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Relevance of the irrigation and soil management system to optimize maize crop production under semiarid Mediterranean conditions

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ABSTRACT

Irrigation system and soil management through the different tillage system may have a significant impact on maize crop performance due to their capabilities to modify soil water content and soil physical and biochemical properties. Over the current climate change scenarios, the evaluation and implementation of agricultural systems that increase the efficiency in the use of the resources, like water or soil fertility, must be a priority. The aim of this study was to evaluate the impact of two well differentiated irrigation systems (i.e. sprinkler irrigation, S, flood irrigation, F) and three different tillage system (i.e. conventional tillage, CT, no-tillage maintaining the crop stover, NTr, no-tillage removing the crop stover, NT) on maize growth and yield % and agronomic efficiency of nitrogen (AE_N) and irrigation water productivity (WP_I) for a four years maize monoculture under semiarid Mediterranean conditions. On average, S irrigation increased maize grain yields by 16 % and AE_N and WP_I by 23 and 33 %, respectively, compared to F irrigation system (with an average total irrigation water applied that was 25 % lower under S irrigation system). The tillage system showed the greatest differences when was implemented under F irrigation, showing CT better crop performance than NT. Under S irrigation, the tillage system had lower o non-impact on yield components, observing similar yield, AE_N and WP_I between CT and NTr and NT tillage systems. This work highlighted that the adoption of water saving irrigation system (like S irrigation), together with the implementation of more conservative tillage practices, such as no-tillage, is a win-win strategy to maintain the sustainability the high-yielding maize system under semiarid Mediterranean conditions.

1. Introduction

In semiarid Mediterranean areas with available irrigation water, irrigation acreage has been increasing due to the much higher crop yields compared with rainfed farming systems. These areas are characterized by high solar radiation conditions and long frost-free periods that together with irrigation allow to obtain high crops productivity (Cavero et al., 2003). Under the semiarid Mediterranean conditions of the Ebro valley (Spain), maize monocropping system is one the most common and is usually managed under high-intensive practices such as conventional tillage and high inputs of water and nitrogen (N) fertilizer (Berenguer et al., 2008; Cavero et al., 2018).

Sprinkler and flood irrigation systems are the most used worldwide for field crops. Sprinkler irrigation acreage is increasing due to several benefits compared to the traditional irrigation system of flood irrigation. Pressurized systems like sprinkler irrigation have shown an increase on crop yields compared to the gravity irrigation systems such as flood irrigation (Playán and Mateos, 2006). However, that is not the only reason behind the increase of irrigation acreage under pressurized systems, since these systems easily allow irrigation automatization and the reduction of the runoff and drainage water losses due to the lower application rate per irrigation event that can be used under these systems (Rawlins and Raats, 1975; Playán and Mateos, 2006; Lecina et al., 2010). Maize is one the most important irrigated crops in Spain (≈400.000 ha), accounting for 40 % of the total irrigated cereals, and is mainly grown in semiarid areas (MAPAMA, 2022a). Flood and sprinkler are the main irrigation systems used for maize in Spain with a higher presence of flood irrigation (53 %) compared with sprinkler irrigation system (28 %), although sprinkler-irrigated maize acreage is increasing compared to flood irrigation (Playán and Mateos, 2006; MAPAMA, 2022a).

Together with the use of irrigation, soil management can have an important role on the crop performance. Compared to the traditional tillage system, characterized by an intensive alteration of the soil surface, no-tillage (NT) systems are an alternative to avoid soil disturbance. It is well established that NT systems can improve soil physical and

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biochemical properties like soil structure and aggregation, resulting in an increasing of soil organic carbon (SOC) and water-holding capacity (Hobbs et al., 2008; Pittelkow et al., 2015). Despite the benefits of NT systems, in Spain, these high-productivity maize systems are grown under intensive conventional tillage practices, representing the NT system only 10 % of the total cropland area and mainly concentred on rainfed areas (MAPAMA, 2022b).

In the last years, different studies have been carried out under Mediterranean semiarid conditions of the Ebro valley to assess the impact of different aspects of the sprinkler irrigation systems on maize crop production and water and nitrogen use efficiency. Examples of these studies are the assessment of the irrigation frequency, irrigation time, the water irrigation pressure and the salinity of irrigation water on maize growth and yield (Cavero et al., 2003, 2018; Isla and Aragüés, 2010; Robles, et al., 2017). Likewise, Pareja-Sánchez et al. (2020) evaluated the combination effect of different tillage systems and the N rate application on maize crop performance under semiarid Mediterranean conditions. However, to our knowledge, there is a lack of information about the interactive effect of irrigation and tillage systems on maize crop performance. Therefore, based on the current climate change situation that predicts water scarcity in Mediterranean areas (Mekonnen and Hoekstra, 2016) and the lack of information about the interactive effect of the irrigation system and the soil tillage system, the objective of this work was to evaluate alternative management practices to the traditional maize production system, with flood irrigation and conventional tillage, that could maintain the sustainability of maize cropping systems under Mediterranean semiarid conditions.

2. Material and methods

2.1. Site and experimental design

To achieve the objective of this study, an experimental field trial was established at the experimental farm of the Experimental Station of Aula Dei (Zaragoza, Spain, 41º 42' N; 0º 49' W; 225 m altitude) covering four maize growing seasons (2015, 2016, 2017 and 2018). The climate in the study area is classified as Mediterranean semiarid with annual mean air temperature of 14.1ºC, annual precipitation of 298 mm and grass reference crop evapotranspiration (ETo) of 1243 mm.

The soil is a Typic Xerofluvent (Soil Survey Staff, 2015) with a silty loam texture, presenting average values of sand, silt and clay values in the 0–50 cm soil profile of 16, 63 and 21 %, respectively, with very small variation between the 4 soil layers analysed. Similarly to soil texture, hydrological characteristics, i.e. field capacity, wilting point, showed similar values over the 4 soil layers considered, reporting average values of 0.26 and 0.14 m^3 m^{-3} for field capacity and wilting point, respectively, resulting in a water holding capacity of 0.12 m^3 m^{-3} (Table 1). The 0–50 cm soil profile is characterized by an average pH (1:2.5 (w/v) soil:water) and soil organic carbon (SOC) of 8 and 1.76 %, respectively.

The selected field was under cultivation during the last decades with a crop sequence characterized by a succession of different cereals crops, winter wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) under conventional tillage and flood irrigation conditions. Previously to the start of the field trail, the crop was winter wheat. In 2015, before the first maize sowing, the field was divided in two parts, to allow the implementation of both irrigation systems, being one part irrigated by flood irrigation and the other part by a hand move sprinkler irrigation with an 18 m x18 m square spacing.

Couple with the two irrigation systems (i.e., sprinkler, S, and flood, F), three soil tillage systems (i.e., conventional tillage, CT; no-tillage maintaining the maize stover, NTr; and no-tillage removing the maize stover, NT) were established, resulting six different treatments with a 6 m × 18 m plot size, arranged in the field as split-block design with three replicates per treatment.

2.2. Soil and crop management

Tillage operation varied depending on the tillage system. Under conventional tillage, one pass of a subsoiler to 0.30 m depth followed by one pass of a disk harrow in winter and one pass of a rotary tiller just before planting maize were performed. For tillage treatments, maize stover was incorporated into the soil with tillage operation. In both no-tillage systems, weed control before maize planting consisted of a glyphosate (36 % a.i. at 5 L ha^{-1}) application each year. Moreover, for the NT treatment, maize stover was removed manually after mechanical harvest (Table 2).

Maize sowing, cv. Pioneer P1785, was done in April in rows 75 cm apart at a density of 89,500 seeds ha^{-1} using a. single-seed drill (Sola Prosem K 255/4) adjusting it for sowing no-tillage and conventional tillage plots. All treatments received the same fertilization, consisting of a total nitrogen (N) application of 250 kg N ha^{-1} split into two applications, a pre-sowing application and one top-dressing application. Pre-sowing fertilization was an application of 800 kg ha^{-1} of NPK 8–15–15 compound fertilizer, resulting in an N application of 64 kg N ha^{-1}. The

Table 2
Schedule of field operations during the 2015, 2016, 2017 and 2018 maize growing seasons.

Field operation	2015	2016	2017	2018
Stover management				
Stover removal		23/12/2015	11/11/2016	20/11/2017
Tillage operation				
Subsoiler and disk harrow	11/03/2015	15/12/2016	31/01/2017	23/01/2018
Rotary tiller	08/04/2015	12/04/2016	17/04/2017	15/02/2018
No-tillage weed control				
Herbicide application	21/11/2014	11/04/2016	07/02/2017	03/04/2018
Planting	09/04/2015	12/04/2016	17/04/2017	25/04/2018
N Fertilization				
Preplanting application	08/04/2015	11/04/2016	17/04/2017	03/04/2018
Top dressing application	02/06/2015	13/06/2016	07/06/2017	11/06/2018
Harvest	30/09/2015	05/10/2016	17/10/2017	02/10/2018

Table 1
Soil characteristics of the experimental field.

Depth	pH	SOC†	$CaCO_3$	Sand	Silt	Clay	FC‡	WP§
m		%					m^3 m^{-3}	
0.–0.05	7.98	1.93	34.9	15.7	61.9	22.3	0.26	0.14
0.05 –0.10	8.20	1.85	34.9	15.4	62.9	21.7	0.26	0.14
0.10 –0.25	8.03	1.75	35.1	15.9	62.1	22.0	0.25	0.16
0.25 –0.50	7.95	1.51	35.3	16.0	63.6	20.3	0.25	0.16

† Soil organic carbon.
‡ FC, Field capacity (-0.033 MPa).
§ WP, Wilting point (-1.5 MPa).

top-dressing application was done at V6–V8 maize growth stage and consisted of 186 kg N ha^{-1} applied as calcium ammonium nitrate N-27 % (13.5 % ammonium N ($N\text{-}NH_4^+$)– 13.5 nitrate N ($N\text{-}NO_3$)). Mechanical harvest with a commercial combine was done in late September or early October each year (Table 2).

2.3. Irrigation management, soil water content monitoring and soil sampling

Irrigation water requirements were determined based on crop evapotranspiration (ETc). Daily ETc values were calculated by multiplying the grass reference evapotranspiration (FAO 56 Penman-Monteith (P-M) ETo) by the crop coefficient (Kc). The (P-M) ETo values were calculated by the FAO Penman–Monteith method (Allen, et al., 1998) using meteorological data from a weather station located 1 km southwest of the field experiment trial. The maize crop coefficient (Kc) was obtained based on the thermal time using an equation developed by Martínez-Cob et al., (2008) at the same location of the experiment. Thermal time was computed as the cumulative daily difference between the daily mean air temperature and a basal air temperature of 8 °C (Kiniry, 1991). The crop irrigation requirements (CIR) were determined weekly as the difference between the ETc and the effective precipitation, which was estimated as 75 % of total weekly precipitation (Dastane, 1978).

Irrigation water applied and irrigation frequency depends on the irrigation system. For sprinkler irrigation system, an irrigation efficiency of 90 % was considered, therefore, the volume water applied corresponding to the CIR plus a 10 % extra to satisfy the crop water requirements in each irrigation event. For this irrigation system, the irrigation frequency was characterized by two irrigation events per week, usually performed on Monday and Wednesday with an application rate of 5 mm h^{-1}, resulting in irrigation water volumes that range from 5 to 30 mm per irrigation event. The water applied in each irrigation event was measured with a flowmeter.

Under flood irrigation, the irrigation events were carried out when the CIR values were above 80 mm, resulting in a frequency that ranged between 10 – 14 days between the irrigation events. The irrigation water applied was calculated based on the irrigated surface, the duration of the irrigation event, and the estimated water flow through the irrigation channel, which was determined using a Cipolletti weir (Dean Hively et al., 2006). In contrast with sprinkler irrigation, the volume of water applied was estimated after each irrigation event, without considering an efficiency index, since to guarantee adequate irrigation, it is necessary to wait until the plot is completely irrigated. Determining an efficiency index for a flood irrigation system requires knowing the infiltration rate, soil roughness, percolation, etc., variables that are difficult to determine and that can change throughout the crop cycle. However, after each irrigation event, the irrigation efficiency was determined, obtaining an average efficiency value of 75 % for the four irrigation campaigns. In order to favour plant emergence and to avoid differences in plant density among treatments (nascence irrigation), irrigation water was applied by sprinkler irrigation to all the plots until V6 growth stage. For each irrigation system, the same amount of irrigation water was applied to all tillage treatments.

In three of the four growing seasons, soil water content at 0–0.05 m soil depth was manually monitored by using a GS3 soil moisture probe (Decagon Devices, Pullman, WA), measuring the soil water content at two different locations in each plot. Sampling frequency was characterised by a weekly frequency, increasing the sampling frequency to a daily frequency during fertilization and for each flood irrigation event. Moreover, soil bulk density was measured once per month in each plot by the cylinder method (Grossman and Reinsch, 2018). Once the trial was completed, in the winter of 2019, a depth sampling was carried out, taking samples for the determination of bulk density at 4 different depths, 0-0.05, 0.05-0.10, 0.10-0.25 and 0.25-0.50 m soil depth.

2.4. Biomass and grain yield and efficiency indexes determination

Maize aboveground biomass and grain yield were determined manually before the machine harvest with the combine. For the manual harvest three 2-m maize rows at two random locations per plot were sampled. The number of plants and ears was counted before cutting all plants at the soil level. The grain was separated from the ear and both parts were dried at 60°C for 48 h and weighed. Besides, a sub-sample of four entire plants was taken, oven-dried at 60°C for 48 h and weighed. Afterwards, the plant and grain samples were grounded and analysed to determine the C and N content by combustion (TruSpec CN, LECO, St Joseph, MI, USA). The rest of the maize plants at each experimental plot was harvested with a commercial combine. Maize grain yield values were standardized to 14 % moisture content and aboveground biomass values were standardized to 0 % moisture.

Total maize aboveground biomass (AGB) was calculated by summing the dry plant biomass and the dry total grain. Maize grain yield was standardized to a 14 % moisture content. The harvest index (HI) was calculated by dividing the total dry grain yield by the total dry aboveground biomass and expressing the result as a percentage. The nitrogen harvest index (NHI) was calculated as the percentage ratio between nitrogen grain uptake and the total nitrogen uptake by the plant (i.e. nitrogen uptake of the grain and the total aboveground biomass). The nitrogen uptake of grain and aboveground biomass was calculated by multiplying the dry grain yield or dry total aboveground biomass by the nitrogen content measured. The total aboveground biomass nitrogen uptake was obtained by summing the nitrogen uptake by grain and aboveground biomass. The agronomic efficiency of nitrogen (AE_N) by grain yield or by total aboveground biomass was determined by dividing the N uptake of grain or the N uptake of total aboveground biomass by the total N fertilizer applied. Irrigation water productivity (WP_I) for the grain yield and the total aboveground biomass were obtained as the ratio between the dry grain yield or the total aboveground biomass by the total irrigation applied, respectively.

2.5. Data analysis

For all variables, normality assumptions were checked in the residuals by a Shapiro-Wilk test. Differences between treatments were evaluated by an analysis of variance (ANOVA) with the year, irrigation system, tillage system and their interactions as fixed effects and block and their interactions as random effects. When significant, differences between treatments were identified at 0.05 probability level using the Tukey test. All statistical analyses were performed with the JMP 10 statistical package (SAS Institute Inc, 2012).

3. Results

3.1. Weather conditions, soil water content, soil bulk density and irrigation management

During the four years considered in this study, the mean air temperature showed a typical Mediterranean pattern characterised by maximum temperatures during the summer months, i.e. June-September, and minimum temperatures over the winter months, i.e. December-February (Fig. 1). Considering the maize growing period, i.e. April-October, the mean air temperature was 19.8, 19.2, 19.9 and 19.7ºC for growing seasons 2015, 2016, 2017 and 2018, respectively. The mean air temperature over the four growing seasons was similar to the mean air temperature of the historical series for the same period (19.6ºC).

Precipitation distribution was characterized by low precipitation during winter and summer months, being autumn and spring months when the highest precipitation occurred, typical from Mediterranean areas (Fig. 1). Over the four maize growing seasons, the total amount of precipitation ranged between 115 and 174 mm. Compared to the historical series (180 mm), only the 2018 growing season presented similar

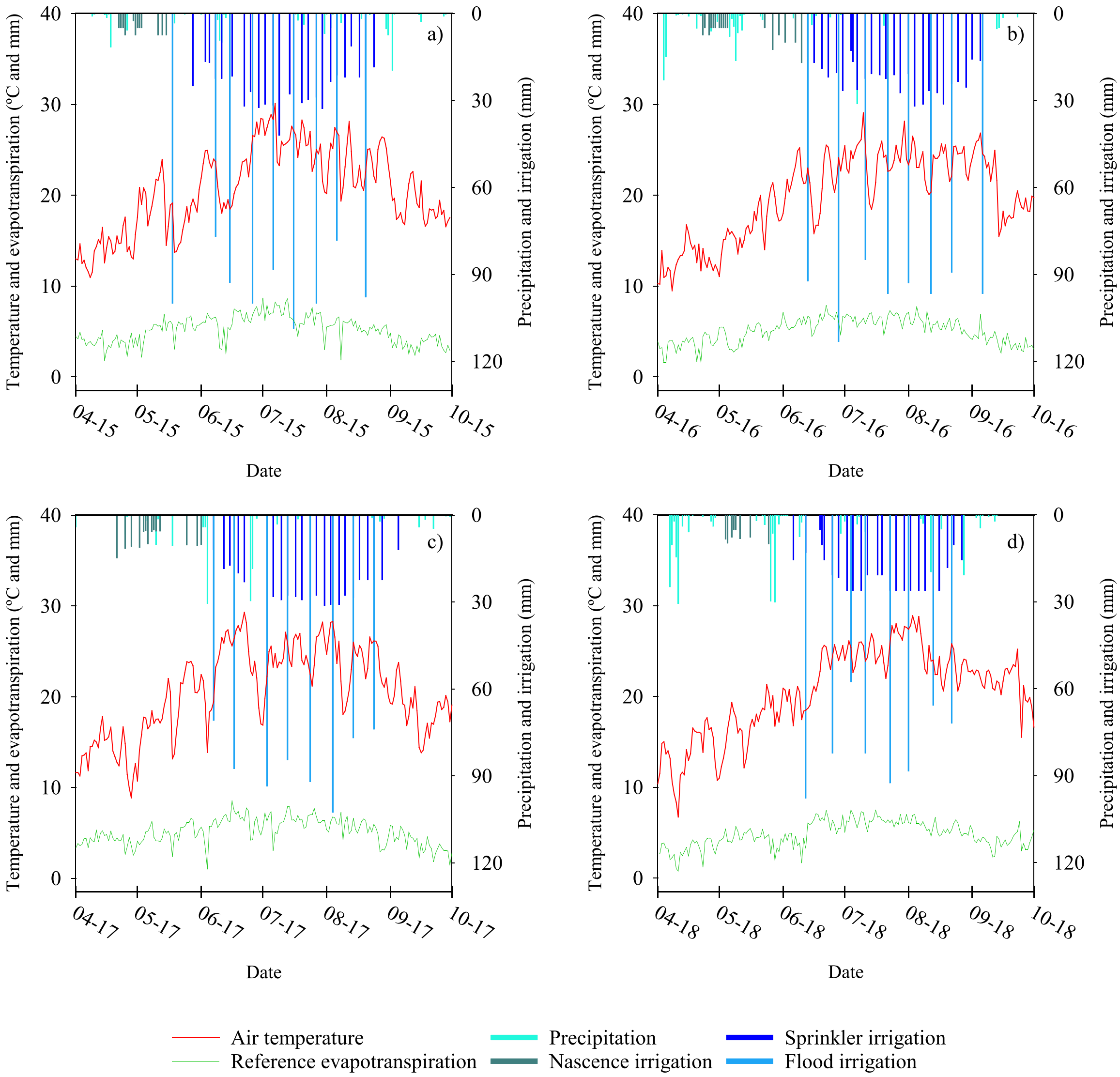

Fig. 1. Daily mean air temperature (red continuous line), reference evapotranspiration (ETo) (green continuous line), precipitation (light blue vertical bars), nascence irrigation (dark green vertical bars), sprinkler irrigation (dark blue vertical bars) and flood irrigation (blue vertical bars) for (a) 2015, (b) 2016, (c) 2017 and (d) 2018 growing seasons.

precipitation (174 mm), while the 2015, 2016 and 2017 growing seasons, reported precipitation values that were 36, 27 and 24 % lower than the historical series, respectively.

Irrigation water applied ranged between 582 and 729 mm and 691–950 mm under sprinkler and flood irrigation systems, respectively (Table 3). On average, the amount of irrigation applied under the flood irrigation system was 20 % higher than in the sprinkler irrigation system.

Soil water content showed a similar pattern over the three growing seasons in which was measured. In three growing seasons, sprinkler irrigation presented more stable water content values, with water content values ranging between 15 % and 30 %. In contrast, flood irrigation showed a short-temporal pattern characterized by a large increase in soil water content just after the irrigation events reaching values above 30 % of volumetric water content, followed by a sharped decrease up to values close to 10 % of volumetric water content 10 days after the irrigation event. (Fig. 2).

Soil bulk density for 2015, 2016 and 2017 growing seasons was significantly affected by the tillage system, observing the highest values under both no-tillage systems, while no significant differences were observed between irrigation systems (Table 4). Likewise, when soil bulk

Table 3
Calculated crop evapotranspiration (ETc), effective precipitation, crop irrigation requirement (CIR) and irrigation water applied in both irrigation systems (sprinkler and flood) in 2015, 2016, 2017 and 2018 maize growing seasons. Numbers in brackets correspond to the number of irrigation events per growing season.

Growing season	ETc	Effective precipitation	CIR	Irrigation	
				Sprinkler	Flood
	mm				
2015	749	92	657	729 (12 *+25)	950 (12 *+9)
2016	763	125	638	708 (17 *+26)	824 (17 *+8)
2017	744	125	619	686 (14 *+24)	874 (14 *+8)
2018	683	158	525	582 (11 *+24)	691 (11 *+7)

* Numbers with aesthetic corresponds to nascence irrigation event.

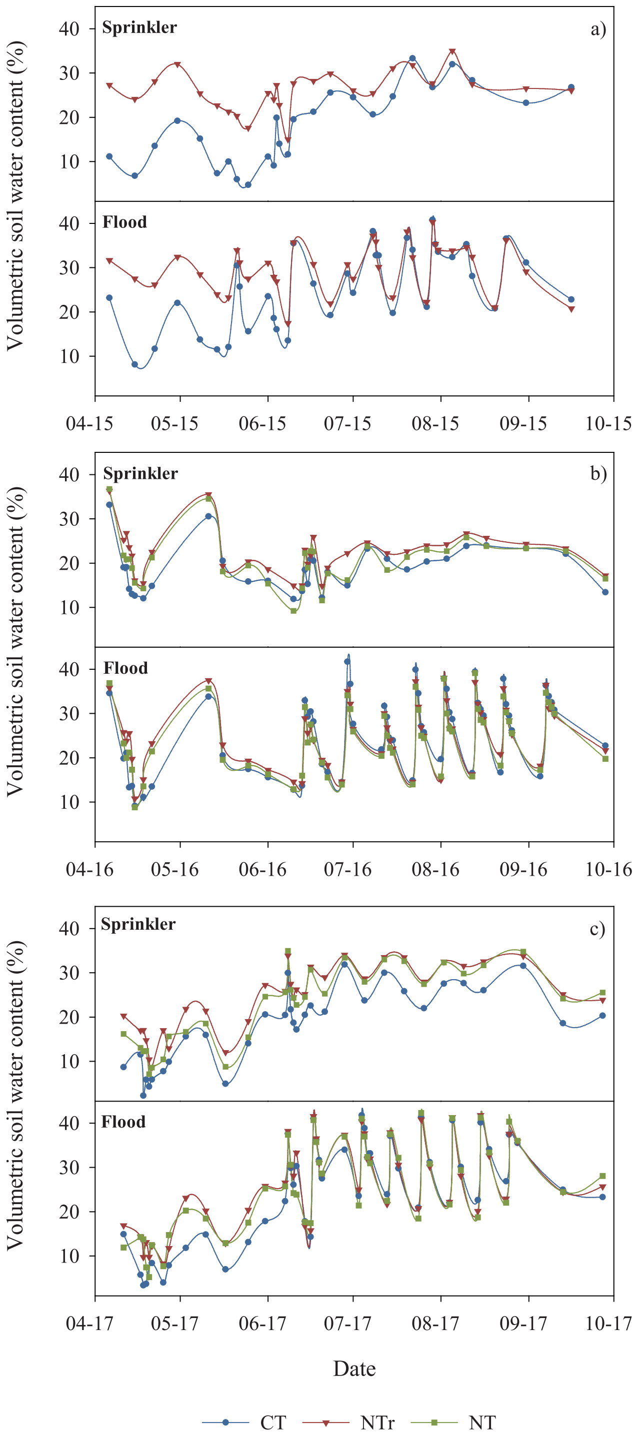

Fig. 2. Soil volumetric water content as affected by irrigation system, sprinkler and flood irrigation system and soil tillage system (CT, conventional tillage; NTr, no-tillage maintaining the maize stover; NT, no-tillage removing the maize stover) for (a) 2015, (b) 2016, (c) 2017 growing seasons.

density was evaluated in depth at the end of the experimental trial, significant differences between treatments were observed in the first three soil layers considered, 0–0.05, 0.05–0.10 and 0.10–0,25 m depth but not for 0.25–0.50 m soil depth (Table 4). Despite the significant differences, no clear pattern in bulk density was observed, with higher or lower values alternating between the different treatments. However, in general, the highest bulk density values were observed for no-tillage while the tillage system tended to show the lowest bulk density values

Table 4
Analysis of variance (ANOVA) of bulk density as affected by) irrigation system (S, sprinkler irrigation; F, flood irrigation), soil tillage (CT, conventional tillage; NTr, no-tillage maintaining the crop stover; NT, no-tillage removing the crop stover) at 0–0.05 m soil depth for 2015, 2016 and 2017 maize growing seasons and at 4 different soil interval depths (0–0.05, 0.05–0.10, 0.10–0.25 and 0.25–0.50 m soil depth) at the end of field experiment (2019).

Effects and levels†	Year			
	2015		2016	2017
Irrigation system (IS)	n.s.*		n.s.	n.s.
S	1.51		1.49	1.45
F	1.51		1.52	1.44
Tillage system (TS)	* **		* **	* **
CT	1.45 b		1.39 b	1.34 b
NTr	1.53 a		1.57 a	1.50 a
NT	1.57 a		1.56 a	1.50 a
IS x TS	n.s.		n.s.	n.s.
Effects and levels†	Soil interval depth			
	0–5	5–10	10–25	25–50
Irrigation system (IS)	n.s.	*	n.s.	n.s.
S	1.39	1.52 a	1.60	1.60
F	1.37	1.41 b	1.58	1.65
Tillage system (TS)	*	n.s.	*	n.s.
CT	1.33 b	1.45	1.53 b	1.63
NTr	1.38 ab	1.50	1.62 a	1.63
NT	1.42 a	1.44	1.60 a	1.61
IS x TS	*	*	* *	n.s.

*n.s., No significant. Asterisks represent different levels of significance.
* ; p < 0.05
* *; p < 0.01
* ** , p < 0.001
† For each effect, year and soil depth values followed by different letters are significantly different according to a Tukey test at P = 0.05 level.

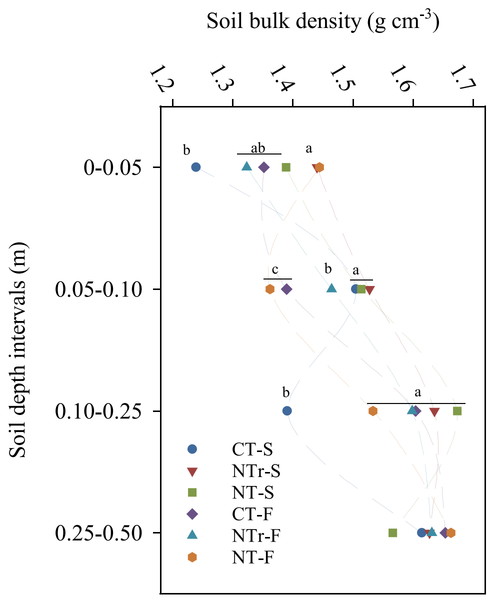

Fig. 3. Soil bulk density by soil depth intervals as affected by as affected by irrigation system (S, sprinkler irrigation; F, flood irrigation) and soil tillage (CT, conventional tillage; NTr, no-tillage maintaining the maize stover; NT, no-tillage removing the maize stover).

(Fig. 3).

3.2. *Crop yield*

Plant density at harvest was affected by the irrigation system and by the interaction of the irrigation and tillage system. Considering the four growing seasons, sprinkler irrigation reported the highest plant density, being on average 2.3 % greater than the plant density values measured under flood irrigation systems. Moreover, plant density was higher in the NT system under S irrigation as compared with both no-tillage systems (NT and NTr) under F irrigation. Under S irrigation, NT tillage reported a 6 % higher plant density compared with the same tillage treatment under F irrigation (Table 5, Fig. 4a). In the same line, ear density was significantly affected by the irrigation system and the interaction of the irrigation system with the growing season, obtaining the greatest ear density values under sprinkler irrigation during the four growing seasons.

The total aboveground biomass was affected by the year, the irrigation and the tillage system and by the following interactions: irrigation and tillage systems, year and irrigation system, and year and tillage system. The highest aboveground biomass value was measured in 2017, reporting values 9 % greater than the four-year average. Moreover, the S irrigation system reported higher total aboveground biomass compared to the F irrigation system, presenting differences between irrigation systems that reached 8 % (Table 5). Likewise, the tillage system showed a significant impact on the total aboveground biomass, observing the lowest values and NT treatment compared to NTr and CT treatments that presented similar values. Finally, the irrigation system coupled with the tillage system had a significant impact on the total aboveground biomass, observing the greatest yield values under the CT-S treatment (Table 5, Fig. 4b).

Maize grain yield was affected by the year, the irrigation and the tillage system and by the following interactions: irrigation and tillage systems and year and tillage system. Average maize grain yield ranged between 12.1 and 16.2 Mg ha^{-1} over the four growing seasons, observing the greatest grain yield values in the 2017 growing season. Overall tillage treatments, the S irrigation system reported average grain yield values 16 % greater than the F irrigation system. Meanwhile, the tillage system also had a significant effect on the grain yields, but differences between tillage systems were lower, being the grain yield obtained under the CT tillage system 6 % higher compared to both no-tillage systems, NTr and NT (Table 5). Regarding the interaction between irrigation and tillage systems, CT and NTr systems under sprinkler irrigation presented the greatest yields. In contrast, when no-tillage, NTr and NT, were implemented under flood irrigation conditions, no-tillage systems reported the lowest maize grain yields. However, the CT-F treatment showed similar grain yield values to the NT-S treatment (Fig. 4c).

Kernel mass was affected by the year, the irrigation system, and the interaction of the year and the tillage system. Contrary to other parameters like total aboveground biomass or grain yield, the greatest kernel mass was measured in the 2015 growing season, without differences in kernel mass for the remaining growing seasons considered in this study (Table 5). Moreover, the irrigation system had a large impact with the greatest kernel mass values for all the tillage systems under S irrigation, observing only significant differences in kernel mass between tillage systems under F irrigation, reporting the NTr tillage system (Fig. 4d).

The harvest index, HI, was slightly affected by the year, the irrigation system and the following interactions: irrigation system and tillage system, and year and tillage system. The harvest index showed a significant increase over the four growing seasons, presenting the lowest values in the 2015 growing season and the greatest values in the 2017 and 2018 growing seasons. Similarly to the rest of the yield components, the S irrigation system reported greater HI than the F irrigation system with average values 8 % higher over the four growing seasons considered (Table 5). Moreover, the interaction between irrigation and tillage system showed that the implementation of the NTr treatment under flood irrigation conditions presented the lowest HI compared to the same tillage system under sprinkler irrigation which presented the greatest HI value (Fig. 4e).

Nitrogen harvest index, NHI, was affected by the year, the tillage system, and the following interactions: irrigation and tillage systems, and year, irrigation and tillage systems. The highest NHI was obtained in 2018 and the lowest in the 2017 growing season, respectively, without observing differences between the 2015 and 2016 growing seasons. There was no significant difference between irrigation systems, while, both no-tillage systems reported an average nitrogen harvest index 5 % greater than the CT tillage systems. Finally, regarding the interaction between tillage and irrigation systems, only significant differences were found between NTr-S and the CT treatments, independently of the irrigation system (Table 5, Fig. 4f).

3.3. Nitrogen and irrigation water efficiency indexes

Agronomic efficiency of nitrogen (AE_N) for grain yield and total aboveground biomass presented similar results. Both variables were

Table 5

Analysis of variance (ANOVA) of plant density, ear density, total maize aboveground biomass, maize grain yield, maize kernel mass, harvest index (HI), nitrogen harvest index (NHI as affected by year (Y) irrigation system (S, sprinkler irrigation; F, flood irrigation), soil tillage (CT, conventional tillage; NTr, no-tillage maintaining the crop stover; NT, no-tillage removing the crop stover) and date of sampling and their interactions.

Effects and levels†	Plant density (nº of plants ha^{-1})	Ear density (nº of ears ha^{-1})	Total aboveground biomass (Mg ha^{-1})	Maize grain yield (14 %) (Mg ha^{-1})	Kernel mass (mg)	HI (%)	NHI (%)
Year (Y)	n.s.	n.s.	* **	* **	* **	* **	* **
2015	84,375	79,898	22.8 b	12.1c	372 a	45c	61 b
2016	84,377	78,287	22.3 b	12.9c	346 b	50 bc	62 b
2017	83,072	80,312	25.0 a	16.2 a	341 b	56 ab	58c
2018	83,704	76,528	20.9 b	14.1 b	335 b	58 ab	67 a
Irrigation system (IS)	* *	*	* *	* **	* *	*	n.s.
S	84,809 a	79,827 a	23.6 a	14.9 a	357 a	54 a	62
F	82,906 b	77,685 b	21.8 b	12.8 b	340 b	50 b	62
Tillage system (TS)	n.s.	n.s.	* *	* *	n.s.	n.s.	* *
CT	84,350	79,770	23.2 a	14.4 a	351	54	60 b
NTr	83,358	77,339	23.0 a	13.6 b	346	51	63 a
NT	83,889	79,158	22.0 b	13.5 b	349	53	63 a
Y x IS	n.s.	n.s.	* *	n.s.	n.s.	n.s.	*
Y x TS	n.s.	* *	* *	* **	*	*	* **
IS x TS	* *	n.s.	* *	* *	*	* *	*
Y x IS x TS	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

*n.s., No significant. Asterisks represent different levels of significance.

* ; $p < 0.05$;

* *; $p < 0.01$;

* ** , $p < 0.001$.

† For each effect, period and variable values followed by different letters are significantly different according to a Tukey test at P = 0.05 level.

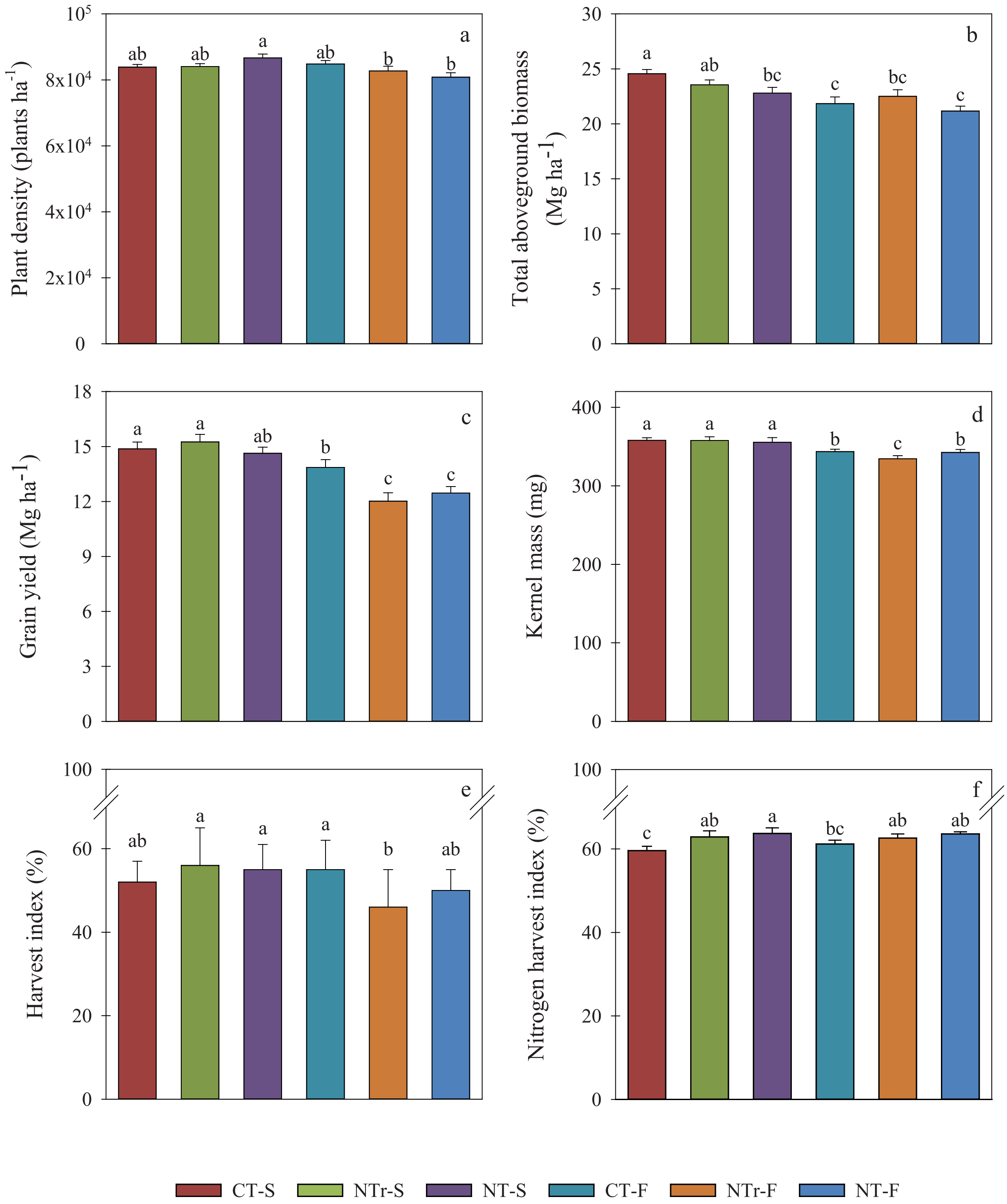

Fig. 4. Plant density (a), maize total aboveground biomass (b), maize grain yield (c), kernel mass (d), harvest index (e) and nitrogen harvest index (f) as affected by irrigation system (S, sprinkler irrigation; F, flood irrigation) and soil tillage (CT, conventional tillage; NTr, no-tillage maintaining the maize stover; NT, no-tillage removing the maize stover). Different letters indicate significant differences between treatments at $p < 0.05$. Error bars represent standard error.

affected by the year, the irrigation system, and the following interactions: the irrigation system and the tillage system, and the year, the irrigation system and the tillage system. The greatest AE_N by grain yield and total aboveground biomass was obtained in the 2017 growing season, while the lowest values were observed in the 2016 and 2018 growing seasons. Moreover, the sprinkler irrigation system presented values of AE_N for grain yield and total aboveground biomass that were on average 23 and 26 % higher, respectively, compared to the values found for the flood irrigation system, however, no significant difference was observed for the tillage system. Likewise, all three tillage systems under S irrigation had higher AE_N than the F irrigated treatments. However, when tillage systems were implemented under F irrigation, significant differences were found between CT and the two no-tillage systems (NT and NTr), reporting CT the greatest AE_N for grain yield and total aboveground biomass (Table 6, Fig. 5a, b).

Irrigation water productivity (WP_I) was affected by year, irrigation system and tillage system and the following interactions: irrigation system and tillage system, and year, irrigation and tillage systems. Over the four growing seasons, the highest WP_I values by grain yield and total aboveground biomass were obtained in 2018 growing season and the lowest values in 2016 growing season. As occurred with the AE_N, the WP_I for grain yield and total aboveground biomass were 33 and 34 %

Table 6
Analysis of variance (ANOVA) agronomic efficiency of nitrogen (AE_N) of grain and total aboveground biomass and irrigation water productivity (WP_I) of grain and total aboveground biomass as affected by year (Y) irrigation system (S, sprinkler irrigation; F, flood irrigation), soil tillage (CT, conventional tillage; NTr, no-tillage maintaining the crop stover; NT, no-tillage removing the crop stover) and date of sampling and their interactions.

Effects and levels†	AE_N grain (kg grain kg N^{-1})	AE_N total biomass (kg biomass kg N^{-1})	WP_I grain (kg grain m^{-3})	WP_I total biomass (kg biomass m^{-3})
Year (Y)	*	* *	* **	* **
2015	53 ab	87 b	13c	28 b
2016	52 b	84 b	12c	24c
2017	58 a	100 a	14 b	27 b
2018	52 b	77 b	18 a	29 a
Irrigation system (IS)	* **	* **	* **	* **
S	59 a	97 a	16 a	31 a
F	48 b	77 b	12 b	23 b
Tillage system (TS)	n.s.	n.s.	* *	* *
CT	55	91	15 a	28 a
NTr	53	85	14 b	27 b
NT	53	85	14 b	26 b
Y x IS	* *	* *	* *	* *
Y x TS	* **	* **	* *	* *
IS x TS	*	*	*	*
Y x IS x TS	n.s.	n.s.	n.s.	n.s.

*n.s., No significant. Asterisks represent different levels of significance.
* ; $p < 0.05$;
* *; $p < 0.01$;
* ** , $p < 0.001$.
† For each effect, period and variable values followed by different letters are significantly different according to a Tukey test at $P = 0.05$ level.

greater under S irrigation compared to the F irrigation treatments (Table 6). Likewise, on average of the four growing seasons, CT reported value of WP_I significantly higher than both no-tillage system, despite differences between tillage systems were lower than 6 and 3 % for WP_I by grain yield and total aboveground biomass, respectively. Significant differences for both efficiency indexes between treatments were only found when the different tillage systems were carried out under F irrigation, with the two no-tillage systems (NT and NTr) having lower WP_I than CT (Table 6, Fig. 5c, d).

4. Discussion

Over the four maize growing seasons studied, both agricultural management practices, irrigation and tillage systems, showed a clear impact on the maize crop performance and on the irrigation water and nitrogen efficiency indexes evaluated.

The irrigation system had a large impact on the yield components studied, presenting significant differences between both irrigation systems evaluated for most of the parameters considered. This effect on plant density was observed even when sprinkler irrigation was applied to both irrigation systems to ensure similar crop development prior to irrigation system differentiation. This impact on plant development could be explained by irrigation uniformity. In this line, Cavero et al. (2001) found that under flood irrigation, water uniformity had direct impact on maize crop performance under similar Mediterranean conditions. Water uniformity under flood irrigation depends on the time that the field is waterlogging and the infiltration characteristics of the soil (Letey, 1985). Therefore, differences in water uniformity through the flood irrigation field could explain the lower plant density measured at harvest.

In general, maize grain yield values obtained in this work were similar to the maize yield values reported by other studies carried out in the same region but only for sprinkler irrigation conditions (Cavero et al., 2003,2018; Cela et al., 2011; Robles et al., 2017). For flood irrigation conditions, Cela et al. (2011) reported maize grain yields ranging from 11 to 14 Mg ha^{-1} in the same area, similar to what was found in our study, and what was found by other authors in similar climatic conditions (Hassanli et al., 2009). On average, the sprinkler irrigation system yielded 16 % more than the flood irrigation system, a result that is in concordance with the results found by Hassanli et al. (2009), who also found a significant increase in the maize grain yield under a pressurized system compared to the traditional irrigation methods, i.e. furrow irrigation.

The greatest grain yields as well as the higher total aboveground biomass observed under the S irrigation system could be explained by a more stable soil water content in the root zone without too high and too low values provided by the higher irrigation frequency and lower irrigation rates at each event under the S irrigation system (Rawlins and Raats, 1975). One of the main advantages of the pressurized sprinkler irrigation system is that allows to increase irrigation frequency and applies lower irrigation rates at each event compared to the traditional irrigation system (Playán and Mateos, 2006). Then, the higher irrigation frequency and lower irrigation rates provided by S irrigation compared with F irrigation (two times per week under S irrigation vs one time every 10 days under F irrigation) avoids the soil water content from decreasing below the allowable depletion threshold for maize (Martin et al., 1990) during the growing season, which contributed to attaining high crop yields, and in more stable soil water content, which is related with a better crop performance (Rawlins and Raats, 1975; Segal et al., 2006; Zhang et al., 2019; Chachar et al., 2020). In line with the findings of the previous authors and as shown in our work, the sprinkler irrigation system provides a more stable soil water content throughout the maize growth period compared to the flood irrigation system. These differences in the soil water content and its temporal dynamic are a key factor that contributes to the greater maize yield obtained under sprinkler irrigation compared to flood irrigation.

It is well established that maize grain yield is very sensitive to water stress during the flowering and grain-filling stage (Farré and Faci, 2009; Sah et al., 2020), thus any water deficit during this period might cause a relevant yield decrease. Moreover, the higher irrigation rates applied in the F system can decrease maize grain yields due to the negative impact of waterlogging on maize growth (Mukhtar et al., 1990; Ren et al., 2016). The previous authors observed a significant reduction in maize grain yield yields, when waterlogging conditions lasted for 3–6 days, showing that the negative effects of waterlogging are particularly sensitive in the early growth stages of plants. In our work, waterlogging conditions under the F irrigation system were observed over the first 24 h after each irrigation event, afterwards, the soil water content started to decrease rapidly reaching soil water content values below 10 % of volumetric water content after 10–15 days. This situation was repeated in every flood irrigation event, resulting in waterlogging conditions followed by water deficit stress some days after the irrigation event occurred. Consequently, these water-limiting conditions might also be happening during critical phenological stages such as flowering and grain filling. Therefore, these explanations would account for the significant reduction in yield components found in the F irrigation system compared to S irrigation.

The tillage system had a lower impact on the maize growth parameters studied compared with the irrigation system. In general, the CT system produced a better maize performance compared to the two no-tillage systems (NT and NTr), especially under the F irrigation system, where the no-tillage system reported the lowest values for most of the parameters considered in this work. However, in general, no significant differences were observed between tillage systems when the irrigation system was sprinkler. Similar reductions in the maize crop performance under no-tillage systems were observed by Afzalinia and Zabihi (2014) and Salem et al. (2015) under Mediterranean conditions as well, who reported a decrease in maize grain yields under no-tillage systems, especially during the first years of implementation. In our study, the no-tillage system was implemented in 2015, in a field with a previous historical management based on conventional tillage practices. This

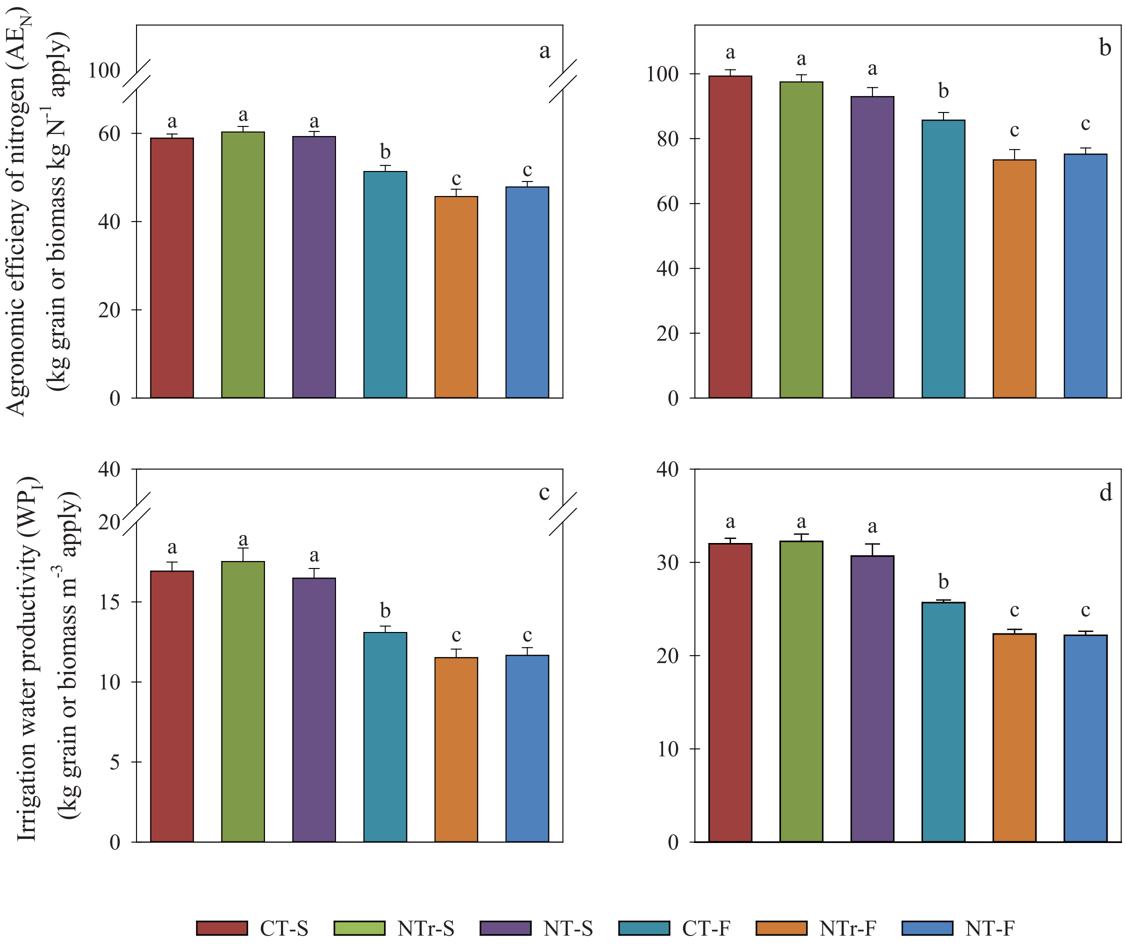

Fig. 5. Agronomic efficiency of nitrogen by grain (a) and by total aboveground biomass (b) and irrigation water productivity by grain (c) and by total aboveground biomass (d) as affected by irrigation system (S, sprinkler irrigation; F, flood irrigation) and soil tillage (CT, conventional tillage; NTr, no-tillage maintaining the maize stover; NT, no-tillage removing the maize stover). Different letters indicate significant differences between treatments at $p < 0.05$. Error bars represent standard error.

short-time implementation of the no-tillage systems could be one possible explanation for the worst performance of this tillage system under flood irrigation conditions since it was observed that the benefits of no-tillage systems in soil properties such as soil structure, water holding capacity or soil porosity improve with time (Teasdale et al., 2007; Blanco-Canqui and Ruis, 2018).

Moreover, as it has been explained before, differences between tillage systems were more pronounced when performed under flood irrigation conditions, reporting both no-tillage systems with the lowest values. Coupled with the short-time implementation of the no-tillage, there were other possible reasons behind like waterlogging, poor crop establishment, and lower root development by compaction that would explain the worse crop performance under no-tillage systems (Pittelkow et al., 2015). In our study, soil bulk density presented higher values under the no-tillage systems compared to conventional tillage system, as it shown. This fact could indicate some compaction problems resulting in more detrimental conditions for root development (Cid et al., 2014). These compaction conditions under no-tillage would explain the longer time under waterlogging conditions observed in no-tillage plots of the flood irrigation system. Indeed, this explanation would also support the lower plant density observed under the NTr-F and NT-F treatments and, thus, the decrease in yield components that NT-F and NTr-F showed.

The largest differences between treatments were observed for both efficiency indices, i.e. AE_N and WP_I. In both cases, S irrigation was the most efficient system independently of the tillage system. In this study, WP_I values were in the range of WP_I values reported by Pareja-Sánchez et al. (2019) and Fernández-Ortega et al. (2023) for irrigated maize crop under similar Mediterranean conditions. The lower WP_I in the F irrigation system was partially explained by the lower grain yield and mostly by the higher irrigation water applied in this F system. This result is line with Kumar Jha et al., (2019) which reported greater WP_I under sprinkler irrigation compared to flood irrigation for winter wheat crops. This finding was explained by a negative linear relationship between WP_I and irrigation amount. Likewise, the reduction of the AE_N index under the flood irrigation system as compared to the sprinkler irrigation system was partially due to the lower grain yield. However, it could also be related to the possible higher N losses under the F irrigation system due to percolation losses (Ritter and Manger, 1985; Power et al., 2000; Spalding et al., 2001; Fang and Su, 2019) as the amount of water applied under F irrigation was higher compared to S irrigation.

The tillage system showed significant differences only under F irrigation conditions, with no-tillage systems being less efficient in the use of N and irrigation water compared to CT. However, no significant differences were observed in both efficiency indices due to stover removal under no-tillage. This result is in agreement with Jin et al. (2015), who reported no differences in maize grain yield in a 12-year comparison of the effect of stover removal in maize under no-tillage conditions. However, the authors reported the negative impact on soil properties such as soil organic carbon, SOC, or soil structure of a continuous stover removal practice, as other authors like Blanco-Canqui and Lal, (2008). This negative impact on soil properties, especially in SOC, was presented by Álvaro-Fuentes et al. (2021) in a study carried out in the same field, showing that the NT treatment reported the greatest losses of SOC after 4 years of maize monoculture, due to the reduction of carbon inputs coming from the maize stover compared to NTr and CT tillage treatments.

5. Conclusions

This study evaluated the impact of different tillage and irrigation systems on maize yield over four continuous growing seasons. The results shown in this study pointed out that tillage and especially irrigation systems had a significant impact on maize yield components and nitrogen and irrigation water use efficiencies. The sprinkler irrigation system increased all yield components and almost doubled the values of the two efficiency indexes assessed compared to the flood irrigation system. Moreover, the no-tillage system showed a negative impact on these parameters when it was implemented under flood irrigation, but no differences were observed under sprinkler irrigation. Likewise, stover removal under no-tillage had not a significant impact on crop performance.

This study stressed that the use of pressurized irrigation systems, which allow higher irrigation frequency and lower water application rates compared to traditional flood irrigation systems, can be combined with no-tillage to increase crop performance by reducing irrigation water inputs Mediterranean conditions, where finding water-saving strategies has become a high priority under the current water scarcity situation and the impacts of climate change.

CRediT authorship contribution statement

Jorge Álvaro-Fuentes: Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Investigation, Conceptualization. **José Cavero:** Writing – review & editing, Writing – original draft, Resources, Methodology, Conceptualization. **Samuel Franco-Luesma:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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