average values (M,%) and coefficients of variation (CV,%) of water application (CU) and soil water uniformity after irrigation at 0-0.35 m in depth (CU_{sa})

Type and location of the sprinkler	2004		2005				2006			
	CU		CU		CU_{sa}		CU		CU_{sa}	
	M	CV	M	CV	M	CV	M	CV	M	CV
SPS 2.5	78	6.2	81^c	5.0	90^b	1.0	78^c	7.1	89^b	1.7
SPS 1	74	5.4	79^d	6.4	88^c	1.1	77^c	6.0	88^c	1.4
MPS 2.5	90	2.3	89^b	1.5	90^b	1.3	89^b	2.6	90^b	1.3
MPS 1	93	3.8	92^a	4.4	92^a	0.7	92^a	2.2	91^a	1.7

SPS 2.5, SPS 1: sprinkler of stationary plate placed at 2.5 m or 1 m height. MPS 2.5, MPS 1: sprinkler of moving placed at 2.5 m or 1 m height. Different letters indicate statistically significant differences ($p < 0.05$).

Table 3. Average values and coefficients of variation (CV%) of yield and its components, water received by the crop and efficiency of water received by the crop (EWRc) for fresh and dry weight of roots and sugar

	Year	SPS 2.5		SPS 1		MPS 2.5		MPS 1		*p* value
		Average	CV	Average	CV	Average	CV	Average	CV	
Number root ha^{-1}	2004	105,000	7.3	112,750	8.6	106,500	11.0	118,000	3.9	0.19
	2005	129,250	10.3	129,500	7.0	118,750	6.2	115,250	10.4	0.19
	2006	117,188	7.4	123,750	2.6	117,500	4.8	115,625	4.8	0.29
Average weight of root (kg)	2004	1.15	7.0	1.12	5.7	1.21	7.8	1.14	6.6	0.28
	2005	0.91	7.2	0.88	6.9	0.87	9.8	0.97	13.5	0.43
	2006	0.98	3.6	1.00	8.0	0.92	12.9	1.05	7.8	0.25
Yield (t ha^{-1})	2004	120.9b	8.3	126.1ab	2.6	129.1ab	7.1	135.0a	2.7	0.04
	2005	117.1a	4.6	114.3a	5.4	103.8b	6.9	111.3ab	3.3	0.03
	2006	114.6	8.5	123.9	8.7	107.9	9.8	121.0	5.1	0.14
Water received (Irrigation + Pe) (m^3 ha^{-1})	2004	7,863b	5.5	8,233b	4.4	8,696ba	3,4	8,818a	3.0	0.007
	2005	8,459	2.6	8,251	6.5	8,014	5.4	8,389	5.6	0.48
	2006	8,024	1.5	8,148	6.1	7,886	7.1	8,168	1.4	0.22
Fresh root weight (kg m^{-3})	2004	14.7	5.3	15.0	4.9	14.6	8.2	15.0	2.8	0.17
	2005	13.7	3.8	13.5	16.0	12.3	4.9	13.0	10.2	0.45
	2006	14.3	7.5	15.2	9.2	14.2	5.9	15.4	5.4	0.30
Dry root weight (kg m^{-3})	2004	2.8	5.3	2.9	4.9	2.8	8.2	2.8	2.8	0.17
	2005	2.8	3.8	2.8	16.0	2.5	4.9	2.9	10.2	0.32
	2006	3.0	7.5	3.1	9.2	3.0	5.9	3.4	5.4	0.13
Sugar (kg m^{-3})	2004	2.3	4.9	2.4	5.9	2.3	9.9	2.3	3.3	0.13
	2005	2.1	7.0	2.2	23.3	1.9	8.6	2.1	4.0	0.61
	2006	2.2	7.2	2.2	7.7	2.3	4.6	2.3	4.6	0.44

SPS 2.5, SPS 1: sprinkler of stationary plate placed at 2.5 m or 1 m height. MPS 2.5, MPS 1: sprinkler of moving placed at 2.5 m or 1 m height. Pe: effective precipitation. *p* value: level of significance ($p < 0.01$). Different letters indicate statistically significant differences.

obtained with MPS at 2.5 m was conditioned by the lower average water applied by the centre pivot in this span. This was due to the improper design of the sprinkler package used this year, a problem that was in part resolved the next year, reducing the differences of water applied between spans.

The lower crop yield obtained in 2005 in comparison with the ones of 2004 is related with the change of soil. As indicated in the methodology, due to crop soil requirements, it was necessary to rotate the crop for the different experimental years, which slightly changed the soil characteristics in each year of the test, mainly the texture. The best results obtained for the first irrigation season is also due to better soil quality found this year as compared to the other years.

Table 3 shows that final crop yield depends more on the number of plants and the total water applied in a specific crop season than on water application uniformity with the different sprinkler-height combinations during the season. This is due to the high level of soil water uniformity obtained in all treatments with respect to water application uniformity. In field-oriented tests designed to be performed with equipment operating under field conditions, these small differences in water applied by different span were inevitable, as it was not possible to better fit the sprinkler package on the machine.

The results obtained show that it can be appropriate to use SPS, although they apply irrigation water less uniformly. This study and others focusing on permanent solid set sprinkler irrigation systems for corn (Martinez, 2004; de Juan *et al.*, 2008) and onion (Jiménez, 2008, Jiménez *et al.*, 2010) show that a CU of around 80% can be sufficient in individual irrigation events to reach good yield uniformity, since the corresponding CU_s can easily reach 90%.

Table 3 shows the yield components: number of roots per hectare (Nr) and average weight of root (AWr). There were no significant differences for any yield component, sprinkler type or height. The coefficient of variation (CV) obtained is normally smaller than 10%, indicating low variability of these parame-

Table 4. Average values and coefficient of variation (CV) of the industrial quality parameters

Parameter	Year	SPS 2.5		SPS 1		MPS 2.5		MPS 1		*p* value
		Average	CV (%)	Average	CV (%)	Average	CV (%)	Average	CV (%)	
Sugar (t ha^{-1})	2004	19.1	6.5	20.2	3.7	20.6	9.6	21.1	2.6	0.07
	2005	18.1	6.0	18.2	16.9	16.3	7.4	18.3	4.2	0.23
	2006	17.5	8.6	18.1	4.0	17.4	8.1	18.2	4.7	0.71
Polarisation (Sugar, %)	2004	15.8	2.6	16.1	1.2	15.9	3.,2	15.7	5.3	0.74
	2005	15.5	4.6	15.9	5.0	15.7	2.4	16.4	3.4	0.24
	2006	15.2ab	4.8	14.6b	6.1	16.2a	3.0	15.0b	2.0	0.03
FEI (t ha^{-1})	2004	118.7	5.8	127.1	4.1	128.7	11.2	130.5	5.6	0.17
	2005	111.6	6.2	113.8	8.8	100.9	6.8	115.2	4.2	0.09
	2006	106.3	8.6	103.4	4.0	109.6	8.0	110.1	4.7	0.71
ITV	2004	84.6b	0.9	87.3a	1.5	87.2a	1.9	87.0a	1.0	0.02
	2005	84.2	1.2	84.6	1.7	83.8	1.8	85.8	1.5	0.20
	2006	85.7	1.7	86.0	1.3	86.6	0.9	86.8	0.9	0.42
Alpha-amino[1]	2004	2.3	8.1	1.8	22.8	1.7	26.2	1.9	17.45	0.21
	2005	2.0	3.9	1.9	10.9	2.1	10.6	1.8	14.30	0.22
	2006	1.7	14.5	1.5	9.8	1.8	14.8	1.4	17.86	0.20
Potassium[1]	2004	4.7	8.4	4.4	4.9	4.4	4.4	4.8	1.96	0.09
	2005	4.6	2.5	4.7	3.8	4.5	4.3	4.7	6.16	0.68
	2006	4.3b	5.2	5.0a	2.7	4.4b	2.8	4.4b	5.90	0.002
Sodium (mmoles/100 g sugar beet)	2004	2.8	8.8	2.2	28.6	2.6	17.4	2.6	19.58	0.41
	2005	1.6	7.2	1.7	12.8	1.7	15.9	1.4	9.82	0.22
	2006	1.0	17.5	0.8	20.7	0.8	10.3	0.9	14.75	0.16
Reducing sugar (g/100 g sugar beet)	2004	0.07	23.7	0.06	13.2	0.06	10.9	0.06	14.9	0.08
	2005	0.07	7.4	0.08	7.7	0.09	11.8	0.08	6.1	0.07
	2006	0.10	4.9	0.10	4.9	0.11	5.5	0.10	6.1	0.10

SPS 2.5, SPS 1: sprinkler of stationary plate placed at 2.5 m or 1 m height. MPS 2.5, MPS 1: sprinkler of moving placed at 2.5 m or 1 m height. FEI: farmer's economic index. ITV: industrial technological value. Different letters indicate statistically significant differences ($p < 0.05$).

ters. For all the test years and all sprinkler-height combinations, sugar yield was between 16 and 21 t ha^{-1}. These values were higher than those found in some references (López-Bellido, 2003; Tognetti *et al.*, 2003), and very similar to the values found by other authors, such as Lopez Urrea & Montoro (2000) and Fabeiro *et al.* (2003).

Industrial quality of sugar beet

The technological quality of sugar beet is not a parameter that can be represented quantitatively, as it is a combination of all the physical and chemical aspects that influence efficiency in the sugar extraction process. The most important variable that determines the technological quality of sugar beet is the proportion of crystallisable sugar (sucrose) and non-crystallisable sugar (sugar in molasses) (Morillo-Velarde, 2001).

Good root quality can be simply described as high sucrose percentage, low sugar molasses percentage and low concentrations of sodium, potassium, and alpha-amino nitrogen, which are the main, non-sugar components of sugar beet. The content of reductive sugar is the parameter that most negatively influences the industrial process.

Table 4 shows the average values and the variation coefficients of the industrial quality of sugar beet for the different sprinkler-height combinations and experimental seasons. Only significant differences in percent sugar and potassium content were observed in 2006, and in ITV in 2004. The lack of significant differences in the sugar yield for the different treatments is because the treatments that applied less water obtained a higher proportion of sugar. The highest sugar yield was obtained with sprinklers located at 1 m, but without significant differences. In general, the best results were obtained with MPS at 1 m and the worst were with SPS at 2.5 m.

In general, the farmer's economic index (FEI), defined as the root production at 16% of polarization, gives values greater than 100 t ha^{-1} for all sprinkler-height combinations. Although significant differences were obtained in root yield in 2004 and 2005, no significant differences were found in FEI for any of the years studied (Table 4). However, this index was greater in the area irrigated with MPS at 1 m in all three years of testing, with low CV values (Table 4), probably due to better water use by the crop since it had lower evaporation and drift losses (EDLs) (Ortiz *et al.*, 2009) and higher CU.

There were only significant differences for ITV and root yield between treatments in 2004, while differences were not significant for sugar yield. The lower ITV values in 2005 show lower quality in yield because of higher sugar in molasses.

Normally, average values of the alpha-amino parameter were obtained. High values of this parameter is not good because it represents impurities in the sugar

Potassium reached average values in all treatments and years studied, and was the only quality parameter analysed that showed significant differences ($p < 0.01$) (Table 4).

This may be related to the significant differences obtained in the percentage of sugar, and both may be related to the amount of N and K applied in the area irrigated with SPS at 1 m, slightly higher than in the rest. These results are similar to those obtained by Abdel-Motagally & Attia (2009) on sandy calcareous soil. Increasing N and K rates significantly increase root and foliage fresh and dry weight and sugar yield. Adding high level of N (285 kg N ha^{-1}) under different rates of K significantly increased sugar loss and increased content and uptake of N and K in both root and foliage, increasing significantly impurities and sugar loss percentage.

Relationships between water application and yield

In 2004, greater water volume was applied with MPS at 1 m (Table 3), which was significantly different from the SPS, but not from MPS at 2.5 m. In 2005 and 2006 differences were not significant, although it was not possible to apply the same amount of water in the four treatments for the limitations in the adjustment of sprinkler package in the centre pivot.

The EWRc values for fresh root weight were very similar in 2004 and 2006 (Table 3), as the area irrigated with sprinklers at 1 m presented higher values (greater than 15 kg m^{-3}). However the variance analysis did not detect significant differences for any of the treatments in any years. In 2005 the values were lower (between 12 and 13 kg m^{-3}), coinciding with the year in which there were smaller but more frequent irrigation events. The EWRc values for fresh root weight were similar to those obtained in other studies in the Albacete area. Fabeiro *et al.* (2003) found EWRc values for the fresh root weight of 14.0 and 18.0 kg m^{-3}, when applying 896 and 690 mm of water, respectively.

EWRc for dry root matter showed very similar values in the three years studied, with no significant differences between treatments. In a comparative study between drip and sprinkler irrigation, Garcia *et al.* (1995) obtained EWRc values for dry root matter of 2.4 and 3.5 kg m^{-3}, respectively, and our values are within these limits.

EWRc values for sugar were between 2.2 and 2.4 kg m^{-3}, with no significant differences between treatments. These values are similar to those obtained by Morillo-Velarde & Moreno (2006) (ranging between 2.2 and 3.9), as well as the results from Ehlig & LeMert (1979) (1.96 kg m^{-3}).

Radiation use efficiency (RUE)

Crop growth can be analysed in terms of the amount of radiation intercepted or absorbed by the crop leaf surface during the growing season and the efficiency of use of this radiation for dry matter (Monteith, 1977; Gosse *et al.*, 1986) or sugar yield (Scott *et al.*, 1973). Total dry matter production and sugar yield are linearly related to the total amount of radiation intercepted by the canopy (Scott & Jaggard, 1978; Milford *et al.*, 1980; Martin, 1986).

As suggested by Scott & Jaggard (1978), we estimated radiation absorption throughout the growing season. Table 5 shows RUE values for total dry matter (TDM) (RUE_{TDM}) and sugar yield (RUEs) for the different sprinkler-height combinations in 2004 and 2005. The RUE_{TDM} was higher in 2005 as a result of less PARa, caused by less crop development due to poor soil quality. However, the analysis of variance showed no differences for sprinkler type or height during the two study years.

The results for RUE_{TDM} are lower than other published data: Biscoe & Gallager (1977) published an average of 3.5 g MJ^{-1}, and Milford *et al.* (1980) obtained 3.16 to 4.12 g MJ^{-1}, with different sowing dates

Table 5. Radiation use efficiency (RUE, g MJ^{-1}) for total dry matter (TDM) and sugar yield at harvest for the two years studied

Treatment	TDM		Sugar yield	
	2004	2005	2004	2005
SPS 2.5	1.9	2.4	1.1	1.3
SPS 1	2.0	2.4	1.2	1.3
MPS 2.5	2.1	2.3	1.3	1.2
MPS 1	2.1	2.5	1.3	1.3
p value	0.28	0.27	0.23	0.42

SPS 2.5, SPS 1: sprinkler of stationary plate placed at 2.5 m or 1 m height. MPS 2.5, MPS 1: sprinkler of moving placed at 2.5 m or 1 m height.

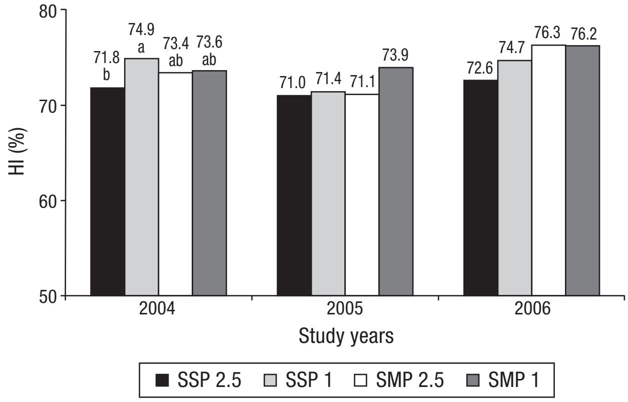

Figure 2. Harvest index (HI) for the four sprinkler-height combinations in the three years studied. SPS 2.5, SPS 1: sprinkler of stationary plate placed at 2.5 m or 1 m height. MPS 2.5, MPS 1: sprinkler of moving placed at 2.5 m or 1 m height. Different letters indicate statistically significant differences ($p < 0.05$).

and various amounts of nitrogen fertilizer. All these values were obtained from sugar beet sown in the spring in northern Europe. Brown *et al.* (1987) provided values of RUE_{TDM} between 1.6-1.9, 1.3-1.5 and 1.3-1.7 g MJ^{-1} when sugar beet received normal irrigation, early and late stress, respectively. López-Bellido (2003) indicated approximate values of RUE_{TDM} of 1.7 gMJ^{-1} for this crop in Spain, which is a lower value than those obtained in this study (Table 5).

The variability in RUEs in the different treatments (Table 5) was lower than that obtained in RUE_{TDM}, with no significant differences between treatments found in the two test years. The values of RUEs obtained in this study were lower than other published data for northern Europe. Values were reported from Scott *et al.* (1973) at 1.93 g MJ^{-1}, 1.67 g MJ^{-1} by Scott & Jaggard (1978) and 1.75 to 2.08 g MJ^{-1} by Milford *et al.* (1980). López-Bellido (2003) proposed 1.0 g MJ^{-1} as a reference for sugar beet produced in Spain. However, this value is lower than those found in this study (Table 5).

Harvest index

Figure 2 shows the harvest index (HI) for the four sprinkler-height combinations in the three years studied. In 2004, the lowest HI value was observed in the area irrigated with SPS at 2.5 m, coinciding with the treatment that received the least water, which was statistically different from the other treatments. In 2005 and 2006, the analysis of variance did not show significant differences between treatments.

Yarnia *et al.* (2008) performed a study to correct the deficiencies of micronutrients in sugar beet. They were able to improve the root yield and the percentage of dry matter and sugar, reaching values of HI of 70% due to increased LAI and NAR when Mn deficiency was corrected. Brereton *et al.* (1986) obtained similar values but with lower root and sugar yields.

Conclusions

The uniformity of soil water was similar to the uniformity of accumulated irrigation, therefore this should be considered instead of water application uniformity during individual irrigation events to obtain the gross depth required for satisfying crop water requirements. CU values around 80% for individual irrigation events with centre pivots can be sufficient to reach proper yield uniformity since the corresponding soil water uniformity can easily reach 90%.

This study approach integrated all factors that condition irrigation in the plot and adequately reproduce what happens in real irrigation conditions with this type of machine. Results do not show a clear advantage in the final crop response by using sprinklers with moving plates (MPS) or stationary plates (SPS). Nevertheless, MPS, and especially those located at 1 m in height, have higher water application uniformity, however, no significant differences were obtained for all factors analysed due the limitations encountered in this experiment. The final yield of sugar beet was more influenced by the amount of soil water available for the crop in a specific crop season than the small differences in soil water uniformity produced by the irrigation with the centre pivot during the season.

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