Field Crops Research 301 (2023) 109017

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

The use of double-cropping in combination with no-tillage and optimized nitrogen fertilization improve crop yield and water use efficiency under irrigated conditions

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ARTICLE INFO

Keywords:
Double-cropping system
Legume
Maize
Tillage system
N fertilization
Water use

ABSTRACT

Maize is one of the main irrigated crops in northern Spain. However, the traditional cropping system used for its cultivation has relied on intensive monoculture, demanding significant inputs, and resulting in occasional unprofitable yields. A promising practice to increase the sustainability of farms is the use of double-cropping systems. The aim of this study was to evaluate the combined impact of introducing a legume prior to maize, together with different tillage systems and mineral N fertilization rates on crop yields and water productivity under Mediterranean irrigation conditions. The study compared monocropping maize (MC) versus legume-maize double cropping (DC) with three tillage systems (conventional tillage, CT; minimum tillage, MT; no-tillage, NT), and three mineral N fertilization rates (zero, medium and high). The legumes employed were pea for grain (2019), vetch for green manure (2020), and vetch for forage (2021). The highest yields were found in DC. On the one hand, the benefits associated with legume cropping allowed for increased grain yield of DC maize; on the other hand, the combined biomass of the legume plus maize led the DC systems to achieve significantly higher total biomass (sum of grain and stover) than the MC systems. In addition, a better adaptation of the maize DC phenological cycle to environmental conditions favoured higher yields in this system. Higher water consumptions in DC systems resulted in lower yield water use efficiency (WUE_y). However, when only irrigation water was taken into account, DC was the system with the highest irrigation water use efficiency for yield (IWU_y). Similarly, the high biomass values generated in the DC system resulted in higher water use efficiency for biomass (WUE_b). The tillage system with the highest yields was NT. These results, together with a higher water retention capacity in NT made the water productivity (WUE_b, WUE_y and IWU_y) of these systems higher. The use of high N fertilizer rates did not show any yield or WUE advantage over the medium rate. The results of this study indicate that in Mediterranean agroecosystems, the use of legume-maize double cropping systems together with NT systems and reduction of N fertilization can be a good strategy to maintain crop yields, while saving N fertilizer, and to improve WUE_b and $IWUE_y$.

1. Introduction

In irrigated areas of NE Spain, the main crop is commonly maize followed by a fallow winter, because it is a crop that provides acceptable yields to farmers. However, the instability in selling prices together with the increase in production costs is leading farmers to look for alternatives to maintain the economic profitability of farms (Alcon et al., 2020; MAPA, 2023). Another issue affecting maize cultivation in this region is its high water consumption. This is especially important in a context of rainfall variability together with the rise of water and energy prices and

Abbreviations: CT, conventional tillage; DC, double-cropping; $IWUE_y$, irrigation water use efficiency for yield; MC, monocropping; MT, minimum tillage; NT, no-tillage; SOC, soil organic carbon; WUE_b, water use efficiency for biomass; WUE_y, water use efficiency for yield.

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https://doi.org/10.1016/j.fcr.2023.109017
Received 19 December 2022; Received in revised form 2 May 2023; Accepted 17 June 2023
Available online 24 June 2023

the predictions of increasing water scarcity (Noto et al., 2022; Tzanakakis et al., 2020).

One of the possible solutions studied to increase the farm profitability is the intensification of the cultivation system by growing two crops in a single year (double-cropping). This strategy has been studied in the region since 1980 s, but only in systems in which the second crop was used for forage (Pujol, 1984; Lloveras-Vilamanya, 1987). Nowadays, cultivation of two grain crops within a year is feasible due to the technical development of agricultural practices and genetic advancement that permitted the production of grain crops varieties with shorter cycles. Gil (2013) found that growing a winter crop before planting maize could increase gross margins by 13–22% compared to maize monoculture. The difference in the economical profit achieved would depend, among other causes, on the plant species chosen. For example, a rotation with legumes directly affects the nitrogen (N) budget, allowing a reduction of the N fertilizer rate needed for the subsequent crop from 30 to 150 kg N ha^{-1} (Unkovich et al., 2008; Kaye and Quemada, 2017; Cordeiro et al., 2022). Furthermore, the growth of legume would help to mobilise the phosphorus present in the soil by releasing carboxylic acids from the root exudates allowing the solubilisation of plant nutrients (Egle et al., 2003; Rebonatti et al., 2023). In addition, legumes are not susceptible to the same pests and diseases as cereals, hence they can interrupt the life cycle of pathogenic organisms, lowering their occurrence and/or severity in the following crop (Zander et al., 2016). Nevertheless, the improvement in yields due to positive effect of legumes incorporation is highly dependent on the soil and climatic characteristics of the cultivation area. For this reason, variations have been found in different European regions with gross margins ranging from − 67–106 € when legumes were used for grain and from 0 to 50 € when legumes were used for forage (Reckling et al., 2016). Specifically, in the Mediterranean region, Álvaro-Fuentes et al. (2009) found that the positive effect of legumes on a subsequent crop, in rainfed conditions, depends on the rotation phase and the year, indicating the need for a further study phase in this area. From an environmental point of view, legumes also result in positive effects such as reduced erosion (Ilker et al., 2018), nitrate loss during winter (Alonso-Ayuso et al., 2014) and increased crop biodiversity (Peoples et al., 2009). Double cropping profitability also depends on the adaptation of maize varieties to the growing area. It is evident that varying the time of sowing can help to reduce the impact of weeds and diseases on the crop if the cycle of these does not coincide with the main crop cycle (Rajablarijani et al., 2014; Rezaei et al., 2021). Furthermore, in the context of rising global temperatures, it is best if maize's reproductive cycle does not coincide with periods of higher temperatures, since this might have a negative impact on pollination and grain filling (Bunting, 1976; Otegui et al., 1995).

Regarding strategies focused on improving water use efficiencies, the use of winter legumes has been shown in some cases to increase water use efficiency (WUE), both by using rainwater during winter (Goshime et al., 2021), and by improving the water retention capacity of the soil (Latif et al., 1992; Stagnari et al., 2017).

The usual soil management for irrigated maize in the region is intensive tillage. In recent years, studies in irrigated maize such as Pareja-Sánchez et al. (2019) or in flood irrigation such as Franco-Luesma et al. (2020), have shown that the use of no-tillage allowed for increased maize yields while reducing costs for cultivation operations. However, there is limited available information on which soil tillage is better under double-cropping systems in irrigated condition. In this regards, some authors found contrasting results. For instance, accumulation of large amount of crop residues might promote physiological problems in plants due to the immobilisation of N by micro-organisms during the decomposition of organic materials. This could be especially problematic when using a second non-leguminous crop (Power et al., 1986; Reberg-Horton et al., 2012). To address these issues, proper management of N fertilization is necessary (Nevins et al., 2020). Specifically, in the Ebro valley region, traditional N fertilization rates by farmers have been 300–350 kg ha^{-1} (Sisquella et al., 2004). N fertilizer application rates have been determined based exclusively on likely plant N uptake and they have not considered the high pre-planting levels of soil mineral N that are common in the area (Berenguer et al., 2009). Previous work has shown that it was possible to reduce N fertilization rates without affecting crop yields (Di Paolo and Rinaldi, 2008). Because of the aforementioned biological N fixation, the reduction in N fertilization rates can be much larger when legumes are used in double-cropping systems (Silva et al., 2020). In the current situation of increasing prices of mineral fertilizers (European Commission, 2022), these measures can lead to significant economic savings on the farm.

The aim of this study was to evaluate the combined effect of cropping systems together with tillage systems and nitrogen fertilization rates on crop yields and crop water use efficiency under Mediterranean conditions. Our hypothesis was that the use of double-cropping systems with conservation tillage and medium N fertilizer rates would lead to greater productivities and resource use efficiencies.

2. Material and Methods

2.1. Experimental design and management practices

The study was conducted over three consecutive seasons (2019, 2020, and 2021) in Agramunt, a municipality situated in the Ebro River valley region of NE Spain (41°48′ N, 1°07′ E, 330 m asl). The area is representative of semiarid Mediterranean climate with a continental trend. The mean annual precipitation in the last 30 years is 442 mm, the mean annual temperature is 14.6 °C, and the annual potential evapotranspiration (PET) is 855 mm. Soil characteristics of the experiment are shown in Table 1. A rainfed long-term field experiment was established in 1996 to compare three rates of mineral N (0, 60 and 120 kg N ha^{-1}) and three tillage systems (conventional tillage, CT; minimum tillage, MT; no-tillage, NT) under barley monocropping (Angás et al., 2006). In 2015, the experiment was transformed to irrigated condition with a solid set sprinklers of 18 × 18 m spacing under maize (*Zea mays* L.) monocropping (Pareja-Sánchez et al., 2017). Tillage treatments were maintained, and mineral N fertilization rates were adapted to maize crop (0, 200, 400 kg N ha^{-1}) with the same experimental layout as the previous rainfed experiment. In 2018, to develop the study of crop diversification and its interaction with tillage and N fertilization, the experimental plots were split in two 3 m wide and 48 m long subplots. Into these new plots two cropping systems (Cs) (winter fallow-maize, monocropping, MC; legume-maize, double-cropping, DC) were included becoming split-plot arrangement of a randomized complete block design with 3 blocs. The same tillage systems (Till) were compared

Table 1
Soil properties of the Ap horizon (0–28 cm depth) in 1996. Initial soil organic carbon content (SOC_i) (1996) and soil organic carbon content (SOC) (0–30 cm) in three tillage systems (conventional tillage, CT; minimum tillage, MT; no-tillage, NT) in 2017.

Soil properties	
Soil classification*	Typic Xerofluvent
pH (H_2O, 1:2.5)	8.5
EC 1:5 (dS m^{-1})	0.15
P Olsen (mg kg^{-1})	35
K Amm. Ac. (mg kg^{-1})	194
Water retention (g g^{-1})	
− 33 kPa	0.16
− 1500 kPa	0.05
Sand (2–0.05 mm)	30.8
Silt (0.05–0.002 mm)	57.3
Clay (< 0.002 mm)	11.9
SOC_i	7.6
SOC (g kg^{-1})	
CT	8.6
MT	10.0
NT	12.2

* According to the USDA classification (Soil Survey Staff, 2014)

as previously (CT, MT and NT). The N fertilization rates (Fert) were zero (0 kg N ha^{-1}), medium (200 kg N ha^{-1}), and high (400 kg N ha^{-1}) for MC, and zero (0 kg N ha^{-1}), medium (150 kg N ha^{-1}), and high (300 kg N ha^{-1}) for DC. The reduction in N rates for DC accounted for the potential biological fixation of the legume crops (Cela et al., 2011). The area's average N fertilization rate is 300–350 kg ha^{-1} (Cavero et al., 2003; Isidoro et al., 2006).

For MC maize, a long-cycle maize cultivar (FAO 700, Pioneer's P1570 hybrid) was used. For DC a short-cycle maize cultivar (FAO 400, Pioneer's P0312 hybrid) was planted as summer crop and legumes as winter crop. The legumes were: pea used for grain (*Pisum sativum* L., var. Furious) during the 2018–2019 season and vetch (*Vicia sativa* L., var. Prontivesa) used as green manure during 2019–2020 and as forage during 2020–2021. The fact of changing legume species or the destination of the legume crop each year is not related to the comparison between legume species, but rather to the common practice of crop rotation in the region. During the three years of the study, MC maize was sown in April; DC maize in early or late June, depending on the harvest date of the preceding legume; and the legume from December to January (Table 2). The sowing rate in maize (MC and DC) was 90,000 seeds ha^{-1} with a separation between lines of 73 cm. In the case of legumes, a density of 100 plants m^{-2} was used for pea and 267 plants m^{-2} for vetch. Planting was carried out with a pneumatic row direct seeding machine equipped with double disc furrow openers (model Prosem K, Solà, Calaf, Spain).

The CT treatment consisted of subsoiler (35 cm depth) followed by one pass of rototiller (15 cm depth) and one pass of roller before planting with almost 100% of the crop residues incorporated into the soil. The MT treatment consisted of a pass chisel (15 cm depth). NT plots were sprayed with herbicide, 1.5 L ha^{-1} of 36% glyphosate [N-(phosphonomethyl)-glycine] without soil disturbance.

N fertilizer was applied manually and only to maize. In MC, pre-sowing fertilization with urea (46% N) was done in April-May (Table 2). It was surface broadcasting and incorporated with tillage in CT or MT and left on the soil in NT. The rate of pre-sowing fertilization was 50 and 100 kg N ha^{-1} for the medium and high rates, respectively. In addition, in both MC and DC, two top-dressing fertilizations were done in stages V3-V5 (May in MC, and June in DC) and V7-V8 (June in MC, and July in DC). These top-dressing applications involved ammonium nitrate (34.5% N) at 75 and 150 kg N ha^{-1} for the medium and high rates, respectively. At the beginning of each growing season, mineral fertilization with P and K was applied equally to all plots (220 kg P_2O_5 ha^{-1} $year^{-1}$ and 474 kg K_2O ha^{-1} $year^{-1}$), to cover the needs of maize and legumes assuming standard yields for the area.

Irrigation began in March and ended in October. Irrigation was applied according to maize requirements, which were determined weekly by subtracting the effective precipitation (75% of total weekly precipitation) from the crop evapotranspiration (Etc) (Dastane, 1978). Etc was calculated by the daily reference evapotranspiration (Eto), obtained using the FAO Penman-Monteith method and meteorological data from a weather station close to the field experiment. The crop coefficient (Kc) was calculated as a function of thermal time (Allen et al., 1998). The water used for irrigation comes from a dam on the Segre River, which directly collects snowmelt. Each year, the Irrigation Collective provides a water analysis, which consistently shows that the water has high quality for agricultural irrigation. It is free from salinity and has normal levels of N, P, and K, making it ideal for agricultural purposes.

The harvest was carried out from May to June for the legumes, in October for MC maize and November for DC maize (Table 2). Harvest residue management differed depending on tillage treatment and crop. In the case of maize, pea, and green manure vetch (2020), it was either tilled into the soil (CT or MT) or left on the soil surface (NT). In 2021, all plant material from the vetch plots was exported and used as forage.

2.2. Soil and crop sampling analysis

Soil samples were collected before sowing and after harvest of each crop (Table 2) from three depths (0–30, 30–60 and 60–90 cm depth) and from two different areas per plot. In these samples, gravimetric water content was determined by drying the samples in an oven at 105 °C. The gravimetric water content was converted to volumetric water content using the bulk density obtained by the soil core method (Grossman and Reinsch, 2002). At crop physiological maturity in grain crops (R6 for maize MC and DC; R7 for pea) and at the beginning of flowering (R1) in vetch crops, stover and grain yield were determined. For maize, 2-meter-long sections of plants were taken from three areas of each plot. For pea, the grain was collected using a 1.5 m wide micro-harvester. Vetch was collected in two parts of each plot by cutting 0.36 m^2 of plants at the soil surface level. For the crops with grain yield (maize and pea), the number of plants and ears/pods were counted and registered. The yield components and moisture were then determined using a sub-sample of two whole plants and five ears in maize and 1 m^2 of pea plant and their corresponding pods. The sub-sample was oven-dried at 60 °C for 48 h and weighed. The grain was threshed and weighed. Grain yield was adjusted to 14% moisture content. These determinations allowed calculating the total biomass as well as crop yield components: number of plants per square meter, number of ears per plant and thousand kernels weight (TKW). Total biomass was calculated as the sum of grain and stover dry weight. Grain and stover N concentration were determined by dry combustion (Truspec CN, LECO, St Joseph, MI, USA). Afterwards, N content of the grain and the stover were calculated by multiplying the biomass of each fraction by its N concentration. For a better understanding of the role of legumes in the DC system, crude

Table 2
Dates of sowing, harvesting, pre-sowing and post-harvest soil sampling, and pre-sowing and top-dressing fertilizations for each year and crop tested.

Year	Crop	Crop operations						
		Sowing	Harvest	Pre-sowing soil sampling	Post-harvest soil sampling	Nitrogen Fertilization		
						Pre-sowing (Urea 46% N)	Top-dressing 1 (NA 34.5% N)	Top-dressing 2 (NA 34.5% N)
2019								
	Maize MC	12/04/2019	14/10/2019	01/04/2019	13/12/2019	01/04/2019	27/05/2019	08/07/2019
	Maize DC	27/06/2019	19/11/2019	26/06/2019	13/12/2019	-	29/07/2019	12/08/2019
	Pea	26/12/2018	18/06/2019	29/11/2018	26/06/2019	-	-	-
2020								
	Maize MC	02/05/2020	23/09/2020	29/04/2020	23/11/2020	01/05/2020	26/05/2020	17/06/2020
	Maize DC	27/05/2020	24/10/2020	19/05/2020	23/11/2020	-	17/06/2020	07/07/2020
	Vetch	09/01/2020	19/05/2020	13/12/2019	19/05/2020	-	-	-
2021								
	Maize MC	25/04/2021	23/09/2021	19/04/2021	05/11/2021	21/04/2021	01/06/2021	15/06/2021
	Maize DC	01/06/2021	13/11/2021	23/05/2021	05/11/2021	-	15/06/2021	05/07/2021
	Vetch	27/12/2020	20/05/2021	23/11/2020	23/05/2021	-	-	-

protein content (CP) was calculated multiplying the N content by 6.25 (Mariotti et al., 2008). Total biomass CP was calculated as the sum of CP in both fractions.

2.3. Water productivity indicators

Crop water use (WU) was calculated as the difference between planting and harvest soil water content plus the rainfall and irrigation received between both dates. This parameter was used to calculate the water use efficiency (WUE) of legumes, maize, and whole cropping system both for total biomass (WUE_b) (Eq. 1) and grain yield (WUE_y) (Eq. 2):

$$WUE_b \text{ (kg biomass } ha^{-1}\text{mm}^{-1}) = \frac{\text{Total biomass}}{\text{WU}} \tag{1}$$

$$WUE_y \text{ (kg grain } ha^{-1}\text{ mm}^{-1}) = \frac{\text{Grain yield}}{\text{WU}} \tag{2}$$

Irrigation water use efficiency for grain yield ($IWUE_y$) was calculated as the ratio between the grain yield produced by maize and the amount of water applied by irrigation or irrigation water use (IWU) (Bos, 1980, 1985) (Eq. 3).

$$IWUE_y \text{ (kg grain } ha^{-1}\text{mm}^{-1}) = \frac{\text{Grain yield}}{\text{IWU}} \tag{3}$$

2.4. Data analysis

Statistical analyses were performed with the statistical package JMP pro 15 (SAS Institute Inc., 2020) and Statgraphics Centurion 18 (Statgraphics Technologies Inc., 2018). Data were checked for normality, homoscedasticity and serial independence by Shapiro-Wilk, Bartlett, and Durbin-Watson test respectively. Outliers were checked using the Grubb's test with a statistical confidence level of 95%. Data were transformed when necessary to pass these tests. A repeated measures analysis of variance (ANOVA) was performed with cropping system, tillage, and N fertilization, sampling date or year or period, and their interactions as effects.

Because the purpose of each legume differs according to the year, grain yield, total biomass and total biomass CP of the legumes were only statistically analysed for tillage and N fertilization and their interactions. For maize grain yield, maize total biomass and total biomass CP, TKW, WUE_b, WUE_y and $IWUE_y$, and whole cropping system (maize in MC and legume+maize in DC) total biomass and total biomass CP, WUE_b, WUE_y and $IWUE_y$ ANOVA tests were carried out with cropping system, tillage and N fertilization, year, and their interactions as effects. When significant, differences among treatments were identified at 0.05 probability level of significance with Tukey HSD test.

3. Results

3.1. Weather conditions during the experimental period

Monthly irrigation, precipitation, average monthly air temperature and cropping duration in vegetative and reproductive phase are shown in Table 3. During the three study years, mean temperature followed the typical oscillations of the Mediterranean climate with minimum values during the month of January (2.0, 4.9 and 3.5 °C for 2019, 2020 and 2021, respectively) and maximum values during the month of July (25.6, 25.3 and 24.6 °C for 2019, 2020 and 2021, respectively), coinciding with maize cropping. Specifically, the highest temperatures occurred during the beginning of flowering (VT) in MC and in vegetative growth (V10-V12) in DC. The cropping cycle duration was 5–6 months for MC and approximately 10 months for DC (4–5 months in legumes and 5–6 months in DC maize) (Table 3). The longer duration of the cropping cycle in DC made it the system with the highest amount of water received totalling by 1110 mm (745 mm for maize and 365 mm for pea), 835 mm (643 mm for maize and 192 mm for vetch) and 869 mm (702 mm for maize and 167 mm for vetch) in 2019, 2020 and 2021, respectively. In MC, the total amount of water received (rainfall and irrigation) was 979, 673 and 767 mm for 2019, 2020 and 2021,

Table 3
Monthly irrigation (I), precipitation (P) and mean air temperature (T) during 2019, 2020 and 2021 for legumes and maize. Coloured bars represent the growing season of each crop in vegetative (V phase) and reproductive phase (R phase).

Month	Year 2019			Crop	Year 2020			Crop	Year 2021			Crop
	I (mm)	P (mm)	T (°C)		I (mm)	P (mm)	T (°C)		I (mm)	P (mm)	T (°C)	
January	0.0	9.6	2.0	Pea (V phase)	0.0	22.0	4.9	Vetch (V phase)	0.0	26.0	3.5	Vetch (V phase)
February	0.0	12.0	7.0	Pea (V phase)	0.0	1.0	8.4	Vetch (V phase)	0.0	18.0	9.7	Vetch (V phase)
March	22.3	2.4	9.3	Pea (V phase)	0.0	37.0	9.6	Vetch (V phase)	8.9	16.0	9.6	Vetch (V phase)
April	10.0	40.7	11.4	Pea (V phase); Maize MC (V phase)	0.0	111.0	13.2	Vetch (V phase)	27.2	30.0	11.8	Vetch (V phase)
May	70.0	62.1	14.8	Pea (R phase); Maize MC (V phase)	1.9	41.0	18.3	Vetch (V phase); Maize MC (V phase)	40.3	28.0	16.6	Vetch (V phase); Maize MC (V phase)
June	111.6	14.9	22.5	Pea (R phase); Maize MC (V phase)	40.5	58.0	20.7	Maize DC (V phase); Maize MC (V phase)	91.6	16.0	22.2	Maize DC (V phase); Maize MC (V phase)
July	200.0	35.9	25.6	Maize DC (V phase); Maize MC (V phase)	208.7	5.0	25.3	Maize DC (V phase); Maize MC (V/R phase)	185.6	24.0	24.6	Maize DC (V phase); Maize MC (V/R phase)
August	177.1	8.0	24.9	Maize DC (V phase); Maize MC (R phase)	228.5	5.0	24.8	Maize DC (V phase); Maize MC (R phase)	254.1	12.0	24.3	Maize DC (V/R phase); Maize MC (R phase)
September	130.4	5.0	20.2	Maize DC (R phase); Maize MC (R phase)	70.1	14.0	19.3	Maize DC (R phase); Maize MC (R phase)	94.8	21.0	20.9	Maize DC (R phase); Maize MC (R phase)
October	58.3	106.0	15.2	Maize DC (R phase); Maize MC (R phase)	13.6	0.0	12.5	Maize DC (R phase)	0.0	3.0	15.2	Maize DC (R phase)
November	0.0	24.0	7.6	Maize DC (R phase)	0.0	1.0	10.4	Maize DC (R phase)	0.0	6.0	8.6	Maize DC (R phase)
December	0.0	44.0	7.8		0.0	14.0	5.0		0.0	20.0	5.0	
Year	779.7	364.6	14.0		563.3	309.0	14.4		702.6	220.0	14.3	

respectively.

3.2. Grain yield, total biomass and total biomass crude protein (CP)

Regarding the growth of legume crops, in 2019, both tillage and N fertilization rate substantially changed grain yield, total biomass, and total biomass CP of pea crop (Table 4). NT had significantly higher pea yield (3.34 t ha^{-1}), total biomass (9.0 t ha^{-1}) and total biomass CP (960 kg ha^{-1}) compared to CT and MT. For the above-mentioned parameters, N fertilization treatment only caused significant differences between the unfertilized and fertilized treatments, but not between the studied rates. In 2020, the only significant treatment was tillage system in which the highest total biomass and total biomass CP of vetch crop was observed in NT (3.1 t ha^{-1} and 984 kg ha^{-1}, respectively). In 2021, the interaction between tillage system and N fertilization rate was significant on both vetch total biomass and total biomass CP. NT was shown to produce the highest total biomass values and, although it was not statistically significant, crop performance was best when NT was paired with the medium rate of N fertilization (7.3 t ha^{-1} and 1121 kg ha^{-1}, respectively for total biomass and total biomass CP).

Maize production was significantly affected by the interaction among cropping system, tillage, and N fertilizer rate (Table 5). In general, maize yields under DC were greater than those under MC (Table 6). The use of NT also favoured high grain yields when combined with medium (11.4 and 11.7 t grain ha^{-1} respectively in MC and DC) or high rates of N fertilization (12.5 and 11.9 t grain ha^{-1} respectively in MC and DC). Maize DC and MC showed similar values for total biomass and total biomass CP when used in conjunction with NT. However, in case of using MT or CT, the highest values of total biomass and total biomass CP were obtained in DC. High rates of N fertilizer were shown to had no effect on maize total biomass or maize total biomass CP when compared to medium rates of N fertilization (Table 6). TKW was on average 14% higher in DC than in MC. In case of DC system, the highest values were found for MT or NT (272 and 278 g respectively) and for medium and high N rates.

Analysing the whole cropping system results (maize in MC and legume-maize in DC), the interaction among cropping system, tillage and N fertilization rate was found to be significant for total biomass and total biomass CP (Table 5). For both parameters, DC was the system with the highest values. In case of DC, the best results were obtained with the use of NT and medium or high rates of N fertilization (mean for the medium and high rates of N fertilization of 33.2 t ha^{-1} for total biomass and 2394 kg ha^{-1} for total biomass CP). Conversely, the lowest values were found for the MC system especially for CT (mean for the three N fertilization rates of 13.7 t ha^{-1} total biomass and 795 kg ha^{-1} biomass CP) (Table 6). For both total biomass and total biomass CP, the use of a high rate of N fertilization did not produce significant differences compared to medium rates.

3.3. Crop water productivity

Averaged across the three study years, DC maize consumed less total water (sum of rainfall and irrigation) than MC (697 and 806 mm in DC and MC, respectively). However, considering the complete legume-maize system, DC was found to be the system with the highest water consumption (950 mm). Nevertheless, if only irrigation water is considered, the difference between the water applied for the MC and DC system was minor (656 and 681 mm in MC and DC, respectively). WUE_b in legumes was significantly affected by the interaction between tillage, N fertilization rate and year (Table 7). During the three study years the highest WUE_b occurred in NT with medium or high rates of N fertilization, although this was only significant in the years 2019 and 2021 (Fig. 1). For none of the experimental years did the use of the high rate of N fertilization result in higher WUE_b compared to the medium rate.

A significant interaction among cropping system, tillage and N fertilization rate was found for all maize water productivity indicators studied (Table 7). WUE_b, WUE_y, $IWUE_y$ were higher in DC maize (30.4, 13.8, and 15.8 kg ha^{-1} mm^{-1} respectively) than in MC (20.0, 9.9 and 12.2 kg ha^{-1} mm^{-1} respectively). For the MC system, the use of CT implied an average reduction of 10–15% on WUE_b, WUE_y, and $IWUE_y$ compared to MT and 25–30% compared to NT. The use of mineral N fertilization (medium and high) implied increases in water use efficiency compared to the zero N rates in both cropping systems. However, no differences were observed on WUE_b, WUE_y, or $IWUE_y$ when using a high or medium rate (Fig. 2).

Analysing the whole cropping system (when both legume and maize were taking into account), significant interactions were observed among cropping systems, tillage and N rates on crop water productivity indicators (Table 7). WUE_b was 29% higher in the DC system than in MC. For treatments with N fertilization, the use of DC reduced WUE_y with

Table 4
Analysis of variance of pea grain yield (2019) (0% moisture); and total biomass (0% moisture) and total biomass crude protein (CP) for each year as affected by tillage (CT, conventional tillage; MT, minimum tillage; NT, no-tillage) and N fertilization rate (Zero, Med and High: 0, 200 and 400 kg N ha^{-1} for MC; 0, 150, 300 kg N ha^{-1} for DC) and their interactions. For each variable, different letters indicate significant differences between treatments at $p < 0.05$. Values in brackets indicate standard deviation.

Treatments	2019 (grain pea)						2020 (green manuring vetch)				2021 (forage vetch)			
	Grain yield (t ha^{-1})		Total biomass (t ha^{-1})		Total biomass CP (kg ha^{-1})		Total biomass (t ha^{-1})		Total biomass CP (kg ha^{-1})		Total biomass (t ha^{-1})		Total biomass CP (kg ha^{-1})	
CT	2.39 (0.83)	b	6.63 (2.09)	c	701 (270)	c	4.47 (1.04)	b	726 (199)	b	4.0 (0.9)	b	654 (134)	b
MT	3.00 (0.81)	a	8.26 (2.28)	b	831 (239)	b	4.63 (0.9)	b	773 (216)	b	4.43 (0.7)	b	696 (123)	b
NT	3.34 (0.74)	a	9.44 (2.0)	a	870 (203)	a	7.94 (1.94)	a	1180 (367)	a	6.6 (1.6)	a	1035 (255)	a
Zero	2.5 (0.9)	b	7.0 (2.4)	b	650 (236)	b	5.2 (2.0)		794 (311)		5.0 (1.4)		794 (220)	
Med	3.1 (0.7)	a	8.1 (2.6)	a	788 (172)	a	5.6 (1.9)		902 (237)		4.9 (2.1)		754 (322)	
High	3.2 (0.8)	a	9.0 (2.2)	a	960 (227)	a	6.1 (2.3)		984 (423)		5.1 (1.1)		837 (181)	
CT-Zero	2.1 (0.9)		5.9 (2.4)		512 (184)		4.5 (0.8)		695 (180)		4.2 (1.0)	d	691 (142)	c
CT-Med	2.6 (0.5)		7.0 (1.5)		671 (125)		4.3 (0.9)		714 (163)		3.4 (0.8)	d	535 (100)	c
CT-High	2.7 (1.0)		7.5 (2.2)		918 (305)		4.6 (1.4)		768 (259)		4.5 (0.5)	d	736 (53)	bc
MT-Zero	2.4 (0.8)		6.4 (2.0)		642 (211)		4.3 (1.2)		685 (240)		4.6 (0.6)	cd	695 (76)	c
MT-Med	3.1 (0.7)		8.5 (1.7)		802 (148)		4.7 (0.6)		828 (149)		4.0 (0.8)	d	607 (130)	c
MT-High	3.5 (0.6)		9.9 (1.7)		1048 (157)		4.9 (0.8)		807 (240)		4.7 (0.5)	bcd	785 (94)	bc
NT-Zero	3.2 (0.9)		8.7 (1.9)		804 (249)		6.9 (2.3)		1001 (396)		6.2 (1.6)	abc	994 (252)	ab
NT-Med	3.6 (0.7)		8.9 (3.9)		903 (177)		7.9 (1.4)		1145 (224)		7.3 (1.8)	a	1121 (284)	a
NT-High	3.3 (0.7)		9.7 (2.0)		919 (198)		8.8 (1.6)		1380 (443)		6.3 (1.2)	ab	988 (232)	ab
ANOVA (*p*-values)														
Tillage (Till)	< 0.001		< 0.001		0.003		< 0.001		< 0.001		< 0.001		< 0.001	
N fertilization (Fert)	0.004		< 0.001		< 0.001		NS		NS		NS		NS	
Till·Fert	NS		NS		NS		NS		NS		0.02		0.02	

Table 5
Analysis of variance (*p*-values) of maize parameters: grain yield (0% moisture) total biomass (0% moisture), total biomass crude protein (CP), thousand kernels weight (TKW); and whole cropping system (maize in MC and legume+maize in DC) parameters: total biomass (0% moisture), total biomass crude protein (CP) as affected by tillage, N fertilization rate, cropping system, year and their interactions.

Source of variation	Maize				Whole cropping system	
	Grain yield (t ha^{-1})	Total biomass (t ha^{-1})	Total biomass CP (kg ha^{-1})	TKW (g)	Total biomass (t ha^{-1})	Total biomass CP (kg ha^{-1})
Tillage (Till)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
N fertilization (Fert)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Cropping system (Cs)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Year	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Till·Fert	< 0.01	< 0.001	NS	NS	< 0.001	< 0.01
Till·Cs	< 0.05	< 0.05	< 0.01	NS	NS	NS
Till·Cs·year	NS	NS	< 0.01	< 0.01	< 0.05	< 0.05
Till·Cs·Fert	< 0.001	< 0.001	< 0.05	< 0.05	< 0.01	< 0.05
Fert·Cs	NS	NS	< 0.01	NS	NS	< 0.05
Till·Fert·Year	NS	NS	< 0.01	NS	< 0.05	< 0.001
Fert·Cs·Year	< 0.001	< 0.001	< 0.01	< 0.001	< 0.001	< 0.001
Year·Till	< 0.05	< 0.05	< 0.001	< 0.05	< 0.05	< 0.01
Year·Fert	< 0.05	< 0.05	< 0.001	NS	< 0.05	< 0.001
Year·Cs	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Year·Till·Fert·Cs	NS	NS	NS	NS	NS	NS

Table 6
Maize parameters: grain yield (0% moisture), total biomass (0% moisture), total biomass crude protein (CP), thousand kernels weight (TKW); and the whole system (maize in MC; legume+maize in DC) parameters: total biomass (0% moisture), total biomass crude protein (CP) as affected by tillage, N fertilization rate, cropping system, year and their interactions. Data corresponds to the mean of 2019, 2020 and 2021 cropping years. Values between brackets correspond to standard deviation. Different lower-case letters indicate significant differences between treatments at $p < 0.05$.

Treatments	Maize								Whole cropping system			
	Grain yield (t ha^{-1})		Total biomass (t ha^{-1})		Total biomass CP (kg ha^{-1})		TKW (g)		Total biomass (t ha^{-1})		Total biomass CP (kg ha^{-1})	
MC-CT-Zero	4.2 (2.4)	ij	10.5 (5.6)	gh	485 (271)	l	207 (44)	ghi	10.5 (5.6)	i	485 (271)	i
MC-CT-Med	7.9 (3.9)	fg	16.1 (7.8)	ef	982 (443)	gh	219 (39)	gh	16.1 (7.8)	h	982 (443)	gh
MC-CT-High	6.9 (5.0)	gh	14.1 (9.5)	fg	910 (574)	hi	230 (43)	g	14.1 (9.5)	h	910 (574)	h
MC-MT-Zero	3.6 (1.3)	j	9.4 (4.7)	h	538 (334)	kl	206 (32)	hi	9.4 (4.7)	i	538 (334)	i
MC-MT-Med	9.3 (3.7)	e	17.2 (6.6)	def	1119 (457)	efg	241 (30)	f	17.2 (6.6)	gh	1119 (457)	gh
MC-MT-High	9.3 (3.7)	e	17.7 (6.2)	cdef	1049 (295)	fgh	252 (35)	cdef	17.7 (6.2)	fg	1049 (295)	gh
MC-NT-Zero	4.3 (1.1)	ij	10.8 (3.5)	gh	519 (225)	l	202 (29)	i	10.8 (3.5)	i	519 (225)	i
MC-NT-Med	11.4 (3.3)	abcd	20.9 (7.3)	abcd	1221 (366)	cde	247 (37)	def	21.7 (6.0)	ef	1221 (366)	fg
MC-NT-High	12.5 (4.3)	a	22.9 (7.1)	ab	1388 (454)	a	260 (36)	cde	22.9 (7.1)	cde	1388 (454)	ef
DC-CT-Zero	5.5 (2.6)	hi	13.7 (5.6)	fgh	673 (302)	jk	244 (46)	ef	18.5 (5.9)	fg	1306 (393)	fg
DC-CT-Med	9.2 (2.6)	ef	19.9 (6.1)	bcde	1159 (329)	defg	268 (37)	bc	24.7 (7.0)	bcde	1756 (402)	de
DC-CT-High	11.0 (2.8)	bcd	23.2 (5.9)	ab	1365 (317)	abc	289 (35)	a	28.6 (6.4)	abc	2122 (377)	bcd
DC-MT-Zero	6.6 (2.5)	gh	15.8 (4.5)	ef	781 (381)	ij	260 (29)	cd	20.9 (4.0)	efg	1455 (442)	ef
DC-MT-Med	10.4 (1.9)	cde	21.9 (4.0)	abc	1202 (238)	def	280 (28)	ab	27.7 (5.4)	bcd	1947 (266)	cd
DC-MT-High	10.3 (1.8)	de	22.5 (5.3)	ab	1247 (428)	cde	278 (30)	ab	29.0 (6.6)	ab	2127 (501)	bc
DC-NT-Zero	6.6 (2.0)	gh	16.1 (3.9)	ef	745 (306)	ij	259 (31)	cde	23.4 (4.4)	de	1675 (485)	de
DC-NT-Med	11.7 (1.8)	abc	25.1 (3.3)	a	1288 (258)	bcd	282 (30)	ab	33.2 (4.2)	a	2318 (429)	ab
DC-NT-High	11.9 (2.0)	ab	24.9 (4.1)	ab	1437 (449)	ab	295 (36)	a	33.2 (3.6)	a	2470 (428)	a

respect to MC (mean of 12.2 vs 11.2 kg ha^{-1} mm^{-1} for MC and DC, respectively) (Fig. 3b). However, $IWUE_y$ was higher in DC system than in MC (mean of 16.0 vs. 15.1 kg ha^{-1} mm^{-1} respectively) (Fig. 3c). In both cropping systems, the tillage treatment with the highest water productivity of the crops was NT (mean of 27.6, 11.3 and 14.9 kg ha^{-1} mm^{-1} respectively for WUE_b, WUE_y and $IWUE_y$). In all situations, N fertilization increased WUE_b, WUE_y and $IWUE_y$ compared to no fertilization, with no significant differences between medium and high rates.

4. Discussion

4.1. Maize cropping cycle adaptation and effects

Our study found that using short-cycle maize varieties resulted in better adaptation to environmental and cropping conditions, leading to higher yields compared to long-cycle varieties. Contrary to our expectations, the short cycle maize (DC) had a similar duration to the long cycle (MC). Previous work has shown that the time required for maize to move from one stage of development to another depends on the amount of heat accumulated (Gilmore and Rogers, 1958). Although DC had high temperatures during the initial period of vegetative development, temperatures during the reproductive period were lower than in MC. This caused the flowering and physiological maturity period of DC maize to be longer than usual in a F400 cycle but did not negatively affect yield. Temperatures are a key factor especially in the anthesis period of maize (Tollenaar, 1989; F. H. Andrade et al., 1993; Stewart et al., 1998; Lizaso et al., 2018; Tiwari and Yadav, 2019). More specifically, temperatures above 30 °C have a negative effect on grain filling (Waqas et al., 2021). It was found that during the reproductive phase in MC, temperatures above these values could negatively affect grain filling due mainly to pollen viability and lower number of pistils but also by causing damage in plant growth and development (Barnabás et al., 2008; Wahid et al., 2007; Ordóñez et al., 2015). This was evidenced by the lower TKW for MC maize. In contrast, DC maize escaped to the effects of high temperatures that were coincident with the vegetative development while temperatures were moderate during the reproductive phase. Similar

Table 7
Analysis of variance (*p*-values) of water use efficiency for total biomass (WUE_b) of legumes; and water use efficiency for grain and for total biomass (WUE_y and WUE_b) and irrigation water use efficiency ($IWUE_y$) maize and the whole system (maize in MC; legume+maize in DC) as affected by cropping system, tillage, N fertilization rate, year and their interaction.

Source of variation	Legumes	Maize			Whole cropping system		
	WUE_b	WUE_b	WUE_y	$IWUE_y$	WUE_b	WUE_y	$IWUE_y$
Tillage (Till)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
N fertilization (Fert)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Cropping system (Cs)	-	< 0.001	< 0.001	< 0.001	< 0.001	NS	< 0.001
Year	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Till·Fert	NS	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Till·Rot	-	NS	NS	< 0.05	NS	< 0.01	< 0.01
Till·Rot·year	-	NS	NS	NS	< 0.001	NS	< 0.05
Till·Rot·Fert	-	< 0.001	< 0.001	< 0.001	< 0.01	< 0.001	< 0.001
Fert·Rot	-	NS	NS	NS	< 0.05	< 0.001	< 0.001
Till·Fert·Year	< 0.01	< 0.01	NS	NS	< 0.01	NS	NS
Fert·Rot·Year	-	< 0.001	< 0.001	< 0.001	< 0.01	< 0.001	< 0.001
Year·Till	< 0.01	< 0.001	< 0.001	< 0.01	< 0.001	< 0.01	< 0.01
Year·Fert	< 0.01	< 0.001	< 0.01	< 0.001	< 0.01	< 0.001	< 0.001
Year·Rot	-	< 0.001	< 0.001	< 0.001	< 0.01	< 0.001	< 0.001
Year·Till·Fert·Rot	-	NS	NS	NS	NS	NS	NS

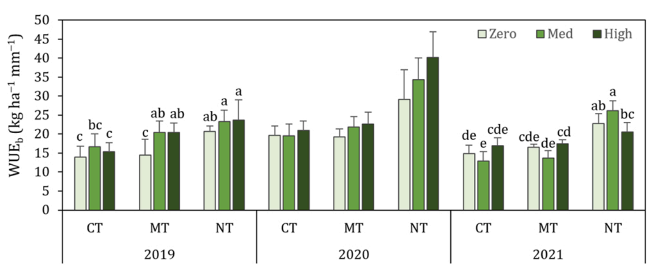

Fig. 1. Legume water-use efficiency for total biomass (WUE_b), as affected by tillage treatments (CT, conventional tillage; MT, minimun tillage; NT, no-tillage) and N fertilization rates (Zero, Med and High: 0, 200, 400 kg N ha^{-1} for MC; 0, 150, 300 kg N ha^{-1} for DC) during thethree consecutive years (2019, 2020 and 2021). For a given year, different lowercase letters indicate significant differences between tillage and N fertilization rates at $p < 0.05$. The vertical bars indicate standard deviation.

results have been found in different experiment in which both the cropping cycle and the sowing date have an important effect on the tolerance to high temperatures and therefore on the yield (Dong et al., 2021).

4.2. Effect of legume crop on maize and whole system yields and water productivity

The results of this study have shown that replacement of winter fallow by a legume increases maize yields while reducing N fertilizer. Several reasons could explain these results. First, we hypothesized that N fixation promoted by the use of a legume before the maize cropping was sufficient to maintain grain yields when pre-emergence urea fertilization was eliminated. Similar results were documented from this region when legumes were used in the cropping system, with reduction of fertilizer requirement of 30–60% for the subsequent crop (Peoples et al., 2009). Second, the higher soil coverage provided by legumes could have played an important role in reducing the infestation of summer weeds associated with maize. Similarly, it has been observed that inclusion of legumes reduced the occurrence of fungal infections such as *Fusarium spp.* in DC maize compared to MC maize (Buddenhagen, 1990; Bilalis et al., 2010; Odhiambo et al., 2010). Other authors have found similar results and noted that the positive effect was because of the breaking of the disease cycle by the sowing of a non-host species such as legumes (Richthofen et al., 2006; Yusuf et al., 2009; Chekali et al., 2016). Finally, recent studies in this same experimental field have shown that the use of legumes increased macroporosity and gas diffusivity in the soil (Talukder et al., 2022). This plays a major role in the yield of the subsequent cropping, in some cases increasing maize yields by 5–20% (Bullock, 1992). In addition, the use of legumes increases SOC. The higher aggregate formation observed in DC (data not published) might have favoured the protection of SOC within soil macroaggregates from microbial attack resulting in longer residence times (Blanco-Canqui and Lal, 2004), and consequently a better soil structure that favours higher cropping yields (Morugán-Coronado et al., 2020).

At the whole cropping system scale, it was observed that legumes significantly increased both total biomass and total biomass CP in DC. The legume produced on average 6.3 t ha^{-1} $year^{-1}$ of total biomass. This may have an impact on the direct economic profitability of the DC system if the crops are taken off from the farm for sale. This is particularly important given the current need for protein crops for both animal feed and human consumption (Semba et al., 2021; Adler, 2022; Medendorp et al., 2022). Specifically, the species used had an average production of 830 kg CP per hectare and per year.

In the crop water productivity analysis, it was found that the use of legumes favoured a higher water productivity for DC maize when only the water consumed by the maize is considered. MC maize received more water because its entire cropping cycle coincided with periods of high evapotranspirative demand (April to September). Although DC maize was planted in months with high water demand as well, the end of the cycle was at times of lower temperature and evapotranspiration demand, which allowed rainwater to be sufficient to supply the crop's water needs. Numerous authors worked with different maize varieties and planting dates, indicating that appropriate planting time and maize cycle could imply a significant reduction of water consumption (Howell et al., 1998; Feyzbakhsh et al., 2015; Lu et al., 2017). As discussed above, the legume has an impact on improved soil properties. Improved soil structure and bulk density improves water holding capacity and protects against surface runoff and deep percolation (Ramos et al., 2019; Talukder et al., 2022). In addition, increasing SOC has been shown to increase porosity (Liu et al., 2019), aggregation, surface area, water absorption capacity (Lal, 2020) and favourable properties of some hydrophilic compound (Bronick and Lal, 2005), then increasing soil water retention.

In the opposite situation, considering the rainwater consumed by the legumes, it was found that the complete legume-maize system has a higher water consumption. Since only the grain yield of maize was considered for the WUE_y, the possible advantage of the legume lies only in improved system properties and not in direct yield. Therefore, although maize yields were higher for the DC system, the higher water consumptions for this system make WUE_y lower in DC. Similar results were observed in different trials with legumes as green manure for maize

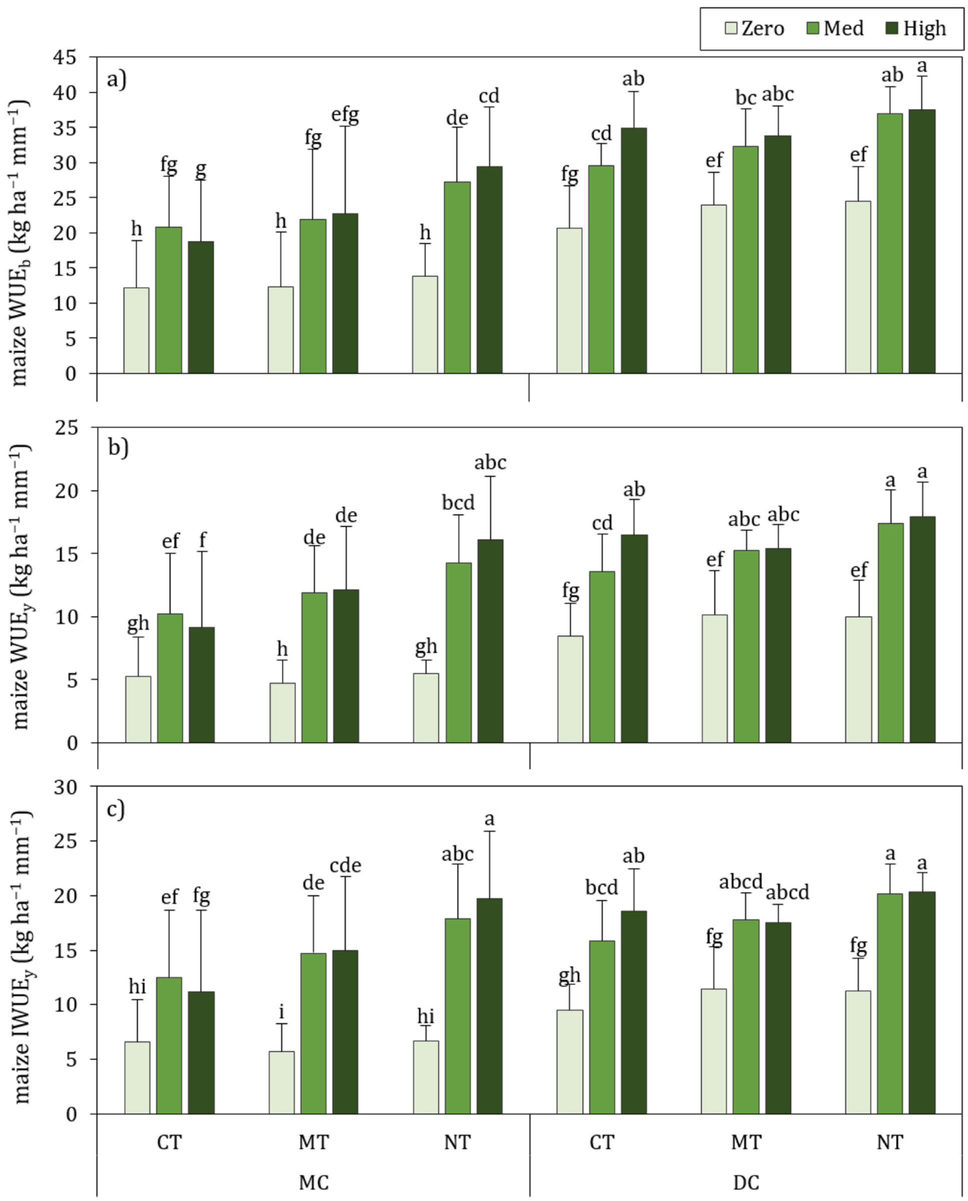

Fig. 2. Cropping system (MC, monocropping system; DC double cropping system), tillage system (CT, conventional tillage; NT, no-tillage) and N fertilizer rate (Zero, Med, and High: 0, 200 and 400 kg N ha^{-1} for MC; 0, 150, 300 kg N ha^{-1} for DC) effects on maize water-use efficiency for total biomass (WUE_b) (a), maize water-use efficiency for yield (WUE_y) (b) and maize irrigation water-use efficiency for yield ($IWUE_y$) (c). The values correspond to three winter crop seasons followed by three maize growing seasons (2019, 2020, and 2021). The different lowercase letters indicate significant differences between treatments at $p < 0.05$. The vertical bars indicate the standard deviation.

or intercropping. In these experiences, the use of legumes also resulted in increased irrigation water demand for the diversified system, especially during years of low rainfall (Zhang et al., 2016; Ma et al., 2021). On the contrary, if we take into account the total biomass of the legume and the maize, WUE_b is higher for DC. Although legume cropping involved some water consumption, it also involved an increase in the biomass produced in the legume-maize system. If only irrigation water is considered, the higher grain yields together with similar irrigation water consumption make $IWUE_y$ for DC higher. This was observed in other experiences in which the adaptation of the cropping system or the sowing dates allowed the optimisation of the irrigation water used and therefore the increase in the efficiency of irrigation water consumption (Zhang et al., 2019; Srivastava et al., 2020).

4.3. Contribution of conservation tillage and optimized N fertilization on double-cropping system

The use of conservation tillage systems increased yields in both legume and maize cropping and, therefore, at the cropping system scale. Conservation tillage and especially NT were the systems with the highest legume yields. Several authors have found that conservation tillage works especially well in legume cropping by generating an environment with increased humidity and warmth, which is favourable for rhizobia establishment (van Kessel and Hartley, 2000; Andrade et al., 2003). This implies a higher atmospheric N fixation (López-Bellido et al., 2011) and thus a higher N input to the subsequent maize cropping. In maize cropping, NT also directly favoured higher yields. It has been shown that maize planting on fresh crop residues can present nutritional problems due to N starvation during residue decomposition. This is of particular relevance for residues with high C:N ratio (Yu et al., 2017; Zou et al., 2020). In our case, the highest C:N values for legumes were found for pea crop (C:N, 20–40). Some authors have found that pea can immobilise up to 28% of the added N with the pea residue itself, which in some cases can cause N starvation problems (Kumar and Goh, 2007). This N deficiency problem might happen more frequently with tillage since it accelerates waste degradation (Liu et al., 2021). On the other hand, when these residues are left on the surface (NT) there is a more gradual decomposition, which does not cause nutritional problems due to N deficiency to the subsequent crop (Dalal et al., 2007). Furthermore, conservation tillage systems have been shown to provide better physical

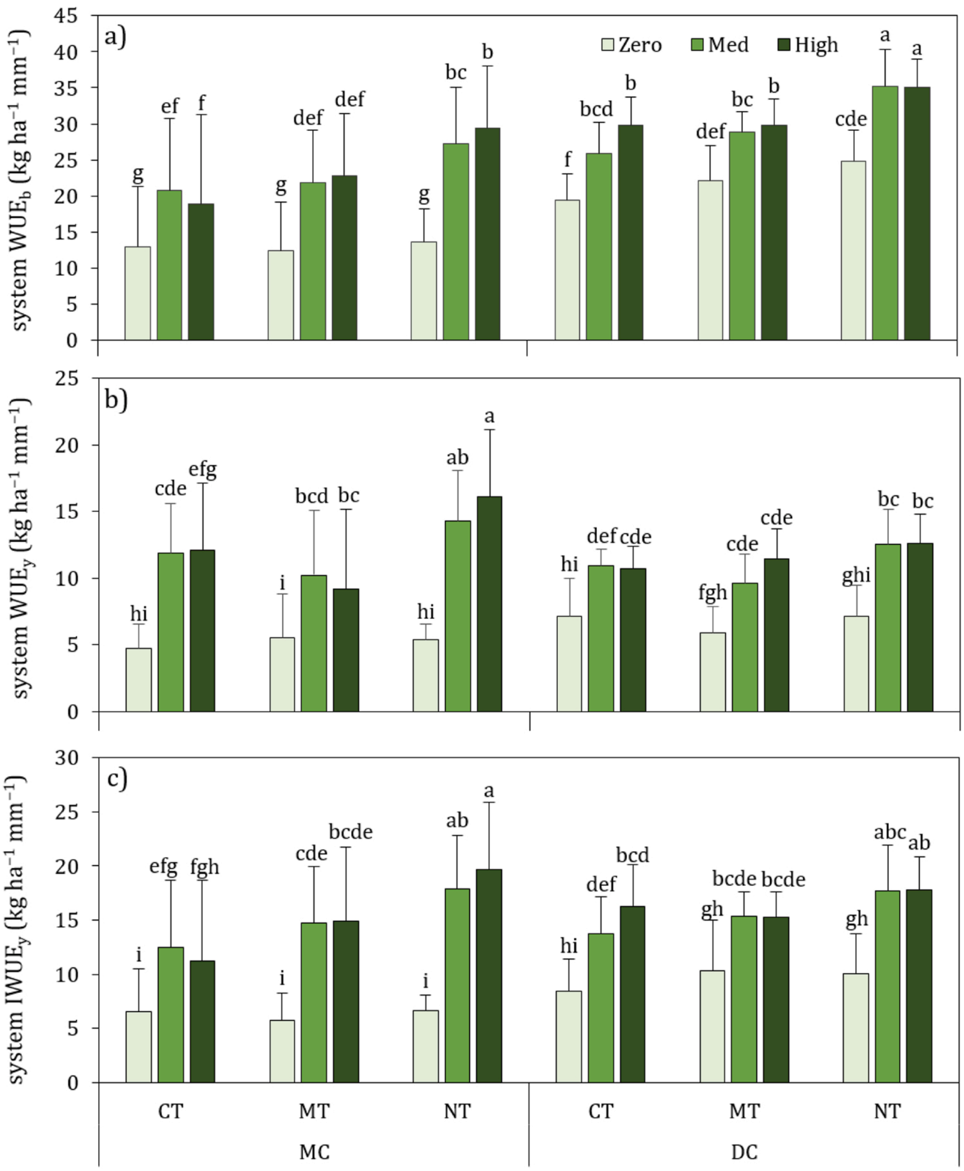

Fig. 3. Cropping system (MC, monocropping system; DC double cropping system), tillage system (CT, conventional tillage; NT, no-tillage) and N fertilizer rate (Zero, Med, and High: 0, 200 and 400 kg N ha^{-1} for MC; 0, 150, 300 kg N ha^{-1} for DC) effects on system water-use efficiency for total biomass (WUE_b) (a), maize water-use efficiency for yield (WUE_y) (b) and maize irrigation water-use efficiency for yield ($IWUE_y$) (c). The values correspond to three winter crop seasons followed by three maize growing seasons (2019, 2020, and 2021). Different lowercase letters indicate significant differences between treatments at $p < 0.05$. The vertical bars indicate the standard deviation.

properties of the soil, including the formation of soil macroaggregates with improved soil structure and increased soil water content (Lampurlanés and Cantero-Martínez, 2003; Pareja-Sánchez et al., 2019). Conversely, the CT favours the mineralisation of organic matter, eliminating the benefits that a soil with adequate SOC levels brings to cropping (Álvaro-Fuentes et al., 2014; Pareja Sánchez et al., 2020). In addition, the poorer soil structure found in CT systems led to waterlogging, which affect the occurrence of phytotoxins that compromise the yields and quality of the crop (Borràs-Vallverdú et al., 2022). Thus, although all tillage treatments received the same amount of water from rainfall and irrigation, the highest water use efficiencies were for the conservation tillage systems. This could be due to: 1) the described enhanced soil physical characteristics in conservation tillage, which favoured better yields in these systems; 2) conservation tillage was more resilient to crust formation than CT (Pareja-Sánchez et al., 2017). This was particularly observed in MC. Recent work in this experimental field demonstrated the capacity of legumes to partially restore the soil pore continuity after tillage practice, making the differences between tillage treatments smaller in DC (Talukder et al., 2022).

The use of high rates of N fertilizer did not lead to higher crop yields in any of the cropping systems used. For the study area, it has been found that the application of 200 kg N ha^{-1} is sufficient for adequate N nutrition of maize (Pareja-Sánchez et al., 2019). With legume diversification, this rate can be reduced to 150 kg N ha^{-1}. However, under CT, in some cases we found that the application of medium rates of N fertilizer was not enough, forcing to increase to high N rates in order to achieve adequate grain and total biomass yields. Several articles have shown that the poorer soil structure in CT leads to increase of surface runoff (Hazra et al., 2019) and deep percolation (Stevens et al., 2010; Issaka et al., 2019) favouring the loss of nitrate. Conversely, higher SOC levels in NT, promotes a higher retention of ammoniated forms of N in the exchange complex (Nõmmik and Nilsson, 1963; Nieder et al., 2011), avoids N losses due to physical soil problems (Van Den Bossche et al., 2009) and allows a slow mineralisation of organic matter, which results in a better N supply to maize throughout the cropping cycle (Balesdent et al., 1990; Osterholz et al., 2017; Kan et al., 2020). Use of high N fertilization rates, since it does not increase yields or reduces the water consumption of the crop, has not proved to be a useful strategy to increase water use efficiency. Therefore, similar irrigation demands, together with higher grain and total biomass yields, allow the DC system combined with NT soil management and medium rate N fertilization to increase water use efficiencies while generating savings in N mineral fertilization.

5. Conclusion

The use of legumes together with no-tillage systems resulted in higher maize yields compared with continuous maize systems. Furthermore, when accounting for the biomass generated by the legume, it was found that the double cropping system had a higher production of total biomass and total biomass CP. These results together with a reduction of mineral fertilization showed that, in Mediterranean farming systems the use of legumes in double-crop maize systems can be a useful strategy to maintain farm profitability. Moreover, in a global context of difficult access to water resources, the use of double cropping together with NT systems have proven to be a system that improves WUE_b and $IWUE_y$ compared to traditional maize monocropping in CT.

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.

Acknowledgements

The authors would like to thank Carlos Cortés and Silvia Martí for laboratory and field assistance. This research work was financially supported by the Ministerio de Ciencia e Innovación of Spain (project AGL2017-84529-C3-3-R; PhD fellowship PRE2018–084610).

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