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Comparing evapotranspiration and yield performance of maize under sprinkler, superficial and subsurface drip irrigation in a semi-arid environment

F. Valentín[1] · P. A. Nortes[2] · A. Domínguez[3] · J. M. Sánchez[4] · D. S. Intrigliolo[2] · J. J. Alarcón[2] · R. López-Urrea[1]

Abstract

In arid and semiarid environments, with shortage of water resources, maize production is competing for available water. This study analyzed the effect of different irrigation systems on maize yield, crop evapotranspiration and its components, i.e., canopy transpiration (T) and soil evaporation (E). A 2-year field experiment was conducted at the ITAP Research facilities located in Albacete (southeast Spain). Four treatments were assessed: surface drip irrigation with a spacing between drip lines of 1.5 m (SDI_1.5) and 0.75 m (SDI_0.75); subsurface drip irrigation (SubDI); solid set sprinkler irrigation (Sprink). In all treatments, irrigation was applied to refill the estimated potential water demand. Crop evapotranspiration (ET_c) and E/T partitioning were estimated using a Simplified Two-Source Energy Balance (STSEB) approach. Although there was an important difference in the irrigation water applied between treatments, ranging from 743 and 722 for Sprink system to 534 and 495 for SubDI system in 2014 and 2015, respectively, yield was unaffected by the irrigation regime, resulting in an increase in the irrigation water productivity (IWP) by an average of 25% when irrigation was applied by the subsurface system. Maize ET_c was affected by the irrigation system, with the SubDI achieving in 2015 a 39% reduction of seasonal ET_c in comparison with the Sprink system. Similar reductions were obtained for separated E and T components with soil evaporation accounting in general for 15–20% of the total ET_c. It is concluded that subsurface irrigation is a water savings strategy for irrigation of maize reducing the consumptive water use and increasing IWP. The final convenience for the widespread adoption of subsurface irrigation will depend on water availability and prices.

✉ R. López-Urrea
rlu.itap@dipualba.es

[1] Instituto Técnico Agronómico Provincial (ITAP) and FUNDESCAM, Parque Empresarial Campollano, 2ª Avda. Nº. 61, 02007 Albacete, Spain

[2] Departamento de Riego, Centro de Edafología y Biología Aplicada del Segura (CEBAS-CSIC) Espinardo, Murcia, Spain

[3] Universidad de Castilla-La Mancha (UCLM), Escuela Técnica Superior de Ingenieros Agrónomos y de Montes, Centro Regional de Estudios del Agua (CREA), Campus Universitario s/n, 02071 Albacete, Spain

[4] Department of Applied Physics, Regional Development Institute (IDR), Univ. of Castilla-La Mancha, Av. España, s/n, 02071 Albacete, Spain

Introduction

According to the Food and Agriculture Organization of the United Nations (FAO) statistics (FAOSTAT 2017), maize (*Zea mays* L.) is the second most cultivated cereal crop worldwide with over 197 million ha, producing over 1.1 billion Mg of grain. Over the past two decades, demand for maize has increased since, in addition to its traditional use, there have been policies put in place that incentivize bioethanol production. This strong demand for maize is putting huge pressure on production, which is competing for available water (Chávez and López-Urrea 2019).

Among the several sustainable development goals established by the United Nations, the "zero hunger" and "clean water and sanitation" directly concern agriculture and particularly those crops like maize. In addition, because maize water requirements can be particularly high (Allen et al. 1998), the need of establishing efficient water management practices is of utmost importance in areas with scarce water resources such, as the Mediterranean Sea basin. Within this

region, agriculture is by far the main water demanding activity (70% of the total water consumed, AQUASTAT FAO 2015) and irrigated agriculture accounts for 40% of the total agriculture production (CIHEAM 2015). However, irrigation is competing with potential users for the already scarce water resources. Recently, there is also an increased pressure from society to maintain water bodies under optimum ecological levels. Climate change predictions for the Mediterranean Sea basin prognosticate an increase in evaporative demand and most likely a reduction in the water availability because of the more erratic and extreme rainfall events (IPCC 2018). Under this context, agriculture is required to search for technologies and management tools to improve water use efficiency (WUE), and when possible, obtaining net water savings.

In agriculture, water used by crops is determined by canopy transpiration (T), soil evaporation (E) and water might also be lost due to surface run-off and deep percolation below the root zone. Using precision irrigation scheduling approaches aimed at matching irrigation applications to crop water needs might result in water use efficiency gains at the farm level, but at a larger scale, water losses by percolation can be recovered even if at the cost of water quality degradation and energy inefficiency if water has to be re-pumped from deep aquifers (Fereres et al. 2003). Because of this, it is important to look for strategies that might reduce the farm consumptive water use leading to net water savings. This could be achieved using deficit irrigation, but maize is considered to be sensitive to water stress since it does not osmotically adjust as well as other field crops to low water status (Hsiao and Fereres 2012).

Strategies to reduce soil evaporation should be then investigated. This includes the possibility of covering the soil surface with organic or plastic mulching (Bu et al. 2013). However, because of the extensive nature of the maize farming systems and the narrow net economic returns, other less expensive and intensive alternatives should be researched. There are a lot of renewed interests in subsurface drip irrigation technology because of new emitters design with apparent less susceptibility to clogging.

Recent works by Trout and DeJonge (2017) or Rodrigues et al. (2013) amounted soil evaporation to about 15–25% of the total evapotranspiration in sprinkler and drip-irrigated maize. A good knowledge of the ratio E/T becomes then critical in this context. Two-source energy balance (TSEB) models allow the estimation of both E and T by establishing a separate balance for soil and canopy components, respectively, in a specific target (Colaizzi et al. 2012; Kustas et al. 2012). This methodology is based on the radiometric thermal characterization of the surface components and has been shown effective to split total evapotranspiration (ET) into E and T in a variety of crops in recent years (Sánchez et al. 2014, 2015, 2019). Sánchez et al. (2014) reported E–T values for sunflower and canola, showing the significance of soil evaporation for initial and development stages. A ratio E–T of 36–64% was shown by Sánchez et al. (2015) for the total growing season in spring wheat. More recently, Sánchez et al. (2019) quantified in 35–40% the contribution of E to the total ET in a drip-irrigated vineyard.

Under this context, the objective of the present research was to assess and quantify the convenience of using subsurface drip irrigation in comparisons with sprinkler and traditional surface drip irrigation systems in maize cultivated in southeast Spain under semi-arid conditions.

Materials and methods

Site description and experimental design

The study was carried out during the 2014 and 2015 seasons at the ITAP Research Facility in Albacete (southeast Spain). Its geographic coordinates are 39º 03′N, 2º 05′W, and its altitude is 695 m above mean sea level. The soil is classified as Petrocalcic Calcixerepts (Soil Survey Staff 2014). Average soil depth of the experimental plot is 40 cm, and is limited by the development of a more or less fragmented petrocalcic horizon. Texture is clay–loam, with 22% sand, 48% silt and 30% clay, with a basic pH (8.4). The soil is low in organic matter (2.1%), and it has a normal content of nitrogen (0.13%) and a high content of active limestone (14.1%). The climate is semiarid, temperate Mediterranean with dry and warm summers. The long-term average annual rainfall is 314 mm mostly concentrated in the spring and fall. Average mean, maximum and minimum temperatures are 13.7, 24.0 and 4.5 °C, respectively. Weather conditions during the experiment were measured with an automated agrometeorological station located at the Research Facility over a reference grass surface. All sensors were located between 1.5 and 2 m above the grass surface, and weather data were registered in 15 min, hourly and daily time steps. Variables measured were as follows: air temperature, relative humidity, wind speed, wind direction, shortwave and longwave radiation, and rainfall. Reference evapotranspiration (ET_o) values were calculated with the daily time step FAO56 Penman–Monteith (FAO56 P-M) equation (Allen et al. 1998) using the recorded meteorological variables. Previous lysimeter studies conducted at the same location pointed out good performance when using this equation (López-Urrea et al. 2006; Trigo et al. 2018).

Maize (*Zea mays* L. cv. DKC6815) was sown on May 14, 2014, and on May 7, 2015. The spacing between rows was 0.75 m and in-row plant spacing averaged 0.16 m, resulting in a plant density of 8.33 plants m^{-2}. Fertilizer was applied before sowing at a rate of 64 kg ha^{-1} of N, 192 kg ha^{-1} of P_2O_5 and 64 kg ha^{-1} of K_2O. Additionally, liquid fertilizer

was applied during the vegetative phase for a total of 140 kg ha^{-1} of N. The maize grain was harvested on 15 October and on 10 October in 2014 and 2015, respectively. The experimental plot was managed according to cultural practices normally carried out in the area, to avoid pests and disease effects on crop performance.

The experimental design was a complete block randomized layout with four replicates of four treatments and split plots for both treatments of surface drip irrigation with different spacing between drip lines. The experimental treatments assessed were: SDI_1.5: surface drip irrigation system with a spacing between drip lines of 1.5 m; SDI_0.75: surface drip irrigation system with a spacing between drip lines of 0.75 m; SubDI: subsurface drip irrigation system with pressure-compensated emitters and a spacing between drip lines of 0.75 m; Sprink: solid set sprinkler irrigation system.

The whole experimental plot has a solid set sprinkler irrigation system with sprinklers placed on a grid of 15 m × 15 m that provide a precipitation rate of 6.2 mm h^{-1} (Fig. 1). However, in those grids of 15 m × 15 m where surface and subsurface irrigation systems were installed, the sprinklers nozzles were disabled. Between repetitions, a total surface area of 15 m × 75 m acted as a safeguard (buffer) against the possible water drift from the sprinkler irrigation treatment to the treatments drip irrigated. For this reason, on both sides of each sprinkler irrigation treatment, a surface of 15 m × 15 m acted as a safeguard (see Fig. 1). Each plot consisted of 15 m × 15 m (20 rows of plants). Each plot of surface drip irrigation was split in two parts of 10 rows of plants; in one part the spacing between drip lines was 1.5 m (SDI_1.5) and the other one was 0.75 m (SDI_0.75). Surface and subsurface drip irrigation was applied with pressure-compensated emitters of 1.6 L h^{-1} (PREMIER LINE PC-AS, Sistema AZUD, Spain) placed 0.6 m apart. In the case of the subsurface irrigation system, drip lines were installed to 0.40-m depth, i.e., at bottom of soil. The irrigation depth applied to each treatment during the irrigation events was controlled by flow meters.

Irrigation management

In the experimental plot, irrigation was applied to replace the potential crop evapotranspiration (ET_c). Soil in the experimental field has a limited (40 cm) rooting depth, and thus, irrigation was managed for only 40 cm of maize root depth. The water holding capacity and permanent wilting point in the 40-cm root zone were 132 and 80 mm, respectively, resulting in total available water of 52 mm. Irrigation water requirements were estimated for each treatment based on the soil water balance approach, to maintain the soil water content in the root zone between field capacity and readily available water (Allen et al. 1998). Soil water content was measured by gravimetry at sowing and harvest dates, to know the amount of soil water available to the crop before and after the beginning of irrigation events. ET_c was estimated based on the product of daily ET_o estimated with the FAO56 P-M equation times a dual crop coefficient. Basal crop coefficient (K_{cb}) values used were: $K_{cb\ ini}$: 0.15 during initial crop stage (from sowing until the crop reached a 15% canopy cover); $K_{cb\ mid}$: 1.10 during mid-season stage (maximum canopy cover); $K_{cb\ end}$: 0.15 for the crop ripening stage. Evaporation crop coefficient (K_e) values were estimated with the FAO56 methodology. The values of the main parameters used to compute K_e were as follows: total evaporable water (TEW): 25 mm; readily evaporable water (REW): 10 mm; fraction of soil surface wetted (f_w): 1.0, 0.35 and 0.0 for sprinkler, surface drip and subsurface drip irrigation, respectively, and f_w was 1.0 for precipitation. Additionally, $K_{c\ max}$, evaporation reduction coefficient (K_r) and exposed and wetted soil fraction (f_{ew}) were calculated using the equations proposed by Allen et al. (1998).
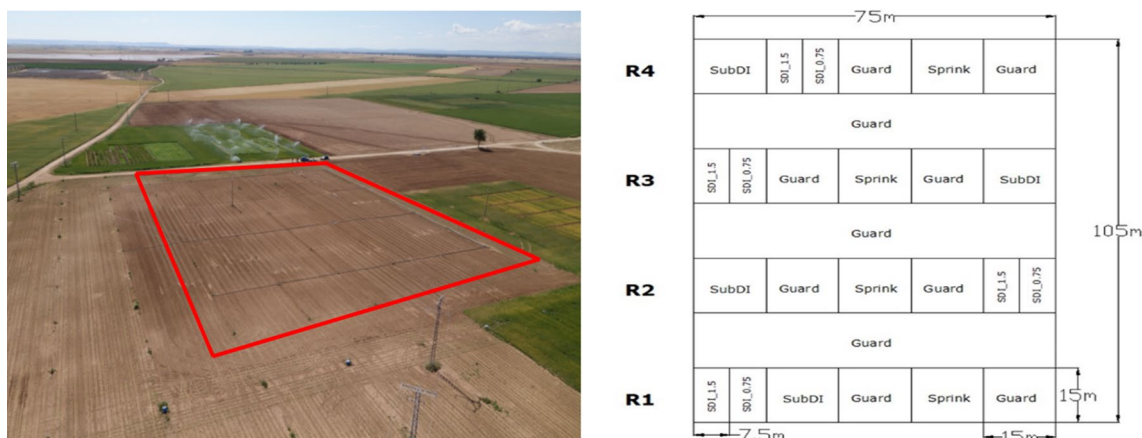

Fig. 1 Aerial view of the experimental plot (red frame), and the area surrounding it (left), and the experimental design (right)

Crop development and yield determinations

Crop growth stages were identified following the recommendations reported by Ritchie and Hanway (1982). Crop height was measured weekly from five plants of each treatment and modeled for the whole seasons. Furthermore, the fraction of ground surface covered by vegetation (f_c) was determined based on the methodology proposed by Cihlar et al. (1987). Every 7–10 days, digital photographs of one repetition per treatment were taken at solar noon vertically from an approximate height of 1.5 m above the crop. Supervised classification of these digital images was later carried out with the help of the ENVI® version 4.8 computer program (Exelis Visual Information Solutions 2012). For a more comprehensive description of this methodology more details are given in López-Urrea et al. (2016).

Above ground biomass was determined at harvest. Seven complete maize plants from each plot were cut at ground level, ears were removed, and the remaining stover dried in a stove at 60 °C to constant weight. Ears were also dried, grains were removed from the cobs, and both components re-dried to constant weight. Total above ground biomass included stover, cobs, and grain. Harvest Index (HI) was calculated as the ratio of dry grain mass to total above ground dry biomass.

Grain yield was determined by hand harvesting the ears from the center 10 m of the center two rows of each plot (15 m^2). Grain moisture content at harvest was measured with a Dickey-john GAC II grain analysis computer (DICKEY-john Corp., Auburn, Ill, USA) and grain yield was normalized to standard commercial yield (14% moisture content).

Infrared temperature measurements and STSEB model overview

In this study, a simplified version of the two-source configuration (STSEB) (Sánchez et al. 2008) was applied to estimate total and separate soil and canopy energy fluxes using the radiometric temperatures as the main inputs, together with biophysical information and meteorological data. For a comprehensive description of the STSEB approach, the reader is referred to Sánchez et al. (2008). The feasibility of STSEB at a field scale has been assessed not only in maize (Sánchez et al. 2008) but also in a variety of crops (Sánchez et al. 2011, 2014, 2015, 2019) over the last decade. According to this framework, an independent energy balance between the atmosphere and each component of the surface is established, what allows a separated estimation of the energy required for soil evaporation (E) and canopy transpiration (T).

For this purpose, a set of three Thermal Infrared Radiometers (IRT) (SI-121, Apogee Instruments, Logan, UT,

USA) were installed in three irrigation treatment SDI_0.75, SubDI and Sprink but not SDI_1.5. These are broad band thermal instruments (8–14 μm) with an accuracy of ± 0.2 °C, a 18º field of view, and a valid temperature range from − 30 to 65 °C. Calibration was assessed before the second field campaign, using a blackbody source (Hyperion R 982, Isotech, England). The deployment of the three IRTs per irrigation treatment in a mast was as follows: one placed at a height of 2 m over the canopy, looking at the surface with an angle of ~ 50º and measuring the composed target temperature (T_R), a second IRT placed at a height of 0.3 m directly pointing to the soil between rows to measure soil temperature (T_s), and a third IRT was placed at a height of 0.15 m over the canopy, looking at the crop with nadir view and monitoring canopy temperature (T_c) at any time during the experiment. All temperatures were corrected for thermal target emissivity and atmospheric effects, following the methodology described in Sánchez et al. (2008). At this point, downwelling sky radiance was calculated from sky brightness temperature values measured by a fourth Apogee radiometer pointing at the sky with an angle of 53º. A single sensor under this configuration, installed in SDI_0.75, was sufficient to characterize the whole experimental plot. Values of canopy emissivity (ε_c) = 0.987 ± 0.005 and soil emissivity (ε_s) = 0.960 ± 0.013 were used for this study (Rubio et al. 2003). IRT measurements were limited to the period DOYs 183–289 in 2014 and 148–264 in 2015.

Additional meteorological data, needed for running the STSEB model, included in situ measurements of air temperature and humidity (MP100, Campbell Scientific Instrument, Logan, UT, USA), wind speed (A100R, Vector Instruments Ltd., North Wales, UK), incoming solar radiation (CM14, Kipp & Zonen, Delft, Holland) and long-wave radiation (CG2, Kipp & Zonen Delft, Holland). Biophysical data were monitored in each treatment as described above.

Statistical analysis

All collected data underwent an analysis of variance (ANOVA) using the XLSTAT 2008 statistical software package for Microsoft Excel. Differences between treatments were assessed by Duncan´s test and the significance level was $P < 0.05$.

Results

Meteorological conditions

Table 1 shows the meteorological conditions for each month during the 2014 and 2015 maize growing seasons. The two seasons at the Research Facility of "Las Tiesas" located in the southeast of Spain were typical of the long-term average

Table 1 Summary of monthly meteorological variables during the 2014 and 2015 maize growing seasons

Season month	T_{mean} (°C)	RH_{mean} (%)	u_2 (m s^{-1})	R_s (MJ m^{-2} day^{-1})	Rainfall[a] (mm)	ET_o (mm day^{-1})
2014						
May	15.8	66.0	2.6	26.1	4.5	4.8
June	19.8	65.4	2.4	26.4	43.4	5.3
July	23.1	57.0	2.6	27.8	0.0	6.8
August	23.7	56.5	2.5	25.8	0.0	6.4
September	20.7	68.2	2.1	18.6	10.0	4.3
October	16.2	73.0	2.3	13.9	16.7	2.7
2015						
May	17.6	62.7	2.6	27.1	7.0	5.4
June	20.5	63.9	2.2	28.0	20.4	5.7
July	26.5	52.7	2.4	27.9	0.0	7.3
August	23.6	65.3	2.7	23.4	8.5	5.3
September	18.1	72.7	2.4	19.7	31.0	3.9

[a]Is the monthly total rainfall, u_2 is the wind speed measured at 2 m, R_s is the global solar radiation, ET_o is the reference evapotranspiration calculated with the Penman–Monteith FAO56 equation

Table 2 Description of maize growth stages during 2014 and 2015 growing seasons (Ritchie and Hanway 1982)

Stage	Description	Season	
		2014 Date	2015 Date
Sowing		14 May	7 May
V7	Designates seventh-leaf	20 June	23 June
R1	Silking. Flowering begins when a silk is visible outside the husks	28 July	22 July
R4	Designates the end of milk stage and the beginning of grain maturation	25 August	27 August
R6	Physiological maturity	17 September	20 September
Harvest		15 October	10 October

weather of study area, although the rainfall during the two seasons was about 37 and 55% lower than the 30-year mean in 2014 and 2015, respectively. Most rainfall during the growing season in the region occurs during the spring and in September. The average evaporative demand was higher in 2015 than in 2014, mainly due to the high ET_o values achieved by the end of May and in July of 2015 season. Average wind speed at 2 m over an irrigated grass surface during the experimental period was 2.4 m s^{-1}.

Crop development and applied irrigation water

Table 2 shows maize critical growth stages during the two seasons for the different treatments. In 2014, stages V7, R1

and R6 were reached between 3 and 4 days later in sprinkler treatment than in the drip irrigation treatments.

Irrigation management in the experimental field followed the standard practice in the area for attaining maximum yields. Surface drip applications were applied every 1–5 days in 2014 and every 1–7 days in 2015, depending on the ET_c rate. Surface drip treatments received 47 and 48 irrigations throughout the 2014 and 2015 seasons, respectively, that varied in depth between 8 mm, in the early initial stage, and 28 mm, both experimental years. Subsurface drip applications were applied every 1–7 days in 2014 and every 1–5 days in 2015, resulting in 50 and 43 irrigations throughout the 2014 and 2015 seasons, respectively, that varied in depth between 5 and 20 mm, both seasons. Although, in the early initial stage two irrigations of 30-mm depth were applied, to obtain the suitable soil water content for ensuring crop nascence. Finally, sprinkler applications were applied every 1–6 days varying in depth between 7 and 25 mm depending on ET_c rate, both experimental years. Experimental field received 42 and 46 irrigations throughout the 2014 and 2015 seasons, respectively.

Maize *ET* estimations using the STSEB approach

Once corrected from atmospheric and emissivity effects, soil and canopy radiometric temperatures were used as inputs to run the STSEB approach, in combination with other required meteorological variables and biophysical parameters. Results of 15-min maize ET_c values were obtained for the available thermal infrared dataset, constrained to DOYs 183–289 in 2014 and 148–264 in 2015, as mentioned above. Particularly, during 2014, these monitored periods did not cover the full phenological development of the maize and

then seasonal ET_c values cannot be derived nor compared to soil water balance estimations. For these reasons, STSEB estimations will be only used to analyze the partition E/T for the three irrigation treatments in terms of total cumulated values and average daily values for the different available phenological stages.

As an example, Fig. 2 shows four plots of the diurnal evolution of ET_c estimates for the three irrigation treatments, covering the four phenological phases from initial stage to

end-season in 2015. Note the four examples correspond to selected days with no irrigation to preserve the analysis.

Hourly and daily values of maize ET were obtained by aggregating the 15-min outputs. Figure 3, right shows the evolution of the accumulated ET_c values during the 2015 campaign. Curves match for sprinkler and surface drip irrigation systems for the first weeks due to low f_c values and similar irrigation amounts. Differences increase from that point to the end of the season. However, a more parallel
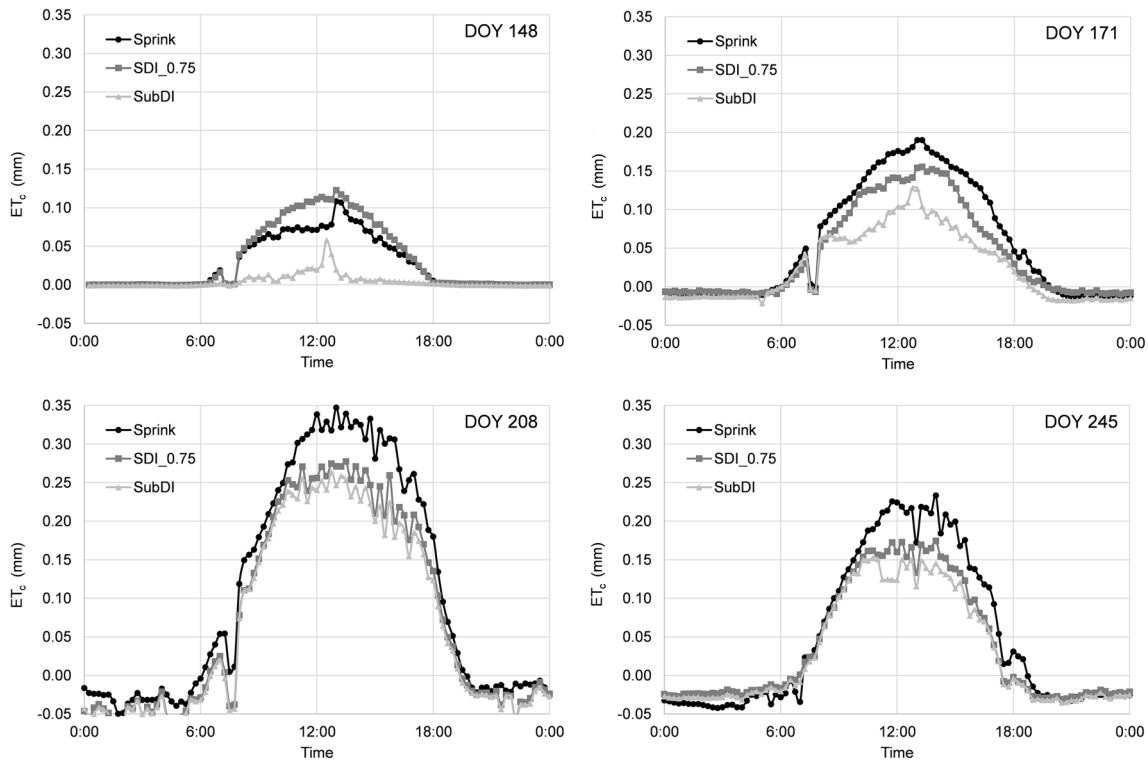

Fig. 2 Diurnal evolution of 15-min ET_c estimations using the STSEB model for the three different irrigation treatments. Four plots are shown corresponding to DOYs 148, 171, 208, and 245, illustrative of phenological phases I to IV (initial, development, mid-season and end-season), respectively
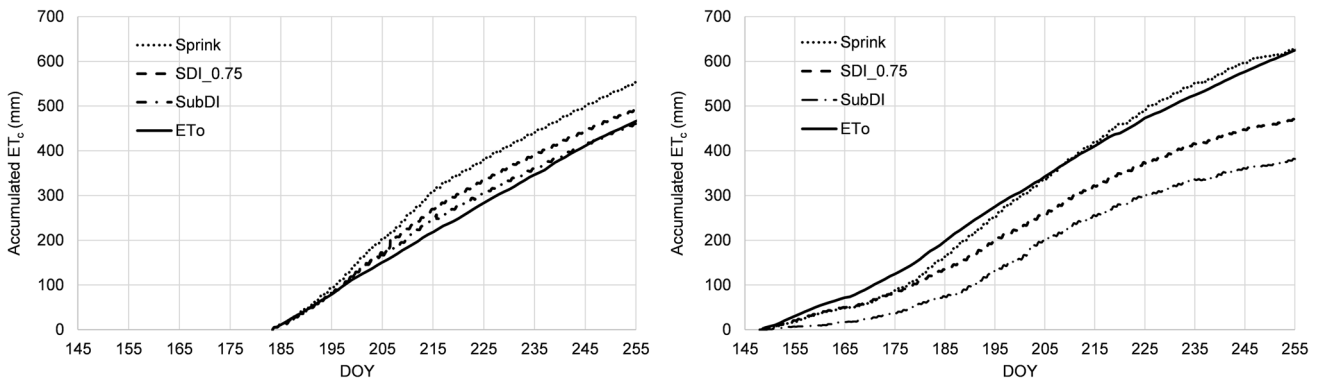

Fig. 3 Seasonal evolution of accumulated ET_c estimations using the STSEB model for the three different irrigation treatments in 2014 (left) and 2015 (right). ET_o values are also superposed

trend can be observed between surface and subsurface drip irrigation from that moment to end-season. Total accumulated ET_c values for SDI_0.75 and SubDI result in a reduction of 25% and 39%, respectively, compared to Sprink. A similar analysis can be extracted from the 2014 campaign (Fig. 3, left), although initial stage was missing this year because sensors were installed later in the season. Focusing on the period from DOY 183–195, all treatments had similar accumulated ET_c in 2014, while the differences were significant among irrigation systems for that period in 2015. This may be due to the different irrigation amounts applied for that period in 2014 (ranging from 88 mm for SDI_0.75 to 69 mm for SubDI) and 2015 (ranging from 143 mm for Sprink to 61 mm for SubDI). For a more in-depth analysis of the different irrigation treatments, separated canopy T and soil E values were calculated following the STSEB scheme. Figure 4 shows the comparison among irrigation treatments in terms of accumulated values of total ET_c and separated T–E for the available dataset. The same magnitudes are plotted in Fig. 5, but now in terms of daily averages and separated by phenological stages. Transpiration is clearly the dominant term in all cases, except for initial stage in 2015. In 2014, a similar irrigation scheduling was applied to both sprinkler and SDI_0.75 treatments, resulting in a reduction of 11% of accumulated T, whereas no difference is observed in terms of accumulated E. A reduction of 25% in water supply resulted in a decrease of 19% in transpiration for the SubDI. A more comprehensive analysis can be conducted for the 2015 campaign because the initial stage of the growing season is also covered. In this case, a reduction of 14% in water supply for the SDI_0.75, compared with the sprinkler irrigation, resulted in a decrease of 30% in transpiration and 25% in total ET_c since no significant reduction was observed in terms of evaporation. For the SubDI, in comparison with the sprinkler irrigation, a reduction of 37% in water supply resulted in a decrease of 39% in transpiration, evaporation, and in total ET_c in this case.

Maize yield response to irrigation systems and irrigation water productivity

Irrigation application varied, in the different irrigation systems employed, from 743 and 722 mm for the sprinkler irrigation down to 534 and 495 mm for the SubDI for 2014 and 2015, respectively (Table 3). As a consequence, pooling data across years, the SubDI resulted in water savings of 24 and 30% in comparisons with the SDI_0.75, SDI_1.5 and sprinkler irrigation. Despite the different water applications, in both years, yield was unaffected by the irrigation regime, resulting in an increase in the irrigation water productivity (IWP) when irrigation was applied by the SubDI system. In terms of the harvest index, only in 2014, significant differences among treatments were registered, with the SubDI slight decreasing the proportion of yield with respect to the vegetative biomass.

Production and irrigation water productivity functions

Crop water productivity (WP), or many times referred to as water use efficiency (WUE), is defined as the ratio between the marketable crop yield and crop evapotranspiration. When irrigation water applied is considered instead of crop ET, the term commonly used is irrigation water productivity (IWP) (Trout and DeJonge (2017)). Figure 6 plots maize yield at 14% moisture content (left) and IWP (right) for each irrigation system versus irrigation water applied. The production function follows the typical yield-applied irrigation water curvilinear relationship. In both experimental years, IWP was higher in SubDI than in the other irrigation systems and there were significant differences ($P < 0.05$) among treatments (Table 3).
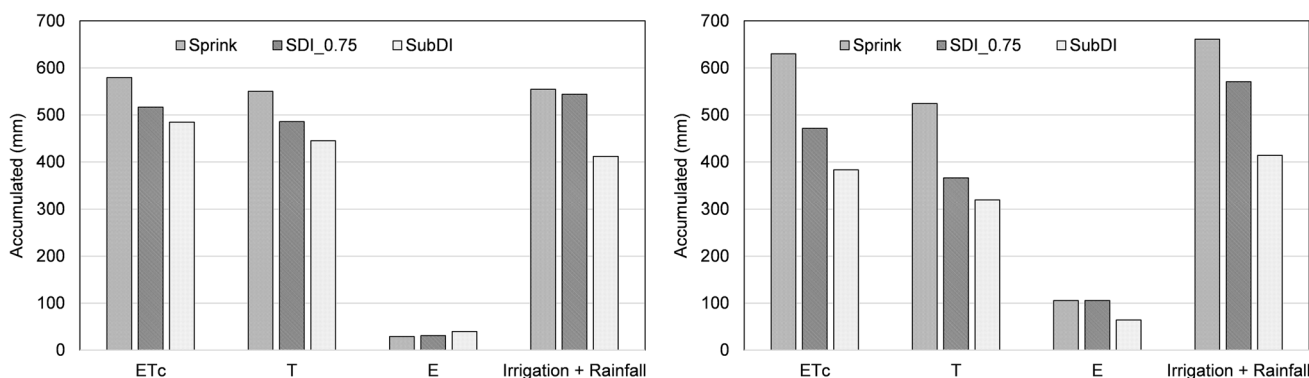

Fig. 4 Accumulated values of total ET_c, separated E–T, and water incomes for the referred periods: 2014 (left) and 2015 (right)
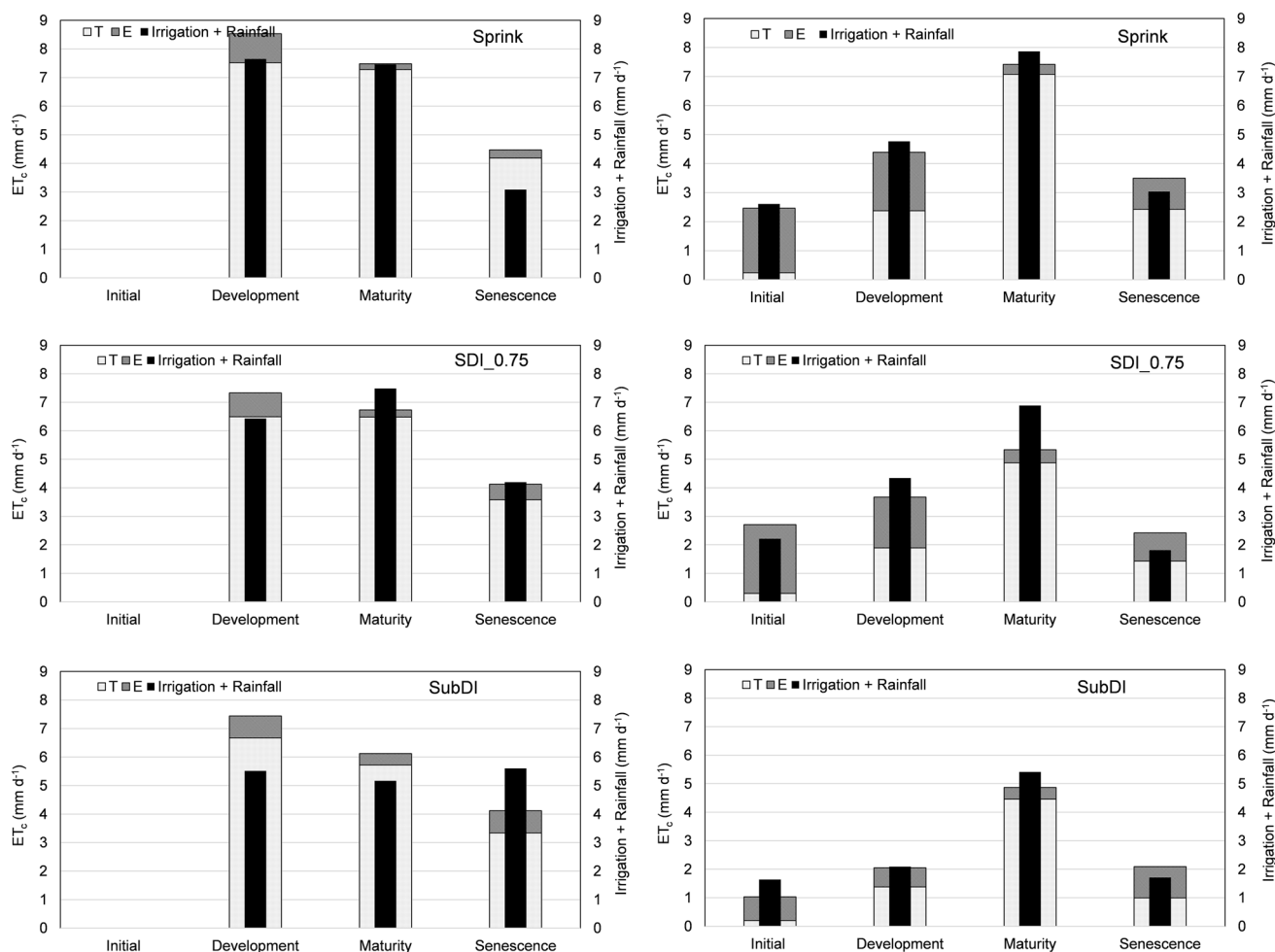
Fig. 5 Average daily values of total ET_c, separated E–T, and water incomes, for the different phenological stages and the three irrigation treatments for the campaigns in 2014 (left) and 2015 (right)

Table 3 Irrigation applications, yield and irrigation water productivity (IWP) in the different irrigation systems applied in the two experimental years

Treatments	Irrigation (mm)		Grain yield (14% moisture content) (kg ha^{-1})		IWP (kg m^{-3})		HI	
Year	2014	2015	2014	2015	2014	2015	2014	2015
SDI_1.5	702	655	14,800	13,622	2.11b	2.08b	0.58a	0.60
SDI_0.75	703	642	14,901	13,708	2.12b	2.14b	0.58a	0.60
SubDI	534	495	13,165	13,643	2.47a	2.76a	0.55b	0.58
Sprink	743	722	14,399	15,382	1.94b	2.13b	0.58a	0.59
P ANOVA			0.319	0.111	0.020	< 0.001	0.036	0.852

Within each year, then the treatment effect was statistically significant at $P < 0.05$ after ANOVA, different letters indicates significant differences at $P < 0.05$ among treatments

Discussion

Despite rainfall being considerably lower than the average, the climatic conditions during the two experimental seasons were within the normal range in the area.

Drought periods are common in Mediterranean ecosystems, and in irrigated agriculture can be compensated by greater irrigation depths and/or a lower irrigation interval. Consequently, the crop development was not affected by extreme or anomalous meteorological events, and the rainfall decrease was compensated by irrigation water, which
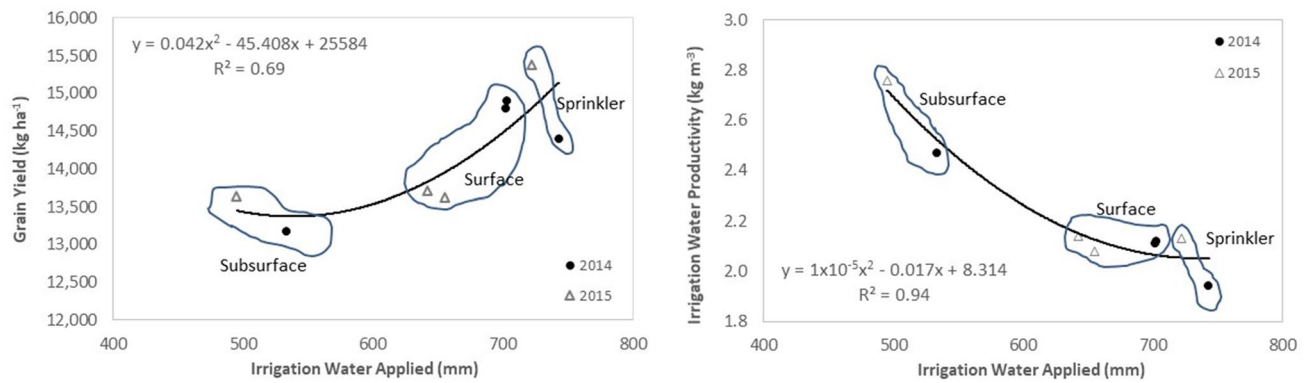
Fig. 6 Relationships between maize yield and irrigation water applied (left), and irrigation water productivity and irrigation water applied (right). Curves and equations are second-degree polynomial regression fits to both years of data

allowed to highlight the differences among the three irrigation systems used in this study.

The lack of significant differences among yields of the different treatments (Table 3) suggests that the crop was fulfilled with its potential water requirements in all the cases, and irrigation schedules were suitable. Consequently, IWP was not conditioned by yield but only by the amount of irrigation water applied to the crop. The WP values reported by other authors show a similar trend to those in this study. Thus, Abd El-Wahed and Ali (2013) increased WP around 22% when comparing surface drip irrigation (1.2 kg m^{-3}) with sprinkler irrigation (0.8 kg m^{-3}). In the case of Rodrigues et al. (2013), the improvement was 6.9% (2.8 kg m^{-3} vs. 2.6 kg m^{-3}, respectively). Payero et al. (2008) reached higher WP and IWP values (around 1.6 and 5.8 kg m^{-3}, respectively) when subsurface drip irrigation was used in Nebraska (USA). Hassanli et al. (2009) found significant differences on yield between furrow and drip irrigation systems, but not between surface and subsurface drip irrigation systems. Thus, the average IWP of the three treatments were 1.5, 1.7 and 2.0 kg m^{-3}. This increase in IWP due to subsurface drip irrigation was justified because of the higher uniformity of irrigation, lower evaporation losses from soil, and easy availability of water within the root zone. In addition, previous research by Abd El-Wahed and Ali (2013) saved 15% of irrigation water comparing drip and sprinkler irrigation in a full irrigated maize crop carried out in Sebha branch (Libya). Hassanli et al. (2009) evaluated the effect of subsurface drip, surface drip and furrow irrigation on water savings, yields and IWP of a maize crop cultivated in Marvdasht (Iran). They concluded that subsurface drip irrigation average saved 10.3 and 13.4% of irrigation water compared with surface drip and furrow irrigation, respectively. In our study, the four treatments received a similar number of irrigation events (ranging from 42 to 50), being the irrigation depth the variable (7–25 mm for sprinkler;

8–28 mm for both surface drip; and 5–20 mm for subsurface drip irrigation).

The lack of differences in terms of yield and IWP between the two types of drip surface irrigation systems (0.75- and 1.50-m distance between drip lines) analyzed in this research (Table 3), would suggest that it is possible decreasing the number of emitter lines in the plot as stated by other researchers. Therefore, Bozkurt et al. (2006) carried out a study in Adana (Turkey) to determine the effects of different surface drip irrigation lateral spacing (0.7, 1.4, and 2.1 m) on maize yield. The 1.4-m lateral spacing treatment was stated as the optimum for this crop in terms of yield (14.3% and 9.6% higher than the 0.7- and 2.1-m lateral spacing treatments, respectively), being the IWP and WP 1.37 and 1.40 kg m^{-3}, respectively. In the case of subsurface drip irrigation systems, Lamm et al. (1997) compared three drip line lateral spacing (1.5, 2.3, and 3.0 m) placed at 0.40–0.45 m depth in Kansas (USA), stating that the highest yield and WP, and lowest year-to-year variation were obtained with the 1.5-m dripline spacing.

To determine what the best management practices in terms of yield and IWP are it would have been convenient to analyze the effect of planting density. Thus, El-Hendawy et al. (2008) compared the effect of this parameter (48,000, 71,000 and 95,000 plants ha^{-1}) on maize yield and IWP in Ismalia (Egypt). These authors stated that 71,000 plants ha^{-1} was the best option, while the highest density value was the worst. It must be bear in mind that in this study, the planting density was 83,333 plants ha^{-1}, which is in-between both values. According to the present results and the previous studies analyzed, it would be interesting to carry out a new research in the area increasing the distance between drip lines in the subsurface treatment up to 1.5 m and decreasing the planting density up to 71,000 plants ha^{-1}.

In the analysis of the effect of the irrigation system on maize ET_c and its partition in E and T components, there were not significant differences in ET_c between sprinkler and

surface drip-irrigated maize for the initial stage (Figs. 2, 5); whereas lower ET_c values are obtained for the subsurface drip-irrigated maize during this stage. Looking into the E/T partition results, this is a consequence of the almost null transpiration, meaning the total contribution to ET_c comes from soil evaporation, significantly reduced in the subsurface drip-irrigated area during this initial stage. This fact has been described by several authors as Allen et al. (1998), being very relevant in crops such as maize in which the portion of bare or low covered soil surface is great during the establishment stage. After a few weeks of crop development, with f_c reaching 0.5, differences in terms of ET_c are evident for the three irrigation systems, with larger values for sprinkler and still clearly lower for subsurface drip during daytime hours (Figs. 2, 5). In mid-season, under full vegetation cover conditions, larger values of ET_c are obtained for the sprinkler, but no differences are observed between surface and subsurface drip-irrigated areas since soil evaporation is not considerable during this stage of full canopy growth.

In terms of cumulated values for the full 2015 experiment, the total amount of water lost as E by each treatment resulted in 106 mm (16.0%), 105 mm (18.5%), and 64 mm (15.5%) for Sprink, SDI_0.75 and SubDI irrigation systems, respectively (Fig. 4). These results are in the line of those reported by other researchers considering the differences in the climatic conditions and soil characteristics. In the case of Rodrigues et al. (2013), sprinkler irrigation system evaporated 26.1% of irrigation water compared with 22.9% of drip irrigation system. Trout and DeJonge (2018) for a 6-year experiment carried out in the west-central Great Plains (USA) using surface drip irrigation on maize obtained 13.8% of irrigation water losses caused by evaporation from soil. In this analysis, it must be considered that only sprinkler irrigation system is penalized by drift and evaporation losses caused by wind, and from the evaporation of irrigation water intercepted by the crop. In this sense, it should be noted that the STSEB approach used to quantify ET_c is a physical model based on the thermal characterization of the surface components, and transpiration results might include some of this crop evaporation for sprinkler-irrigated maize. These reasons could justify the similar accumulated E value obtained for Sprink and SDI_0.75.

Linking transpiration results to maize yield production in 2015 for the different irrigation treatments, we may establish a connection between the 11% reduction in yield and the observed 30% reduction in T for SDI_0.75, compare to Sprink values. This drop in transpiration might be indicative of some stress inducement, responsible of the slight and not statistically significant loss in yield in that year. An additional reduction of 9% in T (up to 39%) has no added effect on yield shortage for SubDI. Something similar occurred in 2014, when the 11% reduction in transpiration did not imply a decrease in yield production for

SDI_0.75 conditions compared to Sprink values, but an additional 9% (up to 19% drop) resulted in a reduction of 12% in yield production for SubDI in this case.

Indeed the present research showed how modern irrigation technologies could result in net water savings and gains in water use efficiency. This might allow either reducing the current pressure on water resources or allocating the water saved to enlarge the irrigated area. In any case, in a context of increasing pressure for water resources among different economic sectors, it is clear that the use of subsurface irrigation can be expanded. The present results, however, did not explore if, in the long-term, emitter clogging, could occur because of the continuous application of the subsurface drip system. We did not also conduct a cost–benefit analysis to quantify if the economic return of using subsurface irrigation in comparisons with superficial drip and sprinkler irrigation could be higher. This, of course, will indeed depend on the water prices, which is an extremely variable factor both geographically and also among seasons within a given location.

Conclusion

The results show that the subsurface drip irrigation system resulted in important water savings, without significant differences in maize yield among treatments, resulting in an increase in the IWP. The separated treatment of soil and canopy components in the framework of the two-source energy balance model provided for quantitative information about the different contributions of soil evaporation and canopy transpiration to the composed maize crop evapotranspiration for the different irrigation systems analyzed. A seasonal ET_c reduction of 25% and 39%, and corresponding T reduction of 30% and 39%, were obtained when irrigation was applied by surface and subsurface drip systems compare to sprinkler, respectively. Seasonal evaporation cannot be neglected, ranging between 15 and 20% of irrigation for the three treatments (SDI_0.75, SubDI, and Sprink), mainly concentrated in the initial and development stages, resulting in a reduction of 40% for subsurface drip irrigation system. These encouraging results suggest that in areas with scarce water resources, where maize is traditionally sprinkler irrigated, the subsurface drip irrigation system could be an alternative to save water and increase the water productivity of this high-demanding water crop.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

Abd El-Wahed MH, Ali EA (2013) Effect of irrigation systems, amounts of irrigation water and mulching on corn yield, water use efficiency and net profit. Agric Water Manag 120:64–71

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation and Drainage, Paper 56, FAO, Rome

AQUASTAT (2015) FAO's Global Information System on Water and Agriculture (online), Consultation. http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en. Accessed 10 Jun 2019

Bozkurt Y, Yazar A, Gençel B, Sezen MS (2006) Optimum lateral spacing for drip-irrigated corn in the Mediterranean Region of Turkey. Agric Water Manag 85:113–120

Bu LD, Liu JL, Zhu L, Luo SS, Chen XP, Li SQ, Hill R, Zhao Y (2013) The effects of mulching on maize growth, yield and water use in a semi-arid region. Agric Water Manag 123:71–78

Chávez JL, López-Urrea R (2019) One-step approach for estimating maize actual water use: part I. Modeling a variable surface resistance. Irrig Sci 37:123–137

CIHEAM. 2015. Statistical review. Agriculture, Food security, Society, Environment (online), Consultation. https://www.ciheam.org/uploads/attachments/70/CIHEAM_Statistical_Review_2015.pdf. Accessed 10 Jun 2019

Cihlar J, Dobson MC, Schmugge T, Hoogeboom P, Janse ARP, Baret F, Guyot G, Le Toan T, Pampaloni P (1987) Procedures for the description of agricultural crops and soils in optical and microwave remote sensing studies. Int J Rem Sens 8:427–439

Colaizzi PD, Kustas WP, Anderson MC, Agam N, Tolk JA, Evett SR, Howell TA, Gowda PH, O´Shaughnessy SA (2012) Two-source energy balance model estimates of evapotranspiration using component and composite surface temperatures. Adv Water Resour 50:134–151

El-Hendawy SE, Add El-Lattief EA, Ahmed MS, Schmidhalter U (2008) Irrigation rate and plant density effects on yield and water use efficiency of drip-irrigated corn. Agric Water Manag 95:836–844

Exelis Visual Information Solutions (2012) ENVI User's Guide. Boulder, Colorado: Exelis Visual Information Solutions, pages used, Boulder, CO

FAOSTAT (2017) FAO Statistical Database (online), Consultation. http://www.fao.org/faostat/en/#data/QC. Accessed 14 Jun 2019

Fereres E, Goldhamer DA, Parsons LA (2003) Irrigation water management of horticultural crops. HortSci 38:1036–1042

Hassanli AM, Ebrahimizadeh MA, Beecham S (2009) The effects of irrigation methods with effluent and irrigation scheduling on water use efficiency and corn yields in an arid region. Agric Water Manag 96:93–99

Hsiao TC, Fereres E (2012) Maize. In: Steduto P et al (eds) Crop yield responses to water stress, Paper 66. FAO, Rome, pp 114–120

IPCC (2018) Summary for Policymakers. In: Global warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Masson-Delmotte V, Zhai P, Pörtner HO, Roberts D, Skea J, Shukla PR, Pirani A, Moufouma-Okia W, Péan C, Pidcock R, Connors S, Matthews JBR, Chen Y, Zhou X, Gomis MI, Lonnoy E, Maycock T, Tignor M, Waterfield T (eds) World Meteorological Organization, Geneva, Switzerland, p 32

Kustas WP, Alfieri JG, Anderson MC, Colaizzi PD, Prueger JH, Evett SR, Neale CMU, French AN, Hipps LE, Chávez JL, Copeland KS, Howell TA (2012) Evaluating the two-source energy balance model using local thermal and surface flux observations in a strongly advective irrigated agricultural area. Adv Water Resour 50:120–133

Lamm FR, Stone LR, Manges HL, O´Brian DM (1997) Optimum lateral spacing for subsurface drip-irrigated corn. Trans ASAE 40(4):1021–1027

López-Urrea R, de Santa Martín, Olalla F, Fabeiro C, Moratalla A (2006) Testing evapotranspiration equations using lysimeter observations in a semiarid climate. Agric Water Manag 85:15–26

López-Urrea R, Martínez-Molina L, de la Cruz F, Montoro A, González-Piqueras J, Odi-Lara M, Sánchez JM (2016) Evapotranspiration and crop coefficients of irrigated biomass sorghum for energy production. Irrig Sci 34:287–296

Payero JO, Tarkalson DD, Irmak S, Davison D, Petersen JL (2008) Effect of irrigation amounts applied with subsurface drip irrigation on corn evapotranspiration, yield, water use efficiency, and dry matter production in a semiarid climate. Agric Water Manag 95:895–908

Ritchie SW, Hanway JJ (1982) How a corn plant develops. Special Report No. 48, Iowa State University of Science and Technology, Cooperative Extension Service

Rodrigues GC, Paredes P, Gonçalves JM, Alves I, Pereira LS (2013) Comparing sprinkler and drip irrigation systems for full and deficit irrigated maize using multicriteria analysis and simulation modelling: ranking for water saving vs. farm economic return. Agric Water Manag 126:85–96

Rubio E, Caselles V, Coll C, Valor E, Sospedra F (2003) Thermal-infrared emissivities of natural surfaces: improvements on the experimental set-up and new measurements. Int J Remote Sens 24:5379–5390

Sánchez JM, Kustas WP, Caselles V, Anderson M (2008) Modelling surface energy fluxes over maize using a two-source patch model and radiometric soil and canopy temperature observations. Remote Sens Environ 112:1130–1143

Sánchez JM, López-Urrea R, Rubio E, Caselles V (2011) Determining water use of sorghum from two-source energy balance and radiometric temperatures. Hydrol Earth Syst Sci 15:3061–3070

Sánchez JM, López-Urrea R, Rubio E, González-Piqueras J, Caselles V (2014) Assessing crop coefficients of sunflower and canola using two-source energy balance and thermal radiometry. Agric Water Manag 137:23–29

Sánchez JM, López-Urrea R, Doña C, Caselles V, González-Piqueras J, Niclós R (2015) Modeling evapotranspiration in a spring wheat from termal radiometry: crop coefficients and *E/T* partitioning. Irrig Sci 33:399–410

Sánchez JM, López-Urrea R, Valentín F, Caselles V, Galve J (2019) Lysimeter assessment of the simplified two-source energy balance model and eddy covariance system to estimate vineyard evapotranspiration. Agric For Meteorol 274:172–183

Soil Survey Staff (2014) Keys to soil taxonomy, 12th edn. USDA-Natural Resources Conservation Service, Washington, DC

Trigo IF, de Bruin H, Beyrich F, Bosveld FC, Gavilán P, Groh J, López-Urrea R (2018) Validation of reference evapotranspiration from Meteosat Second Generation (MSG) observations. Agric For Meteorol 259:271–285

Trout TJ, DeJonge KC (2017) Water productivity of maize in the US high plains. Irrig Sci 35:251–266

Trout TJ, DeJonge KC (2018) Crop water use and crop coefficients of maize in the great plains. J Irrig Drain Eng 144(6):04018009